Evaluation of Poly(etheretherketone) for Use as Innovative Material in the Fabrication of a Removable Partial Denture Framework

By

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A Thesis Submitted in Fulfillment of the Requirement for the Degree of

Doctor of Philosophy

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September 2016

Acknowledgement

First and foremost, I would like to express my thanks and gratitude to Almighty Allah (God) for granting me willingness and strength to establish this work and for His limitless blessings.

I wish also to express my deep love, gratitude and prayers to my loving parents (Ali) and (Layla) who have supported me and prayed all the time so that I be successful in my studies and hence kept me going through the completion of this work.

I would like also to express my gratitude and appreciation to my supervisors Dr. Duncan J. Wood, Professor Paul V. Hatton, and Dr. Anthony Johnson for giving me the opportunity to carry out this thesis under their expert supervision. I deeply appreciate their encouragement, support, invaluable advice, expertise and knowledge which have made go forward towards a PhD with a great experience. And, special thanks to Nuno Sereno, the representative of Invibio® and Juvora™ Ltd for supplying the PEEK material for this study. And I would also like to thank Dr. Robert Moorehead for his support with lab issues.

I will be forever in debt to my sister Ekhlas for she has been always a role model to follow. I am thankful to my young brother, Hussein, for his technical support and advice, my brother-in-law, Hayder, for being a real brother to me, my brothers: Jalal and Muhanned, my albino nephew, Ameer, and his brother, Fedhl, for treating me as a mother and sometimes as a sister, and my nieces, Shadan, the first granddaughter in the family, her sisters: Riyam and Lujain, the youngest ladies in the family.

Great thanks with peace to my beloved country, Iraq, for supporting me financially through the Higher Committee of Educational Development in Iraq (HCED), the scholarship program that supports the most talented students in Iraq, and for giving me the opportunity to be the first candidate in Iraq for a PhD degree as a dental technician.

Thanks to all colleagues and friends in Iraq, the USA and the UK for their support, prayers and wishes for a good luck in my life.

Saja Ali Muhsin
September 2016

Abstract

Since the 1930s, partial denture frameworks have generally been made from metallic alloys and resin polymers such as Cobalt-Chromium (Co-Cr) and Polymethylmethacrylate (PMMA). However, the main limitations of these materials over the last 15 years are related to their biocompatibility, long term performance and it seems neither of these materials meets the ideal properties for satisfactory results for long standing applications. Polyetheretherketone (PEEK) as a new thermoplastic polymer has been successfully used for medical purposes due to outstanding mechanical properties, thermal and chemical stability in implantations. PEEK shows promise for use instead of metals inside the human body.

The aim of this study is to evaluate PEEK polymer as an alternative material for use in the fabrication of removable partial denture frameworks. Initially the evaluation was by denture injection moulding method to explore the material's physical properties, and then with CAD/CAM techniques the mechanical properties were investigated to consider these findings for design considerations. Clasps were then designed and the retentive force tested with thermo-cycling fatigue representing 3 years of insertion/removal. The significant findings of this study relate to its demonstration of the superior mechanical properties of PEEK polymer as a denture base material compared to PMMA, and the exceptional retentive force of the innovative clasp design at different tooth undercuts compared to the conventional Co-Cr clasp design. In conclusion, these study findings indicate the promise offered by PEEK thermoplastic polymer for future use as a denture material.

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ASTM	American Society for Testing and Materials
CAD/CAM	Computer Aided Design/Computer Aided Manufacture
CFR-PEEK	Carbon Fiber Reinforced- Polyetheretherketone
DSC	Differential Scanning Calorimetry
DWOS	Dental Wing Office Software
FCG	Fatigue Crack Growth
FTIR	Fourier transform infrared (spectroscopy)
HA	Hydroxyapatite
HA/PEEK	Hydroxyapatite/ Polyetheretherketone Composite
HCF	Human Corneal Stromal Fibroblast
ICI	Imperial Chemical Industries
K_{IC}	Fracture Toughness
L929- ATCC #CCL 1	Murine Fibroblast Cells
PAEK	Polyaryletherketone
PAN	Polyacrylonitrile
PE	Polyethylene
PEEK	Polyetheretherketone
PEKEKK	Polyetherketoneetherketoneketone
PEKK	Polyetherketoneketone
PET	Polyethylene terephthalate
PP	Polypropylene
Pr	Radius of curvature of the notch
PS	Polystyrene
PTFE	Polytetrafluoroethylene
RPD	Removable Partial Denture
SEM	Scanning Electron Microscope
T_c	Recrystallization Temperature
T_f	Flow Transition Temperature
T_g	Glass Transition Temperature
T_m	Melting Transition Temperature
UHMWPE	Ultrahigh Molecular Weight Polyethylene
Victrex 450CA30	30 % CFR-PEEK (Carbon Fiber Reinforced-Polyetheretherketone)

Chapter One

Introduction

Chapter One: Introduction

Over the last three decades, the advancement of developmental investigation in the scientific field of dental materials has produced a large amount of research data. Since prosthodontic treatments developed in the laboratory have clinical implications which could impact on overall patient approval and the clinical success of those treatments, the drive towards the practice of evidence based dentistry and increase in media coverage have resulted in improved patient knowledge. Patients' awareness of the potential such treatments may lead them to have higher expectations of their dental practitioners and the appliances they provide.

Several materials have been introduced over the last centuries in dentistry for partial dentures. These include wood, ivory, porcelain, hard gold alloys and vulcanite thermoplastic polymer. Since the 1930s, when cobalt chromium alloys and the PMMA polymer were first launched in dentistry, they have become the most commonly used materials for denture bases as an alternative to hard gold alloys (Van Noort, 2013). Even so, failures of partial dentures were generally associated with the material properties (Vallittu and Kokkonen, 1995; Sato *et al*., 2003) and framework design integrity (Rudd and Rudd, 2001a; Rudd and Rudd, 2001b; Rudd and Rudd, 2001c). Currently used denture materials have shortcomings related either to strength or biocompatibility. The complexity and diversity of Co-Cr alloys make understanding their biocompatibility difficult, since any element in an alloy may be released and might influence the body. Moreover, the framework components tend to undergo fatigue fracturing after long-term functioning (Wataha, 2000). In addition, these alloys are difficult materials for dental practitioners to handle, they require special laboratory casting techniques and considerable time for trimming and polishing (Powers and Wataha, 2014). Polymers are used in combination with metallic frameworks; these thermoplastic materials are widely used in prosthetic dentistry. Their lack of strength and toughness makes them susceptible to fracture with up to 10% of dentures fracturing within 3 years of use (Van Noort, 2013); additionally, there is a risk of methylmethacrylate liquid release (Lung and Darvell, 2005). It seems that no denture material has yet fully satisfied the ideal criteria for successful denture base performance. In the modern world biomedical materials play an important role in the manufacturing of a variety of prosthetic devices.

Over the last two decades, PolyEtherEtherKetone (PEEK) has shown itself to be a versatile biomaterial that can be used to produce a variety of medical and dental applications (Kurtz, 2011b; Najeeb *et al*., 2015; Zoidis *et al*., 2015). PEEK is a semi-crystalline thermoplastic biomaterial with potentially excellent mechanical and thermal properties. It has attracted more interest than any other implantable material for medical devices in the last 20 years (Kurtz, 2011b). With a low modulus of elasticity, outstanding solvent resistance, and biocompatibility with bone, this polymer is a candidate to replace metals in the body. PEEK demonstrates greater strength than many metals on a per mass basis (Johnson *et al*., 2000). This could be related to its mechanical properties as well as its high temperature resistance (Thomas and Stuart, 2003). The chemical structure of PEEK presents stability at temperatures exceeding 300 °C, resistance to radical and thermal damage, as well as compatibility with different reinforcing agents like Carbon fibers. Therefore, PEEK is a candidate to replace metallic medical components and devices and has become the leader of the high performance thermoplastic polymers. No studies have yet evaluated PEEK polymer as a new restorative material for fabrication of removable partial denture frameworks. Therefore, this study aims to evaluate the PEEK as a new restorative dental material and in particular for the fabrication of removable partial denture frameworks. This could involve processing and machining by denture injection method and CAD/CAM techniques. This will be accomplished by assessing specific properties regarding material and design considerations.

Chapter Two

Literature Review

Chapter Two: Literature Review

2.1. Denture Base Material

Denture base materials are used to contact the oral tissues and support artificial teeth (Powers and Wataha, 2014). Since the 18th century, a wide variety of denture materials have been introduced to replace missing teeth and their associated structures. Wax was the first material used for intra-oral impressions and models; then ivory was used by carving it into the required denture shape. However, ivory's hygienic prospect limited its use, and in 1728 Fauchard suggested making dentures from porcelain (Fauchard, 1728), assuming that it could be more attractive and coloured as required as well as more hygienic (Young, 2010). In 1744, Duchateau produced the first recorded porcelain denture (Murray and Darvell, 1993).

In the 1850s, a cheap and easy to handle vulcanite material was identified, and this was used to replace unhygienic costly ivory and porcelain dentures. Vulcanite produced accurately fitting prostheses at reasonable cost, making it accessible to a large number of consumers (Khindria *et al*., 2009). Vulcanite denture bases were fitted with porcelain teeth requiring mechanical retention due to lack of chemical bonding between the vulcanite denture base material and the porcelain teeth. Techniques were established to improve this bonding by making undercut holes in posterior porcelain teeth and placing pins in anterior teeth (Engelmeier, 2003; Young, 2010). Nonetheless, this material became less satisfactory due to its lack of translucency which affected the aesthetic results; additionally, its porosity had the potential to increase the accumulation of plaque and oral fluids which consequently made the denture base unhygienic (Young, 2010). Many synthetic polymers such as polyamides, epoxy resin, polystyrene, polyvinyl acrylic, rubber graft copolymers, polycarbonate and polymethylmethacrylate have been developed and tested as potential alternative denture base materials (Stafford *et al*., 1980; Stafford *et al*., 1986). These are organic molecules of many repeating segments (Powers and Wataha, 2014), but may not generally prove successful since many of them are susceptible to distortion due to water sorption as well as being soluble in most solvents, including chloroform (Van Noort, 2013), although some rubber-reinforced polymers of higher impact strength have been used to reduce the risk of fracture (Powers and Wataha, 2014).

Metals and alloys have been introduced for dental application and used in a number of restorations in dentistry by means of casting techniques (Van Noort, 2013; Powers and Wataha, 2014). Great improvements have been made in the physical and mechanical properties of these base metal alloys and their application could outstrip that of the rarely and costly pure metals (Luthy *et al*., 1996; Powers and Wataha, 2014). However, for the last two decades their uses have been limited due to their performance or biocompatible risks.

2.1.1. Denture Base Material Requirements

Despite the fact that the material scientists and researchers have continued to improve the physical and mechanical properties of the materials used in dentistry, none of these materials fulfill all the ideal properties. Any new material used for denture provision, regardless of the method of construction, should aim to improve on what has gone before. To enable this, it is essential to overcome some of the material problems by testing the characteristics and analyzing their performance in practical applications. Many properties need to be taken into consideration in assessing the dental restorative performance of these materials. Therefore, such assessment is one of the most crucial basic factors in selecting material for dental uses.

Biocompatibility is the main requirement in all restorative materials, followed by the mechanical and physical and aesthetic properties to guarantee appropriate function and structural permanence over long periods of time (Anusavice *et al*., 2013).

Van Noort points out that the selection of an ideal denture base material should be based on the following characteristics (Van Noort, 2013):

- Natural appearance
- Effortless manipulation
- High strength, stiffness, hardness and toughness
- Accurate reproduction of surface details with dimensional accuracy
- Low in odour, taste and toxic products
- Does not enhance bacterial growth
- Resistant to the absorption of oral fluids
- Good quality of thermal conductivity
- Good retention to other materials such as polymers, ceramics and metals
- Good radiopacity
- Easy to repair and clean

- Enduring shelf life and reasonably economical to use

McCabe and Walls, meanwhile, indicated that the essential properties of an ideal denture base material should be listed under the following headings (McCabe and Walls, 2013).

Biocompatibility

Biocompatibility is one of the essential material properties of a material selected for medical or dental application. Biocompatibility is “the appropriate biologic response of the body to a material used in a specific application” (Powers and Wataha, 2014). However, the biological performance is the response of the material to the living structure as well as the local and systemic responses of the host to this material (Black, 2005; Kurtz, 2011b). Biocompatibility is the passive interaction between the material and the host; hence, it seems that as yet no biocompatible materials exist for dental application. Nevertheless, any material that evokes only a minimal biological response can still be regarded as a biocompatible material, and such a biomaterial must be nontoxic, non-mutagenic, non-carcinogenic and non-immunogenic at a minimum (Kurtz, 2011b). The material should have the quality of evoking an appropriate biological response from the host when used for specific purpose, and should not generate any destructive harmful products in the biological environment (Anusavice *et al*., 2013; Van Noort, 2013; Powers and Wataha, 2014).

From the materials science and legal points of view, allergic reactions to dental materials are crucial concerns. Restorative dental materials should not cause harmful, toxic, or allergic consequences for the patient’s health. Moreover, dentists have the moral and ethical obligation to minimize the risk of these materials by means of sound practice. Furthermore, they should keep a record for the material used for each prosthesis or restoration to support their understanding of any allergies reported by the patient, as, in addition, the patients have the right to know what is being placed in their bodies (Anusavice *et al*., 2013; Powers and Wataha, 2014).

Chemical Properties

A denture base material should be chemically inert, and insoluble in oral fluids as the mechanical properties of the material may change and become unhygienic, the material should be impermeable to water and oral fluids (McCabe and Walls, 2013).

Corrosion is “an electrochemical reaction of a material, usually metallic, which results in the release of ions from the material, the surface or internal destruction of the material and the formation of new reaction products” (Powers and Wataha, 2014). Meanwhile, tarnish is corrosion of the material surface resulting in discolouration which can be removed by polishing. However, corrosion resistance is an extremely significant consideration in the composition of dental alloys. Since the duplication of the oral conditions is difficult to manage, laboratory studies cannot predict accurately the susceptibility of a material to corrosion in the oral environment (Powers and Wataha, 2014).

Physical Properties

The dental material should provide good dimensional stability, and the denture should keep its shape over a period of time, and resist distortion due to thermal softening and water absorption. As the denture base should be as light in weight as possible, the base material should ideally have a low specific gravity. Despite the fact that the normal temperature in the mouth varies only from 32 °C to 37 °C, a denture base polymer should have higher value of glass transition (T_g) temperature (McCabe and Walls, 2013). This must be sufficiently high; the material may be exposed to hot drinks of temperatures up to 70 °C or cleaned by hot or even boiling water. In addition, a base material of appropriate thermal conductivity can play a significant role in maintaining healthy oral mucosa. The material should reflect a normal reaction to cold and hot stimuli (Powers and Wataha, 2014).

Mechanical Properties

Despite the fact that the polymethylmethacrylate (PMMA) has been widely used as a denture base polymer for many years, this material sometimes cracks or fractures in clinical use (Kanie *et al*., 2000). Low resistance to impact and flexural fatigue are considered to be the main factors in causing such fractures. Many studies have attempted to address these problems by increasing the strength of the denture base polymer either by adding cross-linking or reinforcement of the denture base polymer with fibres or rods such as metal wires or mesh (Carroll and Von Fraunhofer, 1984;

Ruffino, 1985). However, the influence of metal wires on resistance flexural fatigue is minor (Vallittu, 1996).

In clinical use, dentures may fracture due to large transitory force resulting from either an accident or a small force due to repeated stress or strain during mastication. Fractures may develop from microscopic cracks in areas of stress concentration which in turn fuse to become ever growing fissures after loading. This may insidiously lead to material failure resulting from a final loading cycle that exceeds the mechanical capacity of the remaining sound portion of the material (Wiskott *et al*., 1995). Flexural fatigue frequently results in a midline fracture in the denture base, and impact failures usually occur as a result of an accident out of the mouth collision with a hard object. Damage to the denture base material is not the only factor influencing denture fractures; other factors can also involve (Jagger and Harrison, 1998). Denture base fractures can related to the tooth form or functional stress which may increase the deformation of the denture base (Kydd, 1956; Lambrecht and Kydd, 1962); stress concentration due to presence of a large anatomical notch (Rees *et al*., 1989); dentures with under extended or thin flanges, or that have been poorly fitted, repaired or designed (Yunus *et al*., 1994). However, it is the case that when the material exceeds the maximum mechanical capacity under load fracturing may take place due to flexural fatigue (Jagger *et al*., 1999).

The flexural strength of a specimen is the maximum stress developed in that specimen just before it cracks or breaks in a flexure test. Flexural strength is one of the most important mechanical properties for denture base materials. It has been reported that denture base materials with complete polymerization have superior mechanical properties such as transverse and flexural strength compared to those with incomplete polymerization (Jagger, 1978; Grajower and Goultschin, 1984; Harrison and Huggett, 1992).

Therefore, it is essential to measure the flexural strength of dental base materials in order to determine the denture base's resistance to force and trauma (Jagger, 1978). The mechanical behaviour of the denture base, including its flexural strength, depends on the type of material and even on processing techniques (Lee *et al*., 2012). Therefore, acrylic resins and processing methods have been modified to improve the physical and chemical properties of denture bases. The introduction of injection moulding was one of the methods introduced to overcome the adverse effects of compression moulding like dimensional accuracy. Different studies have focused on the use of injection moulded denture base materials and processing techniques with enhanced properties (Garfunkel, 1983; Anderson *et al*., 1988). In addition, injection moulding has the advantages of resistance and stability over conventional moulding techniques (Gharechahi *et al*., 2014b).

Dental materials must have sufficient strength to be used for long-span frameworks to maintain successful performance. Despite some slight variation in opinion, the majority of clinicians consider that a high value of modulus of elasticity is required in the base material to encounter stress, and avoid permanent deformation to the base framework during biting and mastication. However, the most superior advantages are achieved when a relatively thin base section is fabricated from a denture base material of high modulus, with a high value of elastic limit, table (2-1). In addition, the material should have sufficient flexural strength to resist fracturing (Anusavice *et al*., 2013). This could occur due to material fatigue mechanisms causing cumulative flexural stress over a period of time. Hence, the material should provide adequate fatigue life and a high degree of fatigue limitation to prevent the propagation of fractures from small cracks. In addition, the material should have sufficient abrasive resistance, so it can prevent excessive material wear by food or denture cleanser substances (Anusavice *et al*., 2013; McCabe and Walls, 2013).

Table (2-1): Modulus of elasticity of some base metal alloys, adapted from Anusavice *et al*. (2013)

Alloy	**Modulus elasticity (** GPa)
Co-Cr	125- 220
Ni-Cr	145-19
CP Ti	117
Pd-based alloys	110-135
Au-based alloys	75-110

Economic Consideration

Prosthodontic device cost is established according to the type of teeth and the base materials and design. The cost of the metals as a framework for partial denture is a function of the metal density and the cost per unit mass. The density is “the amount of mass in grams that occupies a volume of one cubic centimetre (g/ cm^3)” (Powers and Wataha, 2014). An alloy of high density has a greater weight in comparison to other types of alloys of the same piece size. In addition to cost considerations, a denture base material should have a long shelf life so that it can be purchased in bulk and stored without deteriorating, and it should be easy to manipulate, fabricate and repair without requiring the use of excessive processing equipment. The metal’s cost is the main concern for the dental laboratory owner since the prices of the prosthetic work should be guaranteed over a certain period of time (McCabe and Walls, 2013).

2.1.2. Metallic Denture Base Material

In 1978, a survey of 1000 dental laboratory owners showed that 29% were using Co-Cr and Ni-Cr alloys for cast metal restorations. By 1981, this percentage had increased to 70% as a result of the unstable cost of noble metals at that time. The majority of these laboratories indicated a preference for using Ni-Cr base metal alloys rather than Co-Cr alloys.

Despite the fact that the price of gold and other noble metals has steadily declined, the high acceptance of these alloys has had the effect of slightly retreating this trend (Anusavice *et al*., 2013). Nevertheless, dental prosthetic materials underwent substantial changes in the 20th century. The considerations that are motivating novel developments are economy, performance and aesthetics. The new material should be less expensive and competitive performing better than the old material, whilst providing superior performance to the old product. This could be acheved by improving the fracture resistance as well as the processing techniques and handling characteristics. Table (2-2) shows the evolution of dental casting alloys during the past century (Anusavice *et al*., 2013).

Table (2-2): Major events in the evolution of dental casting alloys (Anusavice *et al.*, 2013)

Event	Year	Economy	Performance	Aesthetic
Introduction of lost wax technique.	1907	√	√	√
Replacement of gold by Co-Cr for removable partial dentures.	1933	√		
Development of resin Veneers for gold alloys.	1950			√
Introduction of porcelain-fused to metal technique.	1959		√	√
Palladium based alloys as alternatives to gold alloys.	1968	√		
Nickel based alloys as alternatives to gold alloys.	1971	√		
Introduction of all-ceramic technologies.	1980s			√
Gold alloys as alternatives to palladium based alloys.	1999	√		

Base Metal Alloys

Non-noble metals are used frequently in dentistry, and the most significant applications are for partial denture frameworks. The most important structural standpoint for these metals is biocompatibility. Despite the fact that many studies and tests have been conducted to improve their performance in biological environments, some metals have demonstrated unsuitability in dental applications. Base metals possess undesirable corrosion characteristics, and may deteriorate during functioning leading to fracture of small components. However, of greater importance are the biological consequences, since corroded products may be taken in by the body after their dissolution from the metal restoration (Ferracane, 2001). Power and Wataha found these alloys to be among the most complex of all the dental casting alloys. They may contain up to 8 elements in addition to the primary elements (Powers and Wataha, 2014). These alloys have relatively high density alongside high yield strength and hardness. Therefore, they are the most difficult of all the alloys to cast, finish and polish, table (2-3) (Powers and Wataha, 2014).

Table (2-3): Physical and mechanical properties of some base metal alloys (Powers and Wataha, 2014)

Alloy Type	Melting range (°C)	Density (g/cm^3)	Yield Strength (Mpa)	Hardness (kg/mm$^{2)}$	Uses
Ni-Cr	1275	7.5	710	340	• All-metal crowns • Ceramic-metal crowns • Partial denture frameworks • Wrought applications
Co-Cr	1400-1500	7.5	870	380	• All-metal crowns • Ceramic-metal crowns • Partial denture frameworks • Wrought applications

Cobalt-Chromium RPD Alloys

Base metal alloys as indirect restorative and prosthetic materials were introduced in the late 1930s for the fabrication of removable partial denture frameworks. Compared with the conventional and previously predominant hard gold alloys, Co-Cr alloys have become extremely popular in many countries for use in these prostheses (Powers and Wataha, 2014). Their greater stiffness and lighter weight, combined with suitable mechanical properties and low cost may justify them becoming an alternative choice to noble metal alloys (Anusavice *et al.*, 2013).

Composition

The chemical composition of Co-Cr alloys for dental base metal casting alloys was specified in the ISO standard No. (6871-1 in 1997), which recommended that the cobalt casting alloy should meet the following requirements:

• Cobalt	main constituent
• Chromium	no less than 25 %
• Molybdenum	no less than 4 %
• Cobalt+ Nickel+ Chromium	no less than 85 %

The majority of removable partial denture frameworks are made from principally metal components. Cobalt is the primary metal in cobalt chromium alloys. The coloured transition element is silver with the atomic number 27. The melting point of this metal is approximately 1500 °C and it provides little ductility at room temperature. The composition of the most common Co-Cr alloys used in dentistry is approximately (Anusavice *et al*., 2013):

- 60 % Co,
- 25 % Cr,
- 10 % Ni,
- 5 % Mo, and
- 0.3 % C

The cobalt and nickel metals may be used almost as substitutes for each other in alloys. They increase the alloy’s hardness; however, nickel to some extent enhances the alloy’s elongation, making it slightly ductile. As with many alloys, molybdenum is added to strengthen and harden Co-Cr alloys. Since the use of large amounts of carbon may make the alloy brittle and difficult to bend or adjust without it tending to fracture, to contract this problem, only a small concentration of carbon should be added. Chromium, meanwhile, is added to improve corrosion resistance (Ferracane, 2001).

The hardness and ductility of any alloy is a good indication of consequent handling difficulties (Carr and Brown, 2011; Anusavice *et al*., 2013; Powers and Wataha, 2014). McCabe and Walls, on the other hand, specified that the typical alloy for adequate mechanical properties should at least contain 35-65% cobalt, 25-35% chromium, 0-30% nickel, a small amount of molybdenum and a trace quantity of other elements such as beryllium, carbon and silicon (McCabe and Walls, 2013).

Casting

Dimensional accuracy is one of the main issues to be considered during framework fabrication; along with its maintenance during clinical performance. Compensation for casting shrinkage from the solidus to room temperature is essential to achieving an accurately fitting cast framework or prosthesis. This could be done either through computer-generated oversized wax design or controlling the mould expansion (Carr and Brown, 2011; Powers and Wataha, 2014). However, Co-Cr alloys for partial denture framework restorations showed approximately 2.33 % shrinkage after casting (Anusavice *et al*., 2013).

2.1.3. Resin Denture Base Materials

Although various resins have been introduced to construct dentures such as cellulose products, phenol- formaldehyde (Bakelite), vinyl resins and vulcanite, these materials have revealed a variety of problems in their performance (Tandon *et al*., 2010).

Despite the fact that vulcanite was the first material used for the mass production of dentures, lack of aesthetic quality led to the suggestion of polymethylemethacrylate material as a replacement (Little, 1982; Van Noort, 2013).

Polymethylemethacrylate (PMMA)

Since polymethylemethacrylate (PMMA) was introduced in 1937, it has become the most commonly used resin, and the most popular polymeric denture base material. This may be due largely to it meeting many more of the criteria for the ideal denture base material compared to previously introduced resins (Johnson and Jones, 1994).

Chemical Structure

Many chemical reactions take place during PMMA polymerization. These include initiation, propagation, termination, chain transfer and tacticity of the polymer chain (Darvell, 2009). PMMA is formed by additional polymerization of multiple methylmethacrylate molecules (Combe and Combe, 1986). In the presence of heat or chemical activation a benzyl peroxide inhibitor proceeds to break down to create free radicals. To form the free radical addition polymerization chain reaction the free radicals act upon the vinyl group of methyl methacrylate, opening the double bond and thereby causing formation of a new single carbon bond, figure (2-1) (Anusavice *et al*., 2013). Depending on the amount of glycol dimethacrylate included in the mixture, two polymer chains or more may be united through the polymerization process (Harrison *et al*., 1978).

The production of another free radical results from the opening of each double bond, and this tends to attack and join another double bond. As a consequence of this tendency, other free radicals are produced and the reaction continues. Chain propagation is the term used for this repeated reaction. It seems that the free radicals link the methyl methacrylate residues together by means of methylene bridges (–CH2–). These chains carrying active free radicals are called live or growing chains (Combe and Combe, 1986).

Depending upon the concentration of available free radicals, chain termination can occur at any time. This results from the mutual reaction of two free radicals which are formed either from the initiator or the chain (Greener *et al*., 1972). The termination of a chain reaction results from hydrogen atoms transferring from anywhere in the system to attack the free radicals. This simultaneously stimulates the other chains, and the new chain reaction may or not be within the existing polymer chain, figure (2-2) (Van Noort, 2013). The methyl methacrylate double bond results in an asymmetrical free radical which in turn produces a carbon atom that also has an asymmetrical environment after the reaction (Darvell, 2009).

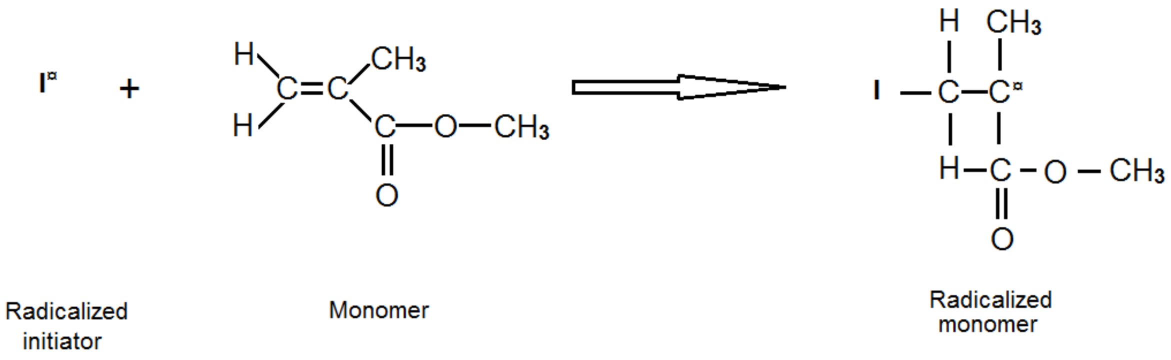


Figure (2-1): Addition polymerization of methylmethacrylate monomer, adapted from Anusavice *et al*. (2013)

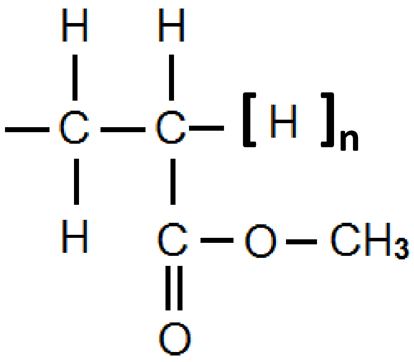


Figure (2-2): Repeating poly(methylmethacrylate) unit, adapted from Van Noort (2013)

Composition

PMMA is usually dispensed as a powder-liquid system (Anusavice *et al*., 2013; Van Noort, 2013). The constituents of the powder and liquid components are detailed according to the acrylic resin activation and processing method.

Heat Activated PMMA

The energy required for polymerization of heat activated or cured resin is provided in the form of heat, or less frequently a microwave oven (Combe and Combe, 1986). The material consists of powder and liquid constituents, table (2-4), and the correct powder/liquid ratio should be followed to avoid errors during denture processing. This is typically 1.6/1.0 by volume or 2.0/1.0 by weight (Van Noort, 2013). The incorporation of too little liquid with the polymer granules will causes the processed acrylic to have a granular texture. This is related to the polymer being partially wetted by the monomer. In contrast, too much monomer in the mixture results in a higher level of polymerization shrinkage. The correct polymer/monomer ratio demonstrates about 7 % polymerization shrinkage (0.5 % linear shrinkage). However, pure monomer shows a level of approximately 21 % by volume (Grant, 1978; Young, 2010).

Table (2-4): Heat-cure resin constituents (Van Noort, 2013)

Powder	Liquid
• Beads or granules of poly methyl methacrylate. • Initiator--- benzoyl peroxide • Pigments/ dyes • Opacifiers--- titanium/ zinc oxides • Plasticizers--- dibutyl phthalate • Synthesis fibers--- nylon/acrylic	• Methyl methacrylate monomer • Inhibitor--- hydroquinone • Cross-linking agent--- ethylene glycol dimethacrylate

Chemically Activated PMMA

The polymerization reaction for chemical cured, self-cured or auto polymerization PMMA, starts as soon as the powder and liquid components are mixed together. Consequently, they should be kept separate until required. The benzoyl peroxide that is present in the pre-polymerized poly (methylmethacrylate) spheres may also be activated by chemicals, table (2-5). Hence, no heat is required for the polymerization reaction to occur. In this type of curing method, dimethyl-p-toluidine, a tertiary amine, is used to activate the polymerization reaction. The reaction is the same as for heat cured materials once the polymerization has commenced (Greener *et al*., 1972; Young, 2010; Van Noort, 2013).

Table (2-5): Chemically cured PMMA constituents (Young, 2010)

Powder	Liquid
• Pre- polymerized PMMA spheres • Initiator--- Benzoyl peroxide (1-2%) • Pigment (1%)	• Methylmethacrylate monomer • Inhibitor--- Hydroquinone (<1%) • Cross -linking agent --- Glycol dimethacrylate (1-2%) • Activator--- Dimethyl-p-toluidine

Light Activated PMMA

Visible light is used to activate denture base resins comprising the composite mixture of constituents illustrated in table (2-6) (Anusavice *et al*., 2013).

Light activated PMMA is supplied pre-mixed in light-proof packages. The conventional investment techniques are not applicable to light activated resins, since the passage of light to the denture base will be prevented by the investment medium. Consequently, no polymerization will take place. However, the material is accurately moulded after setting the teeth onto the cast, and then it is placed in a visible light supply unit. As soon as the PMMA is activated according to the timing and instructions specified by the manufacturer, the denture base is removed from the cast and finished in the same way as with the other polymerization techniques (Anusavice *et al*., 2013; Van Noort, 2013).

Different studies evaluated light activated PMMA in term of hardness and infrared analysis and its relation to the shade and translucency of the material (Ferracane *et al.*, 1986); initiator systems and interfacial initiation of polymerization in adhesive bonding (Imai *et al.*, 1991); and the use of light-polymerized composite removable partial denture base for a patient hypersensitive to chemically cured PMMA (Tanoue *et al.*, 2005).

Table (2-6): Light activated PMMA constituents, adapted from Van Noort (2013)

Material Constituents
• Urethane dimethacrylate
• Microfine silica
• High molecular weight acrylic resin monomers
• Fillers --- PMMA Acrylic beads
• Initiator--- Camphorquinone

Microwave Processing

Poly (methyl methacrylate) resin can also be polymerized by microwave energy. The microwave provides the thermal energy which is essential to allow the polymerization reaction to take place within the resin denture base. Resin specifically formulated for the microwave processing method must be used with a non-metallic investment flask. The speed with which the denture base can be produced is the main advantage of this technique. This polymerizing method demonstrates a dimensional accuracy and physical properties similar to those of conventional materials and resins (Memon *et al.*, 2001; Keenan *et al.*, 2003; Rached *et al.*, 2004).

Injection Moulding

Although compression processing is the most conventional and applicable method for processing denture base material due to its simplicity and relatively high accuracy (Zarb *et al*., 1997), the injection moulding technique has always been of interest to the researchers. The conventional method to process resin dentures is through compression moulding with heat activation in a water bath (Zarb *et al*., 1997; Gharechahi *et al*., 2014b). However, the dimensional changes and shrinkage of denture bases during resin polymerization are unavoidable and have been well documented (Takamata and Setcos, 1988). This is due to the capacity of the pressure exerted by the injection of material to compensate for polymerization shrinkage (Takamata and Setcos, 1988; Gharechahi *et al*., 2014a).

The first injection moulding machines for polymers were designed based upon the die casting methods invented by Sturges in 1849 (Edirisinghe and Evans, 1986). In 1872 the first machine to fabricate plasticised cellulose nitrate was patented by Hyatt (Hyatt, 1872; Ciofu and Mindru, 2013; Chen and Guido, 2016). The machine ram applied pressure to the material in a heated chamber extruding it through a nozzle into a cooled mould to produce continuous rod, sheet or tube. The first attempt to coat metal parts with celluloid in a multi-cavity mould was in 1903. Glass was the material initially used to fill the mould cavity; however, the poor results led to its rejection. In 1929, semi-automatic machines that could be activated by compressed air began to appear in Germany and America. But these devices were limited to use on small objects due to less viscous material and clamp pressures. In Britain, in 1934, a hydraulically activated machine with a pneumatic pressure ram was then produced which had a hydraulically mould clamping system that overcame the flashing inherent in earlier designs. Uniform heating of the material was the most concerning problem at that time, but this was later addressed in rapid developments of features of these machines that included temperature controls, timers and dosing devices. However, it was the introduction of injection pressure, mould closing and barrel heating that facilitated the fabrication of large components. In 1944, a machine was produced that was capable of moulding both thermoplastic and thermosetting materials. It incorporated mould closing and hydraulic clamping, and used injection pressure rather than clamp geometry (Edirisinghe and Evans, 1986). A polymer moulding is produced by introducing molten synthetic thermoplastic polymer into a mould cavity, sufficient to fill completely the mould cavity. Subsequently, during the cooling of the polymer, pressurised air is introduced into the resin within the mould cavity. The polymer moulding cools and hardens in the mould cavity while the air is maintained under pressure. The mould cavity is designed to at least one entrance for the introduction of the injected material under pressurised air using adjacent areas of the moulding to overcome any shrinkage in the polymer.

Since 1958, when the first attempt was made to use an injection moulding system for the fabrication of dentures, the technique has become increasingly popular and more accurate than the conventional processing procedures. In the 1970s a special acrylic resin (polymer dough) was developed by Ivoclar Ltd for use with the injection moulding system (Keenan *et al.*, 2003). This method became more commonplace after many companies and researchers had conducted investigations in to the development of the injection moulding process and the required equipment (Nogueira *et al*., 1999; Ganzarolli *et al*., 2007). The recent progression of the injection moulding system and the optimisation of equipment has been based on careful control of the polymerization procedure by means of continuous injection at pressure (Nogueira *et al*., 1999; Ganzarolli *et al*., 2007). Specially designed apparatus and units are required for this processing method. Also, this system requires injection of a high-performance heated plastic material into a hollow mould under very high pressure. These injection moulding machines could only be used in dental laboratories, in order to operate the system without any source of external pressure.

In most studies, only features of the moulding technique have been considered as variables that affect the physical and mechanical properties of dentures and less attention has been focused on the effect of moulding temperatures on the final thermo-pressed product (Baydas *et al*., 2003; Ahmed, 2012). Since the moulded parts' geometry and flow are important commercial considerations, the design of the injection moulds should be taken into account. Moreover, the surface temperature of the mould could affect the uniform crystallinity of the moulded parts.

Many factors have been reported as potentially affecting the physical and mechanical characteristics of bases during denture processing, such as the thickness, size and the shape of the denture (Woelfel *et al*., 1960; Wolfaardt *et al*., 1986; Barco *et al*., 1979); type of denture materials used (Woelfel *et al*., 1965); and the presence of teeth (DaBreo and Herman, 1991). Some studies have evaluated the physical properties of denture bases by production of different specimens with various shapes (Salim *et al*., 1992;

Baydas *et al*., 2003), while other researchers have utilised complete denture bases in their studies (Jackson *et al*., 1988; Nogueira *et al*., 1999; Abby *et al*., 2011; Venus *et al*., 2011).

Modern injection moulding techniques have demonstrated fewer dimensional inaccuracies than the conventional processing techniques (Strohaver, 1989; Nogueira *et al*., 1999). This method's principles are based on careful control of the polymerization procedure by means of continuous injection at pressure.

The injection moulding technique requires the use of a specially designed flask, into which the unpolymerized resin dough is introduced. Pressure is continuously applied to a reservoir throughout the injection moulding procedure. A carrier with a spring mechanism is used to maintain pressure on the assembly during resin introduction and polymerization. This process was designed to compensate for polymerization shrinkage (Keenan et al., 2003; Anusavice *et al*., 2013). Internal stresses can be avoided by keeping the apparatus and the polymer/monomer mixture at room temperature during introduction of the material to the prepared flask. In contrast, the strength may decrease and this may adversely affect the surface characteristics of the finished denture base (Anusavice *et al*., 2013).The flask is then placed in a water bath for polymerization. During polymerization, additional unpolymerized resin is continuously introduced into the mould. This is accomplished by injection moulding apparatus to offset the polymerization shrinkage (Parvizi *et al*., 2004).

Surface Characterization

Surface topography is important in denture materials as it influences comfort, mechanical strength, and the ability of microorganisms to colonise the device. To improve aesthetics and reduce the adherence of extrinsic stains to the denture base material, finishing of the denture base may require. In addition, a smooth and polished surface must be achieved to minimize adherence of Candida Albicans, which is the most common cause of denture stimulated stomatitis (Pereira-Cenci *et al*., 2006; Nevzatoğlu *et al*., 2007; Karaagaclioglu *et al*., 2008).

In many practical dentistry circumstances adjustment of the denture base is necessary; this process may alter the treated surface of the original denture base. As a consequence, a rougher surface is produced, and this may cause staining as well as plaque accumulation (Berger *et al*., 2006). Many researchers have studied the effects of polishing and finishing tools and agents on the surface topography of the denture base, the biofilm development, and microbial accumulations (Radford *et al*., 1998; Kuhar and Funduk, 2005; Powers and Sakaguchi, 2006; Abuzar *et al*., 2010; Davi *et al*., 2012). One study reported that the surface topography of the acrylic base can be dependent on the polishing grits which in turn may enhance microbial accumulation (Bollenl *et al*., 1997). Another study tested both polished and unpolished specimens, and concluded that the unpolished specimens in different circumstances may have more microbial colonisation than the polished specimens (Kagermeier-Callaway *et al*., 2000). There is no doubt that we can effectively control the surface topography of the denture base polishing surface by using different finishing and polishing tools and agents, chair-side kits and techniques to produce a smoother surface (Combe and Combe, 1986). However, polishing the denture tissue surface is not possible as this may significantly affect the fitting of the denture. There is a lack of research concerning the fitting surface topography of the denture. The processing conditions for the denture base material may affect the fitting surface topography of the denture base as this may contribute to microbial accumulation underneath the denture.

The study by Morgan and Wilson found that thermo-pressed and heat-processed PMMA were less rough than auto-polymerizing PMMA with non-polished surface. To estimate the surface roughness they used different conventional polishing procedures and chair-side kits. Regardless of the polishing method used, they found that the thermo-pressed and heat-cured PMMA still had less surface roughness than the auto-polymerizing PMMA (Morgan and Wilson, 2001). This may be related to the thermo-pressed and heat-cured PMMA have smaller bead size (Berger *et al*., 2006). This also may be related to the physical and chemical properties of the PMMA. The initiator in each PMMA system may play a role in causing the differences found in surface roughness of non-polishing PMMA since heat-processed acrylic resin uses benzoyl peroxide and di-isobutylazonitrile as initiators (Van Noort, 2013). In addition, the chemical accelerator also may play a role in causing differences found in surface roughness of the auto-polymerization system (Quirynen *et al*., 1990; Verran and Maryan, 1997; Berger *et al*., 2006).

2.1.4. Denture Base Limitations in Dentistry

Material Considerations

The major purposes of removable partial denture prostheses are to restore masticatory function; enhance aesthetics; and maintain occlusion. Whilst mechanics relates to a material’s behaviour in a real structure, biomechanics is the application of this material in engineering amendments to the human body (Van Noort, 2013). Biomechanical considerations are an essential element of addressing the physiological needs of the patient with respect to the biological environment. Otherwise, the patient might be provided with an appliance which accelerates degradation and destruction of the oral tissues rather than preserving the hygienic and masticatory mechanisms (Tyson *et al*., 2006).

Since partial dentures are in regular contact with the oral environment, it is essential that a material should not produce any harmful interaction with the biological environment in these moist conditions (Van Noort, 2013). Although noble metals have the ability to withstand corrosion under extreme conditions, the application of some base alloys could replace the rare and costly pure metals (Powers and Wataha, 2014). However, O'Brien (2008) and Takayama *et al*. (2009) found that Co-Cr as base metal alloys respond to chemical attack by variable chemical agents tending to release ions and this increases incidences of corrosion and tarnish (O'Brien, 2008; Takayama *et al*., 2009). Since this tendency may affect the esthetic and hygienic results under function, usage of Co-Cr may become limited in dentistry.

Over the last 15 years these Co-Cr alloys have demonstrated potential effects in practical performance. A study by Wataha (2000) indicated that about 8% of the general population is sensitive to cobalt metal and the same percentage for chromium metal. He argues that frequent exposure to these metals releases ions which biologically interact with the tissues (Wataha, 2000). The biocompatibility of an alloy could be affected adversely by the release of significant amounts of corrosion products (Anusavice and Brantley, 2003; Powers and Wataha, 2014). With the presence of chromium, alloys show some tarnishing and discolouration behaviour if they remain in contact with high concentrations of chloride ions. Moreover, the chlorine environment may enhance pitting corrosion of these alloys. Hence, partial dentures fabricated from these alloys should not be cleaned with commercial denture cleaners or home cleaners with high sodium hypochlorite content (Ferracane, 2001). Nonetheless, a corrosion resistant material could be introduced either by adding components such as gold and palladium metals, which as a characteristic of their nobility react by forming a positive adherent surface film that inhibits any further subsurface reaction (Anusavice and Brantley, 2003). In 1993 the International Organization for Standardization approved standard (10271) that provides test methods for metallic materials in dentistry to monitors electrochemical reactions in the corrosion activities of dental alloys (Anusavice and Brantley, 2003).

Ideally, the dental material should not absorb oral fluids, since this may sustain the growth of bacteria and fungi (McCabe and Walls, 2013).

Theoretically, Co-Cr is the hardest dental alloy with appropriate mechanical properties such as strength, hardness, and wears resistance. Alloys, like any restorative materials, should resist any permanent distortion in shape. The tensile or compressive strength may be referred to as alloy strength. However, the term most frequently used to describe strength is yield strength. This is the load per unit area which is required to permanently deform an alloy. As in other strength tests the Megapascals (MPa) is the most common unit of yield strength (N/m^2 or N/mm^2). On the other hand, the offset is the indication of the quantity of distortion in an alloy. For example, yield strength of 870 MPa and 0.2 % offset in an alloy means that a stress of 870 MPa causes deformation of 0.2 % in this alloy. The yield strength of these alloys could be increased by proper heat treatment (Powers and Wataha, 2014), although the modulus of elasticity of many base metal alloys is greater than that of most other alloys, in particular, gold-based alloys (Anusavice *et al*., 2013). The hardness of an alloy is related to its yield strength.

Generally an alloy with high yield strength will have high hardness and will be more difficult to finish and polish. Hence, hardness is considered as an indication of how easy an alloy is to indent and polish. Alloy hardness is measured by indenting the alloy with a diamond tip under a definite load. Softer alloys reveal a deeper and larger indentation area. The hardness of the base metal alloys ranges from 125 to 380 kg/ mm^2. However, as they are one of the hardest dental alloys, harder even than enamel, they may wear the opposing enamel or material restoration during mastication or other jaw movements (Anusavice *et al*., 2013; Powers and Wataha, 2014).

The alloys used for denture base restorations have many different components, which do not melt at a single temperature. The melting range reflects roughly the melting points of their constituent components. For example, if an alloy of 950-1000 °C melting range is heated gradually from room temperature, the formation of liquid status will be observed at 950-975 °C. Whilst some of the components of the alloy will remain solid, the entire alloy will become liquid once the temperature reaches 1000 °C. The reverse procedure will be take place when the alloy is cooled again (Powers and Wataha, 2014).

In the case of cast appliances the melting range of the metals and alloys should be low enough to form smooth surfaces with the mould wall of the casting investment.

Many techniques have been studied to improve the mechanical properties of PMMA. These have involved using and/or developing an alternative material to PMMA; reinforcing the PMMA with other materials; or chemical modification of the PMMA (Jagger *et al*., 1999). Whilst some of the available denture base materials may be acceptable in terms of mechanical properties, most are not acceptable to patients and dental technicians, due mainly to patient sensitivity, poor mechanical properties in long-term use, or their processing characteristics. There has been interest in denture base materials such as rubbers that may have high impact strength more or less identical to that of the traditional polymethylmethacrylate (PMMA). Nevertheless, their flexural properties are relatively poor and fatigue can be a problem due to failure in performance (Jagger *et al*., 1999).

Since PMMA is relatively low in cost and easy to use, both clinically and in the laboratory fabrication process, it remains the most popular choice for polymeric removable prosthodontics (Phoenix, 1996; Meng Jr and Latta, 2005). However, many studies have described various techniques for reinforcing PMMA through inclusion of other materials (Bowman and Manley, 1984; Carroll and Von Fraunhofer, 1984; Jagger *et al*., 1999; Vuorinen *et al*., 2008; Young, 2010). Reinforcement of the prosthesis with metal wires embedded in the base is one such method attempted. Poor adhesion between the resin and metal or metal alloys is the primary problem with this method; additionally inclusion creates unsatisfactory aesthetic results (Vojdani and Khaledi, 2006). However, a study by Uzun *et al*. found that the use of Carbon and Kevlar fiber reinforcement techniques produced more aesthetically satisfactory results, although the etching process required to improve their incorporation into PMMA and preparation and positioning of the fiber layers required extra time and the use of sensitive techniques (Uzun *et al*., 1999). Further studies found that the most satisfactory technique for reinforcing PMMA involves the use of the glass fibers (Aydin *et al*., 2002; Çökeliler *et al*., 2007). Such studies indicated that besides enhancing the mechanical properties of the PMMA, this technique made it highly polishable, aesthetic and easy to manipulate (Jagger *et al*., 1999; Çökeliler *et al*., 2007). Research continues to attempt to improve the mechanical properties of PMMA by increasing its fracture toughness, impact or transverse strength and wear characteristics by means of either hydroxyapatite filler or Silica (Mc Nally *et al*., 2006; Young, 2010).

Polymer biocompatibility could be one of the major factors limiting the use of PMMA in dentistry. The polymer denture base material of the set denture should not be toxic or irritant to the patient. In addition, the unmixed and uncured states should not be harmful to the dental technicians involved in handling and fabrication. Although PMMA is the most common non-metallic denture base material, there is still the possibility of residual methylmethacrylate monomer being leached out of the denture base into the wearer's oral tissues. This may result in irritation or hypersensitivity (Lung and Darvell, 2005). This theory is supported by studies that have detected frequent allergic reactions to PMMA denture base materials over several years (Alanko *et al*., 1996; Kanerva *et al*., 1997). Alternative materials such as Polysulfone (PSF), nylon and polycarbonate (PC) are suggested for patients with an allergic reaction to acrylic materials (Stafford *et al*., 1986; Tanoue *et al*., 2005). The fact that these materials lack mechanical and physical properties such as transverse tensile strength and water sorption has limited their usage in past years (Pfeiffer and Rosenbauer, 2004; Pfeiffer *et al*., 2005). The PMMA undergoes dimensional changes in denture bases which may produce from a primary wax pattern. This results from volumetric shrinkage during polymerization and the high coefficient of thermal expansion of approximately ($80 \times 10^{-6}/°C$), which provides additional distortion and inaccuracies (Greener *et al*., 1972; Combe and Combe, 1986; Anusavice *et al*., 2013). In addition, accidentally inhaled or swallowed fracture base material cannot be detected on radiographs since PMMA is not a radiopaque material (Bloodworth and Render, 1992; Murray *et al*., 2007).

For operators using PMMA the main risk is of contracting methylmethacrylate contact dermatitis and allergic type reactions (Kanerva *et al*., 1993; Kiec-Swierczynska, 1996). According to Mürer *et al*., skin allergies are 8 times more common among dental technicians than amongst the several populations (Mürer *et al*., 1995). Moreover, wearing gloves during processing procedures provides inadequate protection since the monomer can easily penetrate both latex and vinyl gloves (Hensten-Pettersen, 1998; Meding *et al*., 2006).

Design Considerations

The most frequently lacking feature of removable partial dentures is the maintenance of a retentive component such as clasps. This may depend on many factors ranging from diagnosis, treatment plan, prosthesis design and construction to end with the placement of the restoration and its maintenance (Carr and Brown, 2011). Cast Co-Cr partial denture frameworks are designed to be supported by the teeth and mucosa of the denture bearing area (Tyson *et al*., 2006). Co-Cr alloy is used generally for tooth-supported dentures and occasionally for tissue-borne dentures where strength is required (Johnson *et al*., 2013). The most important features of partial denture framework design are the supporting and retaining elements (Carr and Brown, 2011). According to Carr and Brown, lack of stability of removable partial dentures in the maxilla is 7 times more common than lack of retention, while in the mandible the lack of stability is 1.8 times the lack of retention (Carr and Brown, 2011), table (2-7).

Table (2-7): Technical quality concerns for removable partial dentures (Carr and Brown, 2011)

RPD	Lack of Stability	Lack of Retention	Lack of Integrity	Excessive wear	Reline/ Adhesive
Maxillary	43.9%	6.2%	24.3%	21.6%	3.9%
Mandibular	38.2%	21.2%	13.2%	7.1%	21.6%

The three main functions of a direct retainer in removable partial dentures are support, retention and bracing. RPDs must have sufficient supporting ability to provide a stable occlusal contact.

Many studies have considered the use of Cobalt-Chromium alloys as metal alloys for RPD components parts such as clasps (Ghani and Mahood, 1990; VandenBrink *et al*., 1993; Brantley and Herman, 1993). Although the use of metal frameworks within dentures may increase the strength of the denture, there are many persistent concerns relating to metal supports, such as metal corrosion, allergic reactions, permanent deformation in performance possibly due to the denture being dropped, the unaesthetic appearance of the metal clasps, and difficulties encountered during casting procedures (Kanie *et al*., 2004).

The clasp of a removable partial denture (RPD) is often made from the same cast metal alloy as the metal framework of the denture. The most commonly used metal alloy for this purpose is a Cobalt-Chromium alloy (Blackman *et al*., 1991; Vallittu and Kokkonen, 1995; Mahmoud *et al*., 2007). Nevertheless, it seems that most dental patients of all ages prefer to avoid the use of metal in dental treatment. Due to such increased expectations, non-metal clasp dentures using thermoplastic materials have recently become a treatment option for patients (Takabayashi, 2010). Moreover, non-metal clasp dentures have the advantage of avoiding the allergic reactions that can be caused by metals. However, the present concern about the available thermoplastic materials is the lack of scientific evidence regarding the properties due to the small number of related studies, as well as a lack of studies comparing the various clasp materials

(Vallittu and Kokkonen, 1995). There is, however, some clinical evidence of failures in clasps using these materials, which might actually be fatigue fractures (Yli-Urpo *et al*., 1985; Vallittu *et al*., 1993). Fatigue is represented by the loss of mechanical properties of a material after repeated loading, thereby affecting the structure of the denture (Phillips, 1991). However, Van Noort's interpretation is that fatigue is "the gradual accumulation of minute amounts of plastic strain produced by each cycle of a fluctuating stress" (Van Noort, 2013). Fatigue fracture in a denture clasps is an unlikely occurrences. Fatigue of a denture clasp is based on the constant deflection of the clasp during insertion and removal of the RPD over the undercut of the teeth. The required undercut depends on the length, shape, and material of the clasp (Fraunhofer, 1976; Ghani and Mahood, 1990). Many studies have indicated that fatigue fractures of the RPD framework occur at specific sites that are determined by the design of the castings. The fracture usually occurs in areas where stress concentration is greatest. This phenomenon is associated with the size and shape of the occlusal rest, denture base extension, stress distribution, clasp fatigue as well as the framework integrity (Vallittu and Kokkonen, 1995; Bridgemana *et al*., 1997; Mahmoud *et al*., 2005; Mahmoud *et al*., 2007; Sato *et al*., 2008). Sato *et al*. (2008) conducted a clinical evaluation of the support for removable partial dentures, which depends primarily on the fit, size, shape, and the location of the occlusal rests. They found that poor fitting occlusal rests and the related gaps located between the rest and the rest seat of the abutment; prevent proper transmission of occlusal forces to the abutment. Since the load is transmitted via occlusal rests and the rest seats in tooth-supported RPDs, fracturing of the rest should be expected when the rest is too narrow. Hence, rest size should be in proportion to tooth size to allow correct distribution of forces to the abutment.

The effects of the rest shape on the supporting function were also investigated. Sato *et al*. (2008) recommended that the occlusal rest seat should be spoon shaped to maximize the quality of support; otherwise horizontal dislodging of the rest from its seat will take place (Sato *et al*., 2008). Additionally, occlusal rest fatigue may be observed at the angle where the rest joins the vertical minor connector. This could be facilitated by inadequate thickness of the alloy and by casting defects (Bridgemana *et al*., 1997; Rudd *et al*., 1999; Gapido *et al*., 2003; Sato *et al*., 2008). Another factor that can cause movement of the RPDs is the location of the rests. The research by Sato et al. 2008 indicated that for intermediary missing teeth lingually shifted rests provide inadequate support, whereas buccally moved rests provide better support. Nonetheless, the maximum support for distal extensions for missing teeth is provided by eliminating occlusal contacts with the most distal artificial tooth. Moreover, creation of a mesial rest seat and widening the base is essential along with use of the pressure impression altered cast technique (Sato *et al*., 2001b; Carr and Brown, 2011).

Both the clinician and technician should be aware of the hazards involved in the fabrication of clasps since these may affect their dimensions and behaviour. The clasp of a removable partial denture (RPD) is often made from the same cast metal alloy as the metal framework of the denture. Clasps undergo permanent deformation and fatigue fracture under repeated flexures caused by denture insertion and removal and mastication (Sato *et al*., 2001a).

The retention of a Co-Cr partial denture is performed partly by the force required to produce deflection of a clasp tip through an undercut. Nevertheless, the degree of force required for retention of the prosthesis during function depends on many factors, the proper use of guide planes, the position and number of saddles and the mobility of the teeth (Sato *et al*., 2001b; Carr and Brown, 2011). As yet, some studies have considered the effect of clasp fatigue on the retention properties of denture clasps (Ghani and Mahood, 1990; Vallittu and Kokkonen, 1995; Kim *et al*., 2004; Mahmoud *et al*., 2005). A study by Ghani and Mahood (1990) concluded that the mean force required to provide unit deflection varies according to the form and length of the clasp after one and six months in a dry atmosphere. They confirmed that the flexibility of the clasp improves as the clasp length is increased. Therefore, less force is required for deflection. The effect of taper on the flexibility of a clasp was also investigated. They found that short tapered clasps require less force to achieve the desired deflection than short untapered clasps. However, in this study the effect of longer clasps is less clear, since it seems that extended length is of little importance compared with whether a clasp is tapered or not. Hence, the load required to dislodge a denture after a period of wear is reduced. This may relate to the reduction of the force required for the clasp to pass through the undercut, which ultimately results from loss of retention of the clasp due to permanent deformation and mobility of a tooth (Ghani and Mahood, 1990).

Another study conducted constant deflection fatigue tests to investigate the deflection of Co-Cr alloy clasps. They found that the stiffness of the Co-Cr alloy clasp decreased after repeated loading and that fatigue fracture occurred after approximately 25,000 loading cycles (Vallittu and Kokkonen, 1995).

Another study showed that Co-Cr clasps were unsuitable for placement in deep undercuts due to their rigidity (Bridgemana *et al*., 1997; Kim *et al*., 2004). The cycles were measured to simulate 3 years of clinical use (5,000 cycles). The clasp force was measured when the clasp was initially fitted, and the retentive force after each 500 cycles was assessed. The tests indicated that these alloys undergo permanent deformation in cases of 0.75 mm retentive undercut depth, and this may relate to the fact that such clasps place increased stress on abutment teeth (Kim *et al*., 2004).

Another study revealed that the Co-Cr specimens survived deflections when the undercuts were under 0.25 mm in depth. However, at tensile stress of 640 MPa they were considered to have slightly less than the 0.2 % yield strength of the reported alloys. Nevertheless, all of the other Co-Cr clasps with 0.50 and 0.75 mm preset deflections with stresses above the yield strength failed before achieving 5,000 cycles. The decrease in actual deflections arises from the greater permanent deformation of the clasps. This may contribute to the extension of fatigue life since smaller actual deflections would reduce the highest tensile stress within the clasps. Permanent deformation was identified in the clasps subjected to the greatest stresses below the yield strength of the alloys. This could be correlated partly to the flattening of the surface of the load sphere applied at the clasp tip during testing procedure (Mahmoud *et al*., 2005).

Overall, appropriate design of Co-Cr RPDs and preparation of abutments are essential to the provision of an accurate prosthesis. Identifying the cause of lack of support could contribute to establishing an effective clinical procedure for constructing clasps that can maintain long-term support. However, apparent lack of satisfaction with the mechanical properties of metal clasps, their performance in use and after repeated loading and the visible part of removable partial dentures (RPDs) among researchers and patients lead to suggest and call for their replacement with product made from thermoplastic material.

Recently, many researchers have been developing thermoplastic materials for the construction of a “metal free clasp denture” or “non-metal clasp denture” (Takahashi *et al*., 2012; Osada *et al*., 2013). The material characteristics of more than 10 thermoplastic resins have been evaluated *in vitro* to investigate their mechanical and physical properties (Takabayashi, 2010; Takahashi *et al*., 2012; Tannous *et al*., 2012).

In 2011, and according to ISO 1567, Hamanaka *et al.* measured the mechanical properties of many thermo-pressed thermoplastic denture base materials. They concluded that the material that had a low elastic modulus were easily to manipulate, and would make it possible for larger undercuts to be used for retention than is the case with acrylic resin and Co-Cr clasp design (Hamanaka *et al*., 2011). Extending part of the thermoplastic denture base to the undercut area of the abutment tooth and gingival may provide adequate retention and bracing. In addition, the denture might have great durability if it were made of flexible material rather than metal (Kaplan, 2008; Goiato *et al*., 2008; Katsumata *et al*., 2009).

It seems that non-metal clasp dentures could be superior to conservative clasp dentures on the grounds that they could give more acceptable aesthetic results, be comfortable to wear, and have no metal allergenic effects. Early non-metal designs of RPDs have been commonly monitored and modified in partially edentulous patients. However, these may cause critical damage to tissue as well as function poorly, and to obtain tooth support and bracing, a few studies have indicated that as with conventional clasp dentures a metal rest should be used for non-metal clasp dentures to decrease pressure on soft tissues (Hirota *et al*., 2012; Yoda *et al*., 2012).

2.1.5. CAD/CAM Digital Technologies in Dental Laboratories

CAD is an abbreviation for 'computer-aided design' and CAM stands for 'computer-aided manufacturing'. In the 1970s, Duret and Preston began to investigate CAD/CAM applications in dentistry, followed by Moermann Brandestini in the 1980s. CAD/CAM technology was first used to produce clinical dental restorations in the 1980s. Introduction of techniques for design and milling of dental prostheses led to the development of CAD fabrication and these became relatively common clinical and laboratory procedures (Goodacre *et al*., 2012; Van Noort, 2012). Despite these many advances, CAD/CAM technology has yet to be used for the fabrication of conventional RPDs.

Recently, CAD/CAM technology has become one of the most acceptable processing methods in most modern dental laboratories and among innovative clinicians at chair side (Van Noort, 2012; Najeeb *et al*., 2015).

Generally, CAD/CAM systems consist of three components: a digitalisation tool or scanner that transforms the geometry of an object into digital data and that can be processed by a computer; software that processes data, depending on the application to produce a set of data for the product to be fabricated; and production technology that transforms the data set into the desired product. In dentistry three different production concepts for the CAD/CAM systems were identified, chair side; laboratory; and centralised fabrication in a production centre (Beuer *et al*., 2008a; Lin *et al*., 2013; Euán *et al*., 2014).

Chair side production components are located in the dental surgery and dental restorations can be fabricated without involving of a laboratory. A digitalisation procedure using an intra-oral camera replaces the conventional impression process used in most clinical situations. Direct fabrication of restorations at one appointment could save the patient time and money. Success rates of 90% after ten years and 85% after 12 and 16 years have been reported for inlays produced using this system, in clinical observations of ceramic inlays over a period of 21 years. These impressive results may be related to the accuracy that this system achieves through three-dimensional reconstruction of the occlusal surface (De Nisco and Dentb, 2002; Molin *et al*., 2004; Reiss, 2006). Laboratory production follows conventional working steps involving the dentist and the laboratory. Using the impression taken by the dentist, the laboratory first fabricates a master cast. Then, the CAD/CAM production sequences are completed inside the laboratory. After cast scanning, three-dimensional data are produced on the basis of the master die. The data are processed by means of dental design software and exported to a milling device that produces the original geometry in the dental laboratory. The fitting of the framework can be evaluated and corrected on the basis of the master cast (Raigrodski and Chiche, 2001; Raigrodski, 2005; Lüthy *et al*., 2005).

Centralised production is undertaken by the milling centre. The satellite scanners in the dental laboratory are connected with a production centre via the Internet, enabling data sets produced in the dental laboratory to be exported to the production centre. Next, the CAM device will produce the restorations and send it to the respective laboratory. Hence, elements of production take place chair side and in the dental laboratory, while centralised production takes place in the millings centre (Reich *et al*., 2005). This centre may offer to analogue intraoral data collected from an impression, and scan, design and fabricate the framework from the master cast without scanning. In addition, while it may fabricate the framework, the final prosthetic restoration could be carried out in the dental laboratory (Beuer *et al*., 2008a; Güth *et al*., 2013).

The sintering mechanism is also a new generative CAD/CAM production technique involving addition of materials such as wax, resin or metals. This additive method is already being used in some dental applications, including crowns and bridges, and RPD frames made of Co-Cr alloys (Silva *et al*., 2011; Figliuzzi *et al*., 2012).

In all these methods of production, the construction of the prosthesis remains in the hands of the dental technician.

CAD/CAM Components

The Scanner

In dentistry a “scanner” is a tool used to measure the jaw and tooth structures in three dimensions (3D) and transform them into digital data sets. Basically there are two types of scanner: optical and mechanical. The optical scanner operates through collection of three dimensional structures in triangulation. A definite angle created between the light device and the receptor unit enables the computer to calculate a 3D data set through this angle from the image on the receptor unit (Mehl *et al.*, 1997).

Meanwhile, data can be collected line by line by means of a ruby ball and the 3D structure measured mechanically from the master cast using a mechanical scanner. This scanner provides high accuracy, and all the data collected by the system can be milled directly. However, the data measurement technique of the mechanical scanner is complicated and it has a lengthy processing time compared to the optical scanner (May *et al.*, 1998; Webber *et al.*, 2003).

Software Design

Manufacturers provide special software designed for different types of dental restoration. Such software systems can design and construct crowns, FPD and RPD, full and partial anatomical crowns, inlays, and telescopic primary crowns (Reich *et al.*, 2005; Adusumilli and Lech, 2009; Miyazaki *et al.*, 2009; Miyazaki and Hotta, 2011; Van Noort, 2012).

The construction data can be stored in various data formats. While, the basic standard transformation language is the (.Stl) data (Mehl *et al*., 1997; Al Mardini *et al*., 2005; Scotti *et al*., 2011), many manufacturers used their own data formats.

Processing Devices

The construction data that are collected and produced by the CAD software are converted into milling strips for introduction into the milling device. Milling devices are classified according to the number of milling axes into 3 axis, 4 axis, or 5 axis devices. The 3 axis milling device moves in three spatial directions defined by the X, Y, and Z values. In addition, the component can be turned by 180 degrees in the course of processing, on the inside and the outside. The 3 axis devices have the advantage of simplicity and short milling time, and lower cost compared to those with a higher number of axes. The 4 axis milling device additionally to the three spatial axes incorporates a movable bridge, giving vast turned variables. The bridge constructions can be adjusted with a large vertical height displacement into typical mould dimensions, which can save material and time. Meanwhile, the 5 axis milling device has in addition to the axes of the 4 axis device a rotating axis in the milling spindle (5th axis). This is to enable the milling of multifarious geometries with subsections. Whilst a higher number of processing axes may not necessarily produce a higher quality restoration, accurate digitalisation, data process and production processes may result in increased quality (Beuer *et al*., 2008a).

Milling Processing Conditions

Milling is either a dry or wet process. Dry processing is applied mainly to resin, zirconia, wax and thermoplastic materials which produce less conductivity and generate less heat during the milling procedures. Meanwhile, wet milling involves spraying of cool liquid on the carbide cutters or milling diamond. This is an essential procedure when working with any metal and glass ceramic materials, in order to avoid overheating in the milling process and thereby causing distortion and damage of the final product.

Dental CAD/CAM Processing Materials

Wax, resin, silica based ceramics and metals are the materials most commonly processed by CAD/CAM devices. The use of wax to produce definitive dental restorations by computer could save time, with less resulting errors. It could provide a copying procedure for different materials as a transitory prosthesis. Resin material can be milled to act as a lost wax frame for casting purposes. However, it could also be used directly as a long term interim crown or full anatomical, long term, temporary prosthesis. Silica based ceramics discs and blocks can be used through adding multi-coloured layers to monochromatic blocks for the production of inlays, onlays, veneers, partial crowns and full crowns. Glass ceramics, due to their translucency and aesthetic characteristic, are comparable in appearance to natural tooth structures (Tinschert *et al*., 2001; Taskonak and Sertgöz, 2006). Yet, because of the financial implications, whilst chrome cobalt alloys, titanium, titanium alloys are processed using dental milling devices; precious metal alloys are limited due to high metal attrition and material costs.

Nevertheless, CAD/CAM technology has made it possible to machine interesting new materials such as high performance ceramics, thermoplastics and titanium with high accuracy.

Lately, the use of CAD/CAM technology in dentistry has produced impressive results compared to traditional dental technical construction procedures; figure (2-3). Quality and productivity has been improved by means of standardised production processes, thereby transforming dental laboratories from traditional manufacturers into modern and digitalised production centres. However, cost implications and limitations due to software and production procedures are serious drawbacks of this fabrication technology (Von Steyern *et al*., 2005; Van Noort, 2012).

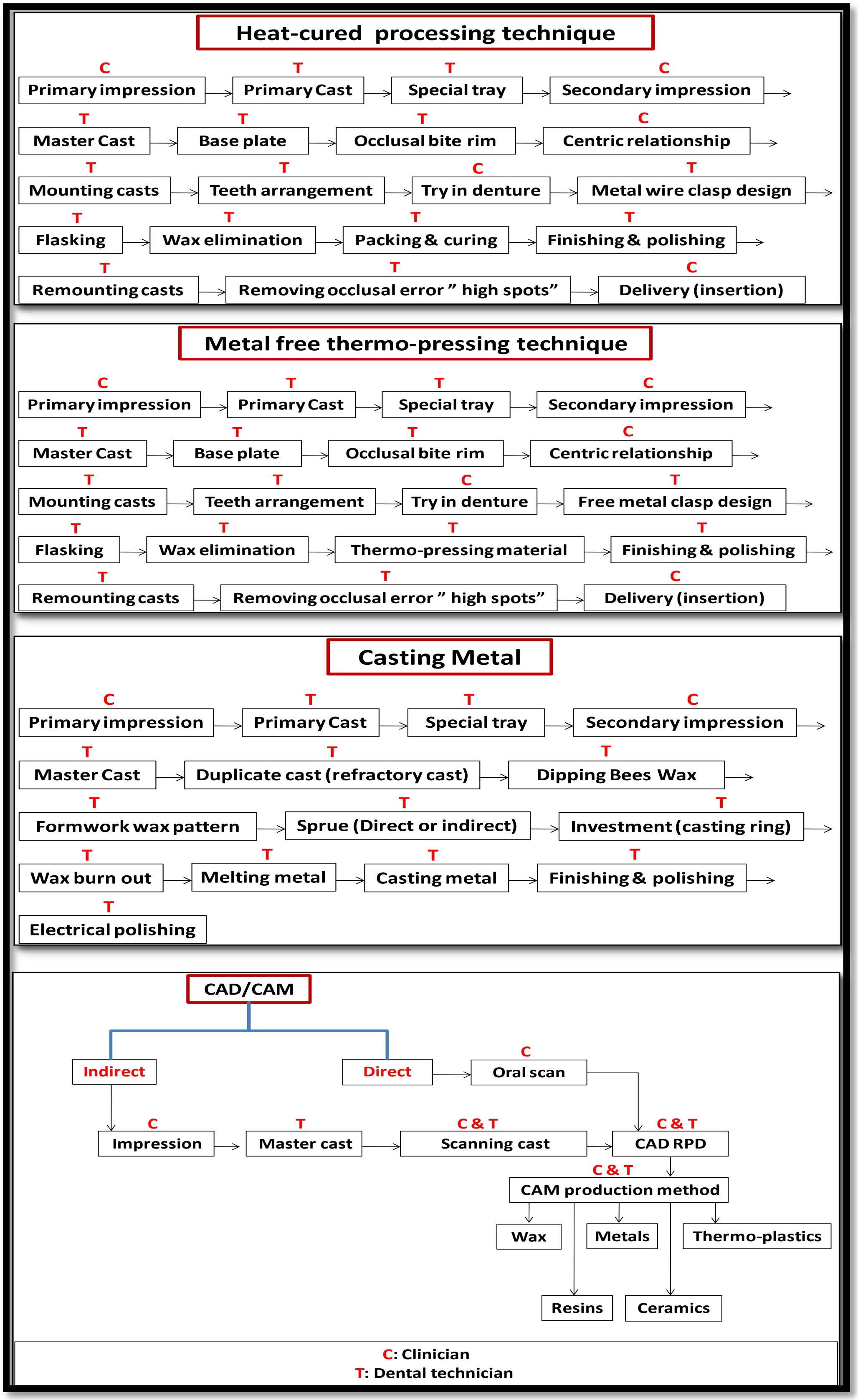


Figure (2-3): Diagram showing the processing methods used to fabricate the RPD framework

2.2. Polyetheretherketone (PEEK) Polymer

2.2.1. An overview of the Polyaryletherketone (PAEK) Group Family

Polyaryletherketones (PAEKs) are polymer group family represented by ultrahigh molecular weight polyethylene (UHMWPE), which has demonstrated outstanding thermoplastic performance. In the 1980s, the Polyketone family was first launched commercially in industry in the engineering and manufacturing world. The PAEKs chemical structure and the architecture of linear aromatic groups demonstrated the preferred physical properties in long durability performance alongside environmental complexities. They consist of aromatic rings connected by ether or ketone linkage. The polymer acronym in this group refers to the number and the order of repeated segments. For example, PEK refers to the poly-ether-ketone units; and PEKK to the poly-ether-ketone-ketone segments. PAEK polymers are more crystalline than those with bulky side groups like polystyrene (PS), and less crystalline than those with flexible backbones, such as polyethylene (PE) and polypropylene (PP) (Reitman *et al*., 2011). However, PEEK is one of the family members and identified as "polyaromatic semicrystaline thermoplastic polymer", based on a chemical formula of $(\text{-}C_6H_4\text{-}O\text{-}\ C_6H_4\text{-}O\text{-}C_6H_4\text{-}CO\text{-})n$, and is generically branded as Polyetheretherketone (Invibio, 2004a; Kurtz, 2011b).

2.2.2. Polyetheretherketone for Medical Purposes

PEEK has a historical and contemporary classification as a medical grade polymer. In 1987, ICI commenced production of the Victrex PEEK for industrial purposes. In 1993, the Victrex PEEK became commercially available, and in 1998, Victrex introduced the PEEK-OPTIMA® for implantation purposes. In 2001 Victrex supplied PEEK with grades appropriate for long-standing implantation after launching Invibio Biomaterial Solutions. Despite the fact that the name of the group and the resin grades has changed, the PEEK by ICI, Victrex, and Invibio were all produced through fundamental technical polymerization and at the same plant location. Since the 1980s, and as a result of liability and technical complexities, many industrial PAEK polymers have been withdrawn from the market, table (2-8). However, PEEK-OPTIMA® seems to be sustainable as a biomaterial polymer. PEEK biomaterials were designed under the OPTIMA trade name. Polymer classification was based on their molecular weight as controlled by their flow properties in melt, table (2-9) (Kurtz, 2011b).

Table (2-8): Summary of PAEK materials related to implant use (Kurtz, 2011b)

Polymer	Trade Name	Producer	Comments
PEEK	OPTIMA (Biomaterial)	Invibio (Subsidiary of Victrex) Thornton- Cleveleys, UK	Manufacturer and supplier of long term implantable PEEK in CE and Food and Drug Administration approved devices since 1998.
PEK		Invibio (Subsidiary of Victrex) Thornton- Cleveleys, UK	Available only in experimental quantities
PEEK	Victrex	Victrex, Thornton- Cleveleys, UK	Provide PEEK for blood/tissue contact less than 24 h
PEEK	Gatone	Gharda- India	No record of supplier implantation studies. Discontinued for medical use when acquired by Solvay in December 2005
PEEK	Keta-Spire	Solvay Advanced Polymers, LLC	Not available for implant use.
PEEK	Zeniva	Solvay Advanced Polymers, LLC	Implantable grade available
PEEK	VISTAKEEP I	Evonik	Implantable grade available
PEKK	PEKK	DuPont, Wilmington, DE	Discontinued for medical use by DuPont
PEKK	OXPEKK	OPM, Enfield, CT	Implantable grade available. Base resins supplied by Cytec
PEKEKK	Ultrapek	BASF, US	Discontinued in December 1995

Table (2-9): Historical and contemporary classification for PEEK medical grades (Kurtz, 2011b)

Grade / Property	General-purpose	Medium- flow	Easy- flow
Historical Victrex classification	450	381	150
Invibio classification	OPTIMA LT1	OPTIMA LT2	OPTIMA LT3
Melt flow index	3.4	4.5	36.4
Molecular weight (M_n)	115,000	108,000	83,000

PEEK Biomaterial

Despite the fact that the PAEK family was launched commercially in industry in the 1980s, according to Kurtz, research into PEEK history and background as a biomedical material only started in the late 1990s. This was established through the development of medical devices such as pharmaceutical packaging, suture anchors, spine and hip implants. Since the literature on PEEK derived from polymer engineering, polymer and materials science, clinical and trade journals, studies were limited to consideration of the properties of this biomaterial. Additionally, there were limited references or guidance for materials scientists and biomedical engineers using PEEK in the design and development of medical device (Kurtz, 2011b). However, in 1998, PEEK was commercialized as a biomaterial for implants (Invibio Ltd., Thornton Cleveleys, United Kingdom) (Green and Schlegel, 2001), and the research into PEEK biomaterials is expected to advance further in the future (Williams, 2001). Later on, a comprehensive review began of the scientific literature with a view to providing clear guidance on use of PEEK as a biomedical material. Many studies indicated successful clinical performance of PEEK among orthopaedic and spinal patients as well as in implants used for joint arthroplasty (Wang *et al*., 1999; Toth *et al*., 2006).

Generally, the application of PEEK as unfilled polymer is the most popular form. However, for implant purposes much research has focused on PEEK biomaterial's biocompatibility with bioactive materials, including HA (hydroxyapatite) as a surface coating or as a composite filler (Ha *et al*., 1997; Yu *et al*., 2005). Later still, the biomaterial studies indicated that PEEK and related composites can be engineered with a wide range of mechanical, physical and surface properties, depending on the form of implant application (Kurtz, 2011b; Moskalewicz *et al*., 2013).

The combination of two or more substances at a microscopic level may produce a material that demonstrates superior physical and mechanical characteristics to those of the original component parts. The outcome material may be termed "composite" if the reinforcing constituent consists of long or continuous fibres, whereas if the additives are in the form of isolated particles such as flakes, powder or short fibres, then it is called "compound" (Kurtz, 2011b).

In the late 1980s, the potential use of carbon fibre reinforcing PEEK attracted the interest of the medical implant community (Williams *et al*., 1987). Its versatile mechanical and physical properties as well as its outstanding biocompatibility can offer sustainability when used in combination with modern imaging technologies. The CFR-PEEKs have demonstrated stiffness to closely match that of the cortical bone. Therefore, they have been widely used as alternatives to cobalt chromium and titanium alloys for hip designs (Yildiz *et al*., 1998a; Yildiz *et al*., 1998b). At the initial stage this material was of interest only to academics; however, this material became commercially available many years later to replace implant grade metallic alloys. In addition, the continued use of carbon fibres within the material offered extreme durability along with high strength and fatigue resistance (Hull and Clyne, 1996; Kurtz, 2011b). Moreover, there is no significant effect on the transverse flexural strength and it has outstanding resistance to steam, boiling saline solution and gamma irradiation effects (Kwarteng and Stark, 1990). Furthermore, it shows high compressive strength durability after physiological saline conditioning (Zhang *et al*., 1996), as well as in the aggressive environment of the human body (Evans and Gregson, 1998). Therefore, the CFR-PEEK material was selected for commercial development for implantable applications requiring high load bearing medical devices (Kurtz, 2011b).

Synthesis

PEEK is one of the PAEKs family groups which are chemically inert and insoluble in all conventional solvents at room temperature. However, it can be dissolved completely by using esoteric solvents like diaryl sulfones. It seems essential to understand the steps used in the manufacturing of the raw materials since these techniques may potentially affect the properties and the qualities of the stock shapes and the moulded components (Kurtz, 2011b). Although recent studies have tended to enhance the fabrication of PEEK composites by using carbon and glass fibers (Song *et al*., 2007; Van Rijswijk and Bersee, 2007), this study will focus on the synthesis and fabrication of unfilled PEEK polymer.

The successful polymerization of PEEK polymer should be established by using solvents such as benzophenone or diphenylsulfone at high temperatures of above 300 °C. There are two main routes in the production of PAEKs: the electrophilic route, which involves linking an aromatic ether species through ketone groups, and the neucleophilic route, which involves linking aromatic ketones by means of an ether bond (Kurtz, 2011b).

Many studies have attempted to fabricate PEEK polymer by electrophilic routes. Nevertheless, this method enjoyed only limited success in the commercial world since the finished synthesised polymer suffered from high temperature instability as well as difficulties in moulding or extrusion it without further cross linking and degradation (Colquhoun and Lewis, 1988; Ueda and Oda, 1989; Kemmish and Wilson, 2005). However, the nucleophilic route to PAEK polymers offers a simple pathway to PEEK polymer, with the addition of suitable solvents like benzophenone or diphenylsulfone, which should be inert and provide thermal stability to phenoxide species used in the synthesis of PAEK polymers. Hydroquinone and sodium or potassium carbonate was used to control the inherent instability of bisphenate to oxidation. Moreover, high temperatures above 300 °C were needed to reach high molecular masses. Furthermore, a slight excess of difluorobenzophenone enhanced the control of molecular weight, leading to fluorine- terminated chains, figure (2-4) (Kurtz, 2011b).

In 1977, ICI patented this process and sold it under the brand of "Victrex PEEK", providing by this route the majority of PEEK polymer used in industrial applications. Attwood *et al.* point out that such a route provides PAEK polymers with various properties through the use of different bisphenols in their production. They found that

PEEK as a dominant member of the PAEK family has a glassy state at room temperature; and at about 143 °C the glass transition temperature occurs, while at around 343 °C the crystalline melt transition of PEEK might take place (Attwood *et al*., 1981).

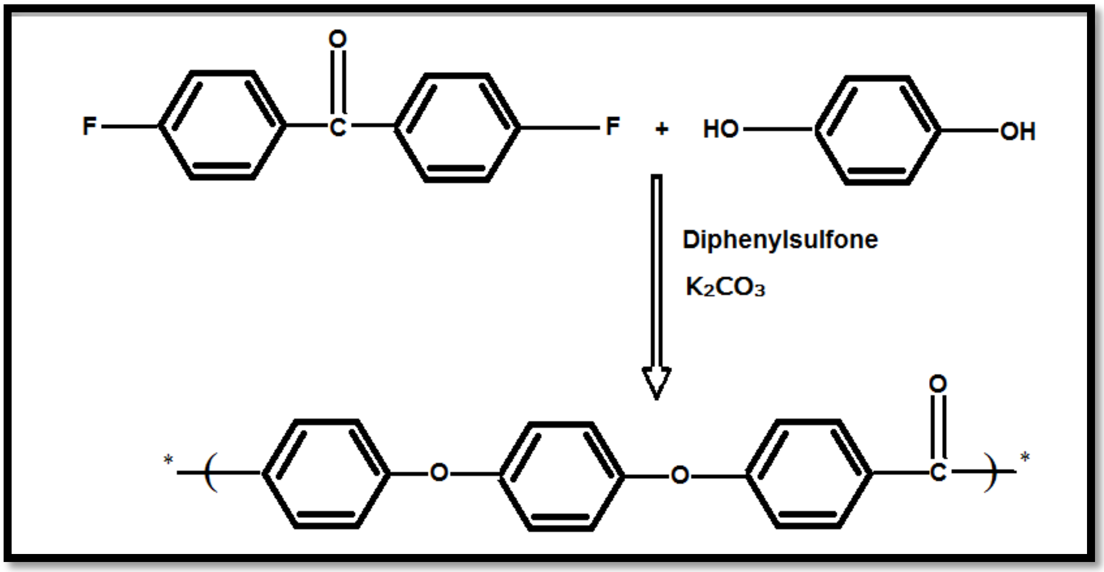


Figure (2-4): Schematic representation for the PEEK synthesis, adapted from Kurtz (2011b)

Processing

PEEK is a high temperature thermoplastic material provided in a range of viscosities in relation to the processing method, table (2-10). It is processed by using different traditional techniques including injection moulding, extrusion, compression moulding, and film and Fibre production.

Table (2-10): Traditional plastic processing methods for PEEK-OPTIMA, adapted from Kurtz (2011b)

PEEK-OPTIMA®	Viscosity	Processing Method	Uses
LT 1	High	Machining Injection moulding	Medical device components
LT 2	Medium	Extrusion	Thin walled parts (tubing)
LT 3	Low	Injection moulding	Thin walled parts

Whereas LT1, standard grade, is available in powder form (P) for compounding, or as granules (G) for injection moulding, LT2 is an optimized grade for melt strength and viscosity and is recommended for tubing processes; and LT3, is a high flow grade for injection moulding (thin walled parts). However, commercially, granules are the only form available for implantable grade PEEK- OPTIMA. Milling or grinding the granules to the desired particle size is the only way to obtain the powder type of medical grade PEEK polymer. PEEK-OPTIMA, which as a quality control measure, undergoes melt filtration to ensure cleanliness and biocompatibility before the polymer is granulated into cylindrical pellets for marketing (Kurtz, 2011b).

Injection Moulding

This technique is an attractive manufacturing method for mass production of PEEK components. The PEEK granules or pellets have typically been used for the injection moulding method. These are poured into a hopper in the machine and automatically introduced into a heated screw. The molten PEEK flows into a heated mould once the heated screw has melted and pressurizes the molten polymer. Then, the moulded sample is automatically driven out from the mould after PEEK component solidification.

Commercially, the injection moulds were optimized and designed for each part concerned taking into account the features of the part’s geometry and flow, and the pressure capabilities of the molten polymer injection system. Characteristically, the injection moulding of PEEK requires barrel and nozzle temperatures of about 400 °C. Moreover, to ensure uniform crystallinity of the moulded parts, the mould surface temperature for PEEK is recommended as being in the range of 175-205 °C. Since failure to achieve the required mould temperature results in rapid cooling and insufficient time for the crystallization of this part. Although it seems possible to increase the crystallinity of amorphous or low-crystallinity PEEK by means of annealing, this process may lead to distortion and dimensional changes. The shrinkage of the crystalline region within the cooled polymer should be taken into account in the component design since it depends on the mould and the polymer melt temperature. For example, PEEK-Optima can produce consistent parts with dimensional tolerances as low as 0.05% if the operation is carried out under the recommended injection moulding conditions, table (2-11), (Invibio, 2004a; Kurtz, 2011b).

There is substantial interest in quantifying the nature of re-crystallization and other thermal history related to metastability of polymer crystals, which is due to the importance of re-crystallization regarding elevated temperature properties (Cebe and Hong, 1986; Sauer *et al*., 2000). PEEK has been investigated using different variables such as melting, heating rates (Lee and Porter, 1987; Medellin-Rodriguez *et al*., 1996; Denchev *et al*., 2000) and crystalline behaviour using special study techniques (Medellin-Rodriguez *et al*., 1996; Sauer *et al*., 2000). However, no studies have acknowledged the effect of mould temperature on the PEEK's physical and mechanical properties in relation to the PEEK provided in industry as a final product. According to Kurtz and to Invibio's processing guide, injection moulding parameters such as mould temperatures, design, and geometry of the parts could affect PEEK flow and hence the uniformity of the moulded parts (Invibio, 2004a; Kurtz, 2011b).

Table (2-11): Typical injection moulding temperature profiles for PEEK-OPTIMA, adapted from Kurtz (2011b)

Material	Rear T (°C)	Middle T (°C)	Front T (°C)	Nozzle T (°C)
Unfilled PEEK	355	365	370	375
Radiopaque PEEK (Barium sulphate- filled PEEK)	355	365	370	375
CFR-PEEK	365	380	390	395

Extrusion

The manufacturing process whereby long stock shapes like rods, sheets, and monofilament fibres are produced is called extrusion. This technique is similar to the injection moulding system regarding the use of PEEK pellets and granules as a starting raw material. The exceptional step in this process is that the molten polymer is pressurized and forced through a heated die, and cooling to room temperature takes place gradually along an extrusion line. The dominant system for the manufacturing of medical device components is the extrusion of PEEK-OPTIMA stock shapes followed by a machining process. This material can be obtained in rods ranging from 6 to 150 mm in diameter and plate with a thickness of 40 mm. However, since a thermal scheme is involved in the extrusion and annealing of stock shapes, slight variations in the mechanical properties of the extrusion components result when compared with the injection moulded method (Invibio, 2004a; Kurtz, 2011b).

Compression Moulding

This moulding technique provides for stock shapes such as plates and thick sheets. It consists of two heated platforms, and the resin powder or granules are placed in the lower platform on which a depression for the plate or sheet is prepared. Then, the two metal plates are pressed together and heated to unite the resin. This process is typically used in the production of industrial components with extremely thick sections or for low volume production. It is relatively more economical than the injection moulding process; however, the long cycle is time consuming. In addition, this technique requires use of a heat press, oven, and a tool of low grade steel or metal to withstand the level of stress, shear, and involved loads. Furthermore, the use of granules and pellets results in weak points in the final components since they represent granular boundaries in the moulded parts. Hence, the fine powder grade of PEEK polymer has been recommended for the compression method. Nevertheless, this process may offer higher crystallinity and tensile strength than the injection method (Invibio, 2004a; Kurtz, 2011b).

Film and Fibre Production

The mechanical performance and the purity of the PEEK fiber and film form provide promise for usage in medical devices, especially for implantable grade application. PEEK film made up of thin sections is produced by processing extruded polymer using suitable die and haul-off equipment, and then the film can be handled and stored for the next procedure. The PEEK film can be provided in either crystalline or amorphous form. This can be achieved by controlling the temperature of the casting drums in the haul-off equipment, although the fully amorphous film becomes more challenging as the thickness of the PEEK film increases. On the other hand, PEEK monofilament can be produced by drawing the PEEK extrudate after extrusion. The drawing requires orientation within the fiber prior to heat setting. The resultant monofilament is characterized by toughness, extreme orientation, and controllable diameter. This diameter can be retained in its set form when the material is subjected to a heat above the glass transition temperature (Kurtz, 2011b).

Machining

Economically, it is unviable to manufacture injection moulding tools for prototype designs or short production runs. Hence, the most common process for this situation is to machine the PEEK-OPTIMA polymer material to form the components. This material can be machined and finished by the same methods and equipment used for other engineering thermoplastics. Carbide and diamond tipped tools are required for working on this material since they demonstrate outstanding physical properties and wear characteristics. However, stress may build up during this procedure due to localization of heat at the cutting point, so annealing should be done to relieve this stress. Since polymeric material has lower thermal conductivity compared to metals, the heat build-up during machining is rapid. Hence, cooling with fluid is recommended to reduce the heat generated by working the material, whilst for medical grade PEEK polymer-based materials water or air jet cooling is suggested (Invibio, 2004a; Kurtz, 2011b).

2.2.3. PEEK Structural Design

PEEK is consider as homopolymer, prepared by the repetition of monomer segments or units, and represented basically by an aromatic molecular chain which is organized by ketone and ether linkage; figure (2-5) (Reitman *et al.*, 2011).

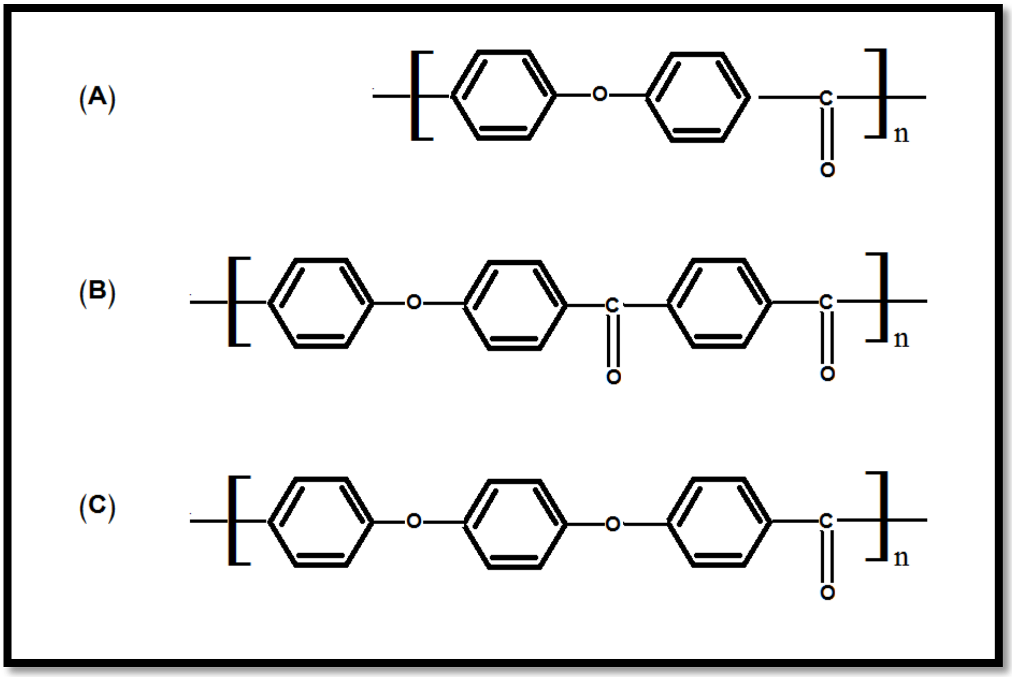


Figure (2-5): The chemical structure of some PAEK homopolymers: **A,** PEK; **B,** PEKK; and **C,** PEEK, adapted from Kurtz (2011b)

Morphology

Like many semicrystaline polymers PEEK has two phases. It consists of an amorphous region and crystalline tangled lamellae. However, the crystalline content of PEEK fluctuates and this depends upon the history of thermal processing. In addition, the molecular chain is not static but vibrates in response to thermal energy or external deformation (Reitman *et al*., 2011).

PEEK polymer can be quenched from the melt to an amorphous glassy solid form. This process is characterized by the material's lack of long range order resulting from the various conformations of the polymer chains that prevents efficient regular packing. Generally, amorphous materials are transparent and of lower density than their crystalline counterparts. In addition, they may show a lack of chemical resistance as well as inferior mechanical properties in comparison with crystalline forms. As in many commercial polymers, the amorphous content is related to the distribution of the chain lengths, the interconnected nature of the crystallizable sections, in addition to defects which may prevent full crystallization, such as chain ends. Hence, when PEEK is cooled slowly, the chains have the freedom to twist around themselves to form the spaghetti or lamellae folds of which are known as crystals. However, the crystals are embedded in a messy area called the disordered or amorphous region thereby revealing the two microstructure phases as numerous semicrystalline polymers; figure (2-6).

Many studies have measured the degree and crystallinity of PEEK and its morphology in association with its thermal behaviour and compared these measurements with those for linear aromatic polymers related to polyethylene terephthalate (PET) (Blundell and Osborn, 1983; Cebe and Hong, 1986; Capodanno *et al*., 1997).

According to Atkinson *et al.,* the crystallinity of PEEK could be up to 40 % given that most typically polymer crystallinity is between 30-35 % (Atkinson *et al*., 2002). The two morphological phases take place when the crystalline regions become dispersed in the amorphous polymer. This process was successfully applied by Blundell and Osborn to predict and describe PEEK density (Blundell and Osborn, 1983). However, a few studies have illustrated the exhibition of rigid amorphous precrystalline ordering, since that ordering is the intermediate point between the disordered amorphous condition and the ordered arrangement characteristic of the crystalline phase (Jenkins *et al*., 2003).

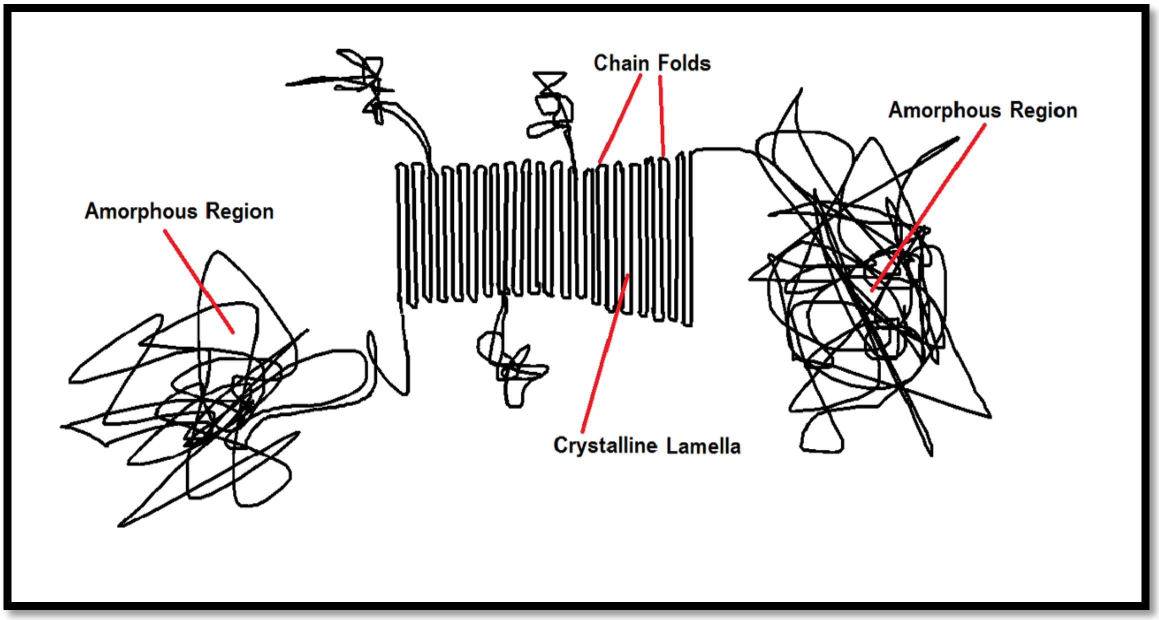


Figure (2-6): A schematic representation of PEEK microstructure showing the amorphous and crystalline regions, adapted from Kurtz (2011b)

Crystalline Unit Cells

The unit cell of the crystal is a structural phenomenon represented by the alignment of the chains in a symmetric repeating manner. The PEEK chains fold and pack to form unit cell lamellae which grow into three-dimensional spherulites. The physical properties are determined by the number and the size of these spherulites, which in turn depend on the nucleation and growth processes. Although PEEK's crystallization behaviour is connected strongly to the thermal history, many studies have suggested that the processing conditions can cause positive and negative birefringence development in the crystallites (Blundell and Osborn, 1983; Kumar *et al*., 1986). Chemically, the PEEK repeated unit contains three aryl rings which in turn expand to six aryl rings for symmetry, although the dimensional arrangement of the PEEK unit cells depends on the crystallization temperature (Hay *et al*., 1989; Blundell and D'mello, 1991). Any defect such as the mismatching of adjacent chains within the PEEK crystal structure might be expected to occur at low crystallization temperature. However, this could be related also to variations in the angle between the planes of adjacent phenyl groups which has been determined to be 40° for PEEK (Hay *et al*., 1989).

Typically, PEEK exhibits high nucleation density, so the lamellar detail of the spherulites cannot be visualized by polarized light microscope, although it can be successfully viewed under the scanning electron microscope (SEM) using specific etching techniques (Olley *et al*., 1986). However, the nucleation, growth and crystal morphology of the PEEK can be affected by the introduction of fillers and reinforcements. Such inorganic components could restrict the chain movement and provide an outline for crystal growth (Mehmet-Alkan and Hay, 1993).

2.2.4. Mechanical Properties of PEEK

Assessment of the failure of any material is an essential requirement of dealing with engineering components. Regardless of the various reasons for failure of materials, fracturing due to stress concentration on static or cyclic loading is the dominant factor in material fatigue. This is additional to the most challenging factor that designers face, which is the maintenance of reliable performance under repetitive loading conditions. Stress concentrations such as notches and cracks are the most common types of initiation of static fracture or fatigue failure mechanisms of material components in any design feature (Sobieraj and Rimnac, 2011). However, the majority of research on the fracture properties of materials has focused on describing the methods of fracturing or the analysis of fracture surfaces (Anderson, 2005; Meyers and Chawla, 2009; Berer *et al*., 2013; Dowling *et al*., 2013).

Fracture Studies

Impact strength is a measure of the energy absorbed by a material before it fractures (Hertzberg *et al*., 1996). The Charpy and Izod tests are high strain impact tests. They measure the energy absorbed by a material during high speed impact. The basis of both tests is the dropping of a pendulum from a define height that results in impacting and fracturing of a cracked or notched specimen (Hertzberg *et al*., 1996; Dowling *et al*., 2013). However, the results of these tests are extremely reliant on the specimen size; notch geometry; the magnitude and rate of the loading; and the technique used for supporting the specimen. The material will not possess intrinsic behaviour properties unless all the test conditions are held constant.

However, according to ASTM F 2026-10, a notch Izod fracture toughness of at least 4 KJ/m^2 is the only fracture property requirement for PEEK as an implantable material (ASTM). According to Kemmish and Hay PEEK's impact strength or toughness increases as the molecular weight is increased and it decrease as the crystallinity is enhanced (Kemmish and Hay, 1985). Additional studies have supported that when reported that the fracture toughness of the unfilled PEEK is affected by several morphological parameters. PEEK's fracture toughness decreases with the lowering of its molecular weight (Chu and Schultz, 1989; Chivers and Moore, 1994), and fracture toughness increased when the crystallinity percentage was decreased (Karger-Kocsis and Friedrich, 1986; Talbott *et al.*, 1987; Tseng, 1987; Chivers and Moore, 1994). In addition, Chu and Schultz stated that fracture toughness increases when the size of the PEEK spherulities decreases. However, other studies produced different fracture toughness mesurements that indicated that fracture toughness increases when the loading rate is decreased (Karger-Kocsis and Friedrich, 1986), and the temperature is increased to between 50 °C and 150 °C (Hertzberg *et al.*, 1996; Dowling *et al.*, 2013; Anderson, 2005). Furthermore, the fatigue crack growth (FCG) behaviour of PEEK can also affected by molecular weight, percent crystallinity, and spherulite size parameters, table (2-12) (Tseng, 1987; Chu and Schultz, 1989; Saib *et al.*, 1993; Saib *et al.*, 1994).

Table (2-12): Material and testing parameters' effects on PEEK mechanical properties, adapted from Kurtz (2011b)

Material/ Testing Parameter	Effects on Impact Toughness	K_{IC}	FCG Resistance
↓ Molecular weight	↓	↓	↓
↓ Percent crystallinity	↑	↑	↓
↓ Spherulite size		↑	↑
↓ Radius of curvature of the notch (Pr)	↓		
↓ Loading rate		↑	
↑ Ageing	↓		

Notch Studies

There has been some clinical success with the use of Polyetheretherketone (PEEK) as a load bearing orthopedic as implant material containing stress concentrations (notches) built into the design (Sobieraj *et al.*, 2010; Sobieraj and Rimnac, 2011). However, no work has been conducted to examine the impact behaviour of unfilled PEEK as a denture base material with the use of notches.

PEEK may be prepared in industry under several different thermal cycling and annealing sequences. It may be quenched from the melt, or slowly cooled at different rates, then annealed at specific temperatures (Invibio, 2004b; Kurtz, 2011b). The moulding temperatures and crystallinity could significantly impact the mechanical behaviour of PEEK and this was effectively characterised by the test results. The morphology characteristics that can affect PEEK's mechanical properties should be considered. The rate of cooling from the melt affected the degree of crystallinity, crystal perfection, and inter-chain spacing in the amorphous regions. Applying annealing treatments to the PEEK for machining purposes may improve the degree of crystallinity, additionally, it releases stress that could be generated during this process and thereby reduces dimensional changes to the resultant product. However, this may result in degradation of the polymer through cross-linking reactions.

The presence of a notch in any tested material as a stress concentration may increase the tendency for brittle fracture (notch weakening). However, the material can demonstrate a failure after yielding at a stress greater than the un-notched stress (notch strengthening). This depends on the ability of the material to undergo plastic deformation in the notched area (Goolsby and Chatterjee, 1983). It seems that there is insufficient literature regarding PEEK fracture behaviour in the presence of notches. However, Sobieraj *et al*. (2010) and (2011) recorded many observations in a monotonic tension study of PEEK 450G. They assumed that PEEK is a notch-weakening material and tested its behaviour with several notches of diverse severity. In addition, they found that the ultimate fracture stress increased as the notch severity decreased. Furthermore, this study revealed that PEEK undergoes a dramatic change in its fracture micromechanism. In the early stage the specimens showed evidence of yielding and necking resulting from the primary fracture mechanism of the smooth specimens; this was followed by cavitation, then voids, flaw formation, crack growth and the final fracture, figure (2-7) (Sobieraj *et al*., 2010; Sobieraj and Rimnac, 2011). Table (2-13) shows other mechanical properties for PEEK material related to test method (Kwarteng and Stark, 1990; Godara *et al*., 2007; Kurtz, 2011b).

Table (2-13): PEEK-OPTIMA LT1 mechanical properties related to test methods, adapted from Kurtz (2011b)

Test	Test Method	Results
Tensile strength	ISO 527	100.69 MPa
Tensile elongation	ISO 527	32.21%
Flexural strength	ISI 178	163.88 MPa
Flexural modulus	ISO 178	3.99 GPa
Impact strength (Notched Izod)	ISO 180	7.0 KJ/m^2
Density	ASTM D792	1.30 g/cc
T_g (onset)	DSC	146.77 ˚C
Melt temperature	DSC	341.30 ˚C
Re-crystallization temperature	DSC	289.77 ˚C
DSC: Differential Scanning Calorimetry		

2.2.5. Chemical Properties of PEEK

Chemical Stability

The outstanding chemical resistance of PEEK results from its chemical structure. Aryl rings attached via ketone and ether groups were located at opposite ends of the ring, figure (2-8). This stabilizing chemical structure provides the PEEK with delocalization of higher orbital electrons along the entire macromolecule. This results in the PEEK being inherently highly unreactive to chemical, thermal as well as post-irradiation degradation (Kurtz, 2011b).

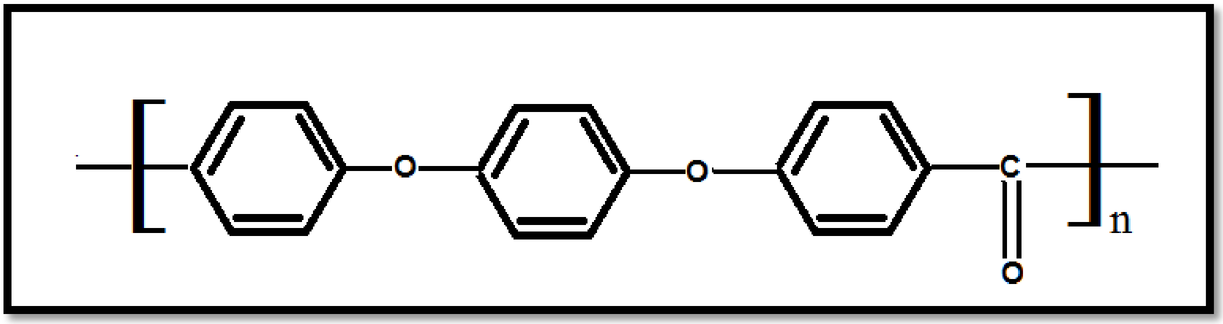


Figure (2-7): The chemical structure of PEEK, adapted from Kurtz (2011b)

Water Solubility

PEEK has water solubility of 0.5 % w/w; however, it seems not to be chemically damaged by long term water exposure, even at temperatures of up to 260 °C (Stober *et al*., 1984; Searle and Pfeiffer, 1985; Boinard *et al*., 2000). According to Meyer *et al*., unfilled PEEK is not susceptible to hydrolysis, while the interface between the polymer and reinforcements could show weakness in fluid environments (Meyer *et al.*, 1994).

Theoretically, there are two potential mechanisms for water infiltrating into polymer composites: diffusion and wicking mechanisms (Godara *et al.*, 2007). However, water absorption with PEEK and its carbon fiber composites (CFR-PEEK) could follow an exponential relationship over time (Boinard *et al.*, 2000). Differential swelling of the matrix and the fiber takes place as the water creeps into the composite. This results in minor changes within a few micrometers adjacent to the reinforcing fiber inside the interface region of the matrix (Godara *et al.*, 2007). However, a study by Boinard *et al.* revealed that water absorption by PEEK may reduce its crystallinity (Boinard *et al.*, 2000). Despite the fact that water sorption has a slight effect on PEEK's mass behaviour (Stober *et al.*, 1984; Searle and Pfeiffer, 1985; Boinard *et al.*, 2000), it is very important to take account of these results in biomechanical testing for PEEK composite materials for implant applications (Kwarteng and Stark, 1990; Brown *et al.*, 1990; Zhang *et al.*, 1996). This is because any small uncounted changes in weight could be a marker for material loss, for instance in a wear experiment. Zhang *et al.*'s study focused attention on estimation of the fluid absorped by the PEEK prior to conducting a long term mechanical test. They found that presoaking the specimens for 30 days revealed absorption of fluid by PEEK of 98 %/weight.

Cyclic compression fatigue tests for CFR- PEEK in saline at temperatures ranging from 37-95 °C, showed that after 5000 h there are no significant changes in the compressive strength and modulus or in Poisson's ratio (Zhang *et al.*, 1996), and the flexural mechanical properties after exposure to high temperature saline environments (Kwarteng and Stark, 1990; Brown *et al*., 1990).

Steam Sterilization of PEEK

Since autoclaving is the most commonly used sterilizing system for medical devices, the PEEK and CFR-PEEK composites have been examined under pressurized steam method (Kwarteng and Stark, 1990; Godara *et al*., 2007). No significant reduction in the flexural strength was noticed when samples of CFR-PEEK (APC-2/AS-4) prepared by ICI were exposed to up to 100 autoclave cycles. In addition, the tensile strength of PEEK-OPTIMA LT1 does not degrade over 2500 h when subjected to continuous pressurized steam of 200 °C and 14 bar (Kwarteng and Stark, 1990). However, a slight modification was detected to the PEEK microstructure in the interphase region adjacent to the fiber following the use of nanoindentation and nanoscratched testing methods. The observation indicated that the interphase region width was increased from 3 to 5 µm after steam sterilization. In contrast, generally, composite bulk behaviour was unaffected by sterilization in terms of the measured PEEK parameters (Godara *et al*., 2007). Overall, previous studies have shown that the main properties of PEEK are relatively unchanged by long-term exposure to steam or repeated autoclaving (Kurtz, 2011b).

2.2.6. Thermal Properties of PEEK

Thermal Transitions

Many thermoplastic polymers undergo three main thermal transitions when heated; glass transition temperature (T*g*), melting temperature (T*m*) and flow transition temperature (T*f*) (Zhang *et al*., 1993; Kurtz, 2011b). The study by Candia *et al.* found that dynamic mechanical analysis of PEEK demonstrated three thermal transitions: melting transition (*α*), glass transition (*β*), and a third transition (*ɣ* transition) which can be detected at very low temperatures and is associated with hydrogen bonding as an effect of absorption of water (Candia *et al*., 1994). However, PEEK components can demonstrate an additional transition temperature, which is called a recrystallization transition temperature (T*c*), and this depends on how it was originally processed (Kurtz, 2011b). The specific molecular structure of PAEKs and the limited chain flexibility combined with the polymer backbone can provide the polymer with a high T*g* and crystalline T*m*. This is significant for the medical device designer, since PEEK is a polymer that exhibits performance at a temperature below both melting point and transition temperature, and this limits the recrystallization or physical ageing (Reitman *et al*., 2011).

Since crystallinity may obstruct the molecular motion, many studies have tested PEEK material for the effect of crystallinity on the adjacent amorphous region (Ballara *et al*., 1986; Atkinson *et al*., 2002). They found that there is a slight increase in the glass transition temperature or an increase in the width of the transition period. In addition, adequate molecular motion could result in slow densification of the amorphous phase, which could be described as a physical ageing. However, this seems not to affect PEEK's heat capacity except in its glass transition region (Kemmish and Hay, 1985). Further research on physical aged PEEK samples has investigated the relationships between properties. Researchers recognized that these aged samples were of increased density that decreased the toughness of the material (Atkinson *et al*., 2002). Furthermore, PEEK demonstrated an increase in the tensile yield stress and more localized yielding, while the impact strength was decreased (Kemmish and Hay, 1985).

PAEK polymers, due to their crystallinity characteristics, revealed elasticity behaviour in the region above the T*g* and below the T*m*. In this temperature region the chain units were sufficiently mobile within the amorphous area to allow the recrystallization and the lamellar thickening to increase the crystallite overall (Ballara *et al*., 1986; Blundell and D'mello, 1991). Moreover, larger crystals can be achieved by slow cooling from the melt point (Cebe and Hong, 1986). The changing nature of the crystal characteristics could have an important effect on the material's mechanical properties, including its hardness (Tung and Dynes, 1987).

Thermal Stability

As PEEK polymer is used at high temperature different processing conditions and in various applications in industry, the study of its thermal stability is essential. Although PEEK thermal degradation occurs at temperatures between glass and melt transition temperature, these may exceed the PEEK processing temperatures needed to produce volatile degradation products.

According to Hay and Kemmish, thermal degradation accompanied by the production of volatiles was difficult to measure at temperatures under 427 °C (Hay and Kemmish, 1987). Other studies found no significant differences in degradation when using Fourier transform infrared (FTIR) spectroscopy techniques for PEEK and CFR-PEEK composites at temperatures between 400 and 480 °C (Cole and Casella, 1992; Cole and Casella, 1993). Nevertheless, based on the previous findings, thermal degredation in the region of 37 °C might not be a concern during clinical use of PEEK biomaterials (Kurtz, 2011b).

Effect of Temperature on Structure and Properties

The morphology of the PAEK polymers seems to be stable under clinically applicable temperatures and conditions; therefore, PAEK-based devices' structure and properties have historically been controlled during manufacture.

Since injection moulding methods are the main conventional process for melting polymers, the low induction of orientation molecules of some polymers results in extremely crystalline skin surfaces than the specimens' core (Wilfong, 1989). However, in PAEK polymers with little ordering and less thermal conductivity, in addition to the quenching effect of the mould, the amorphous surface is increased, enhancing the organization of molecules, which continue until the core cools.

In injection moulding conditions, parts of the polymer may reveal different levels of crystallinity and this might have diverse effects on the material's properties since the polymer cooling rate varies depending on its thickness. Even so, typical warm mould temperatures of 180-220˚C provide a highly crystalline surface with no quenched or amorphous characteristics. Nevertheless, the formation of a skin on the surface can be managed either by polishing away any remarkable crystalline material, or establishing moulding test specimens of appropriate thickness to provide a thin and insignificant surface skin, or by subsequent thermal treatment (Wilfong, 1989).

According to Cebe *et al*., the mechanical properties of PEEK are affected by microstructure development during processing. The larger, more perfect crystals have weak boundaries, so the material exhibits less damage tolerance, thereby allowing easier crack initiation and propagation (Cebe *et al*., 1987).

Effect of Fillers on PEEK Structure and Properties

Generally, inorganic fillers are used to modify the properties of polymers. PEEK for an implantable application is available commercially in unfilled form and carbon fibre and barium sulphate may be added to enhance the required properties (Kurtz, 2011b). Adding such fillers provides an additional phase to the original morphological crystalline and amorphous phases of PEEK. This phase is characterized by changes in nucleation and the growth of crystals during both physical patterns, as well as alterations in thermal conductivity (Mijovic and Gsell, 1990). The polymer crystallizing chains are affected by the presence of the filler as the PEEK composite cools from the melt (Seferis, 1986). Furthermore, these fillers enhance an additional region in the composite PEEK material called an “interphase region”, which is observed at the microscale, and this localizes the material’s micromechanical behaviour (Godara *et al*., 2007).

2.2.7. Biocompatibility of PEEK

In 2008, Withy *et al.* drew the attention to the fact that polyetheretherketone polymer could be used in the food processing industry as a coating for corrosion resistance (Withy *et al*., 2008). However, as Fitch *et al.* (2010) point out; it has had extensive use for biomedical purposes, particularly in the past two decades. It is considered as an ingenious thermoplastic material for use in reconstructive shock and spinal implants; in addition it shows extreme biocompatible stability when sterilized by steam, ethylene oxide or other chemicals (Fitch *et al*., 2010). PEEK is one of the critical biomaterials that have potential to be used instead of metals inside the human body (Invibio Ltd., Thornton Cleveleys, United Kingdom) (Jarman-Smith, 2008; Green, 2012). Green, in 2012, made clear, alongside the ISO (10993-5) and (10993-18) in 2009, that this material had no cytotoxic effects on biological tissues after one year of vivo implantation studies. Furthermore, chemical analysis of the implanted sites revealed unaffected consequences. These experiments may indicate that such materials could be applied passively as medical devices such as implants, healing caps and gingival formers as well as in prosthetic rehabilitation devices such as maxillofacial implants and abutments (Green, 2012).

2.2.8. Polyetheretherketone (PEEK) in Dentistry

PEEK Material as a Dental Implant

PEEK dental implants have not been extensively used clinically and therefore more studies are essential to identify their long-term efficacy in human subjects.

Considering adequate biocompatibility, implant healing abutments can be constructed using PEEK (Koutouzis *et al*., 2011; Hahnel *et al*., 2014). Koutouzis *et al*. suggested that there is no significant difference in bone resorption and soft tissue inflammation between PEEK and titanium abutments (Koutouzis *et al*., 2011). In addition, oral microbial flora attachment to PEEK abutments is equivalent to that of titanium, zirconia and polymethylmethacrylate abutments (Hahnel *et al*., 2014). Titanium could be replaced by PEEK in constructing implant abutments, since the elastic modulus of bone and PEEK reduces stress shielding effects and encourages bone remodeling (Najeeb *et al*., 2015).

PEEK Material as a Fixed Prosthesis

Using CAD-CAM production methods for restorations makes it possible to construct dental prostheses chair-side (Reich *et al*., 2005). CAD/CAM designed PMMA and composites fixed dentures have exhibited superior mechanical properties compared to traditional prepared fixed dentures (Alt *et al*., 2011; Stawarczyk *et al*., 2012). PEEK is a material that may be used as an alternative to PMMA for CAD/CAM restorations. PEEK fixed partial dentures constructed using CAD/CAM technique have exhibited higher fracture resistance than the pressed granular-shaped PEEK dentures (Stawarczyk *et al*., 2014). The fracture resistance of CAD/CAM milled PEEK fixed dentures is much higher than that of comparable lithium disilicate glass-ceramic, alumina, and zirconia restorations (Beuer *et al*., 2008b; Kolbeck *et al*., 2008).

Despite the significantly low elastic moduli and hardness of PEEK, the abrasive resistance of PEEK is competitive to that of metallic alloys (Zok and Miserez, 2007). However, no clinical studies have attempted to compare the abrasion produced by PEEK crowns on teeth to that produced by other materials such as ceramics and alloys. As yet, no studies have indicated whether PEEK crowns function efficiently with the dentin and enamel. Considering PEEK's abrasion resistance, mechanical attributes and adequate bonding to composites and teeth, a PEEK fixed partial denture would be expected to have an acceptable survival rate (Najeeb *et al*., 2015).

PEEK Material as a Removable Prosthesis

Dentures could be constructed using PEEK CAD/CAM (Kurtz, 2011b). Tannous *et al.* stated that denture clasps made of PEEK may have lower retentive forces compared to Co-Cr clasps (Tannous *et al*., 2012). However, the clasp dimensions and testing conditions may not represent the genuine clinical situations. In addition, an application of PEEK in a removable dental prosthesis was reported that successfully used PEEK material as an alternative material to metals and acrylic resins (Costa-Palau *et al*., 2014; Zoidis *et al*., 2015). Yet, more studies are needed to evaluate the efficacy of PEEK prostheses compared to conventional metal and acrylic prostheses, as few published clinical studies or systematic reviews have focused on the use of PEEK as a denture material. Nevertheless, given the superior mechanical and biological properties of PEEK, dentures constructed from this polymer could well be routinely constructed in the near future.

2.3. Aims and Objectives

The literature review shows that the most conventional denture base materials suffer from serious limitations, and poly(etheretherketone) or PEEK shows great promise as an alternative biomaterial for the manufacture of dental prosthesis. However, while PEEK chemistry and properties have been studied extensively, relatively little attention has been directed at its adoption into dentistry, especially with respect to its utility and how it might be processed in a dental technology laboratory. The aim of this research was therefore to carry out a detailed investigation of the behaviour and performance of PEEK as a denture base material, its processability in the dental technology environment, mechanical properties and finally the design considerations that will undoubtedly influence clinical performance. The specific objectives of the research project were therefore:

1. To optimize the gypsum moulding temperature for thermo-pressing purposes.
2. To investigate the effect of mould temperature on the injectability and thickness behaviour of thermo-pressed PEEK-Optima®NI1.
3. To explore the surface roughness of PEEK-Optima®NI1 thermo-processed at different mould temperatures.
4. To evaluate the mechanical properties such as impact strength, flexural properties and tensile strength of machined PEEK-Juvora™ by CAM and PEEK-Optima®NI1 thermo-pressed by denture injection method at different mould temperatures
5. To investigate the retentive force of PEEK clasp design at different tooth undercuts with thermo-cycling fatigue test representing 3 years of insertion/removal use.

These individual objectives above are divided into separate chapters (four to eight) where they are considered separately before giving a final discussion and conclusions versus other denture base materials. On completion, this research will provide essential knowledge that will help determine whether PEEK should be adopted for the manufacture of dental prosthetics, and also assist the community in developing an optimised processing route including design parameters.

Chapter Three

General Materials and Methods

Chapter Three: General Materials and Methods

3.1. Materials

The PEEK polymer in this study was supplied by Invibio Ltd Company as part of an agreement with the University of Sheffield. A granular form of medical grade PEEK-Optima®NI1 polymer and PEEK-Juvora™ discs were used to accomplish this project, figure (3-1) and (3-2). All the materials, equipment, units and machines used in this study are listed in the following tables (3-1) to (3-3).

Table (3-1): The study units, equipment and machines and their supplier

Dental laboratory units, equipment and machines:	Suppliers and Origin
3D Dewax unit	(MAX, Germany)
3D Wax printer (3Zlab)	(Solidscape, Japan)
4-point tester unit (2.5 KN, 2000)	(Instron Lloyd, England)
Autocycle notching cutter machine	(Ray Ran Polytest, England)
Casting furnace	(Vecstar 1 and 2, Italy)
Chewing simulator machine	(Central Lancashire University, UK)
Dental lab furnace	(Vecstar, UK)
Dental lab vibrator	(Silfradent, Italy)
Dental laboratory sandblaster machine	(Renfert, Germany)
Digital micrometer	(Highcap, China)
DWOS dental scan unit	(Dental Wings, Germany)
Electrolytic polishing unit	(BEGO, Germany)
Flasks (thermo-press system)	(Bredent, Germany)
Grinder polisher machine (Metallographic)	(kemet, England)
Impact tester machine (IT 503)	(Tinius Olsen's, England)
Light microscope	(Discovery stereo-V8, UK)
Modular 3S electronic induction casting machine	(Iconium, Italy)
Multi-channel LCD digital thermometer (Yct, 717)	(Thermosense, UK)
Multi-cure denture unit	(Paco, UK)
Profilometer (Ra tester machine)	(TR200, USA)
Roland milling machine	(DWX-50, USA)
SEM	(Philips, Germany)
Single digital thermometer with USB sensor (Yct, 717)	(Thermosense, UK)
Tensile tester unit (2.5 KN, 2000)	(Instron Lloyd, England)
Thermopress 400 machine	(Bredent, Germany)
Ultrasonic cleaner unit (Quantrex, S200)	(Sweepzone^{TM}, USA)
Vacuum mixer unit	(Degussa, Germany)
Wax extraction unit	(Dreve labormat TH, Germany)

Table (3-2): The study's dental laboratory consumables and their suppliers

Dental laboratory consumables:	Suppliers and Origin
Acrylic Sep	(Bredent, Germany)
Aluminium cartridge	(Bredent, Germany)
Base plate wax	(Degussa, Germany)
Ceramic crucible (Heat-resistant)	(BEGO, Germany)
Co-Cr RPD casting alloy	(BEGO, Germany)
Dewax solution	(BioGenex, Germany)
Die stone (Esthetic base® gold, type IV)	(Dentona®, Germany)
PEEK- Juvora™ blank discs	(PEEK-JUVORA™, JUVORA Ltd., UK)
PEEK-Optima®NI1 granules	(Invibio Ltd., UK)
Phosphate gypsum investing materials	(BEGO, Germany)
Plaster and stone solvent solution	(Metrodent, England)
Polymethylemethacrylate granules (PMMA, Brecrystal HP)	(Bredent, Germany)
Polymethylemethacrylate resin (PMMA, Heat-cured resin)	(Candulor, Switzerland)
Pressure spot indicator pastes (COLTENE® PSI)	(Visadent, Switzerland)
Rhino Rock model resin	(DB lab, UK)
Silicone duplicating material (Metrosil Plus)	(Metrodent, England)
Soft paraffin	(Ecolab Ltd, UK)

Table (3-3): software programs used in this study and their suppliers

Software and programs:	Suppliers and Origin
3D modeling computer program	(Google SketchUp, 2013)
DWOS RPD design (V-5.2.2.)	(Dental Wings, Germany)
Endnote referencing manger (X7)	(Software Download Service, UOS)
SPSS (V-22)	(Software Download Service, UOS)

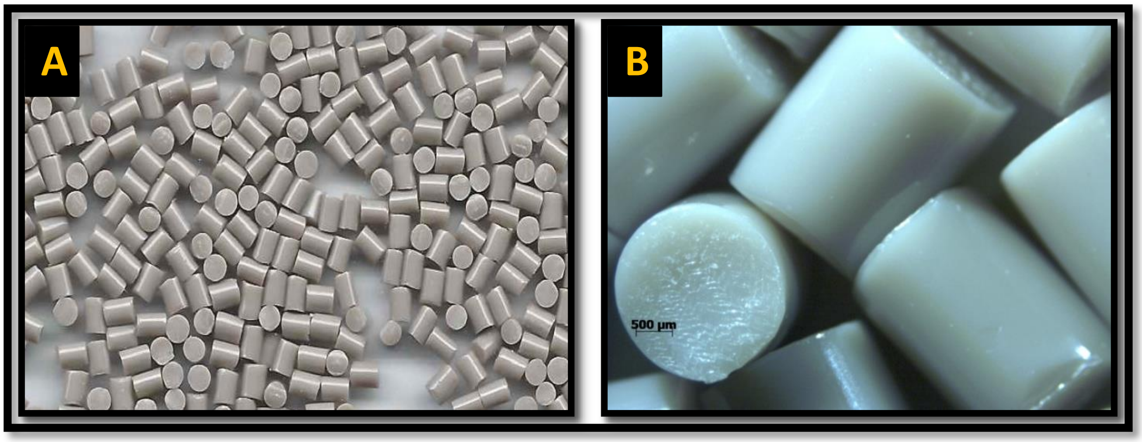


Figure (3-1): A. High-resolution optical micrographs of PEEK-OPTIMA®NI1 granules; **B.** PEEK granules under light microscope

Figure (3-2): PEEK-Juvora™ discs

3.2. General Methods

3.2.1. Innovative Methods

Innovative techniques have been designed and created to achieve certain objectives of this study, including testing procedures and design and fabrication of special tools and jigs. These innovative methods include the following:

Mould Temperature Monitoring Technique

One of the study objectives was to evaluate the effect of mould temperature on the properties of the thermoplastic injected PEEK using thermo-pressed method. Non-uniform distribution of mould temperature may affect the properties of the final injected product. Therefore, the temperature was monitored in different locations inside the furnace and the mould cavity during the preheating treatment; figure (3-3). Further detail about the preparation and the moulding technique in this innovative method will be given in chapter four.

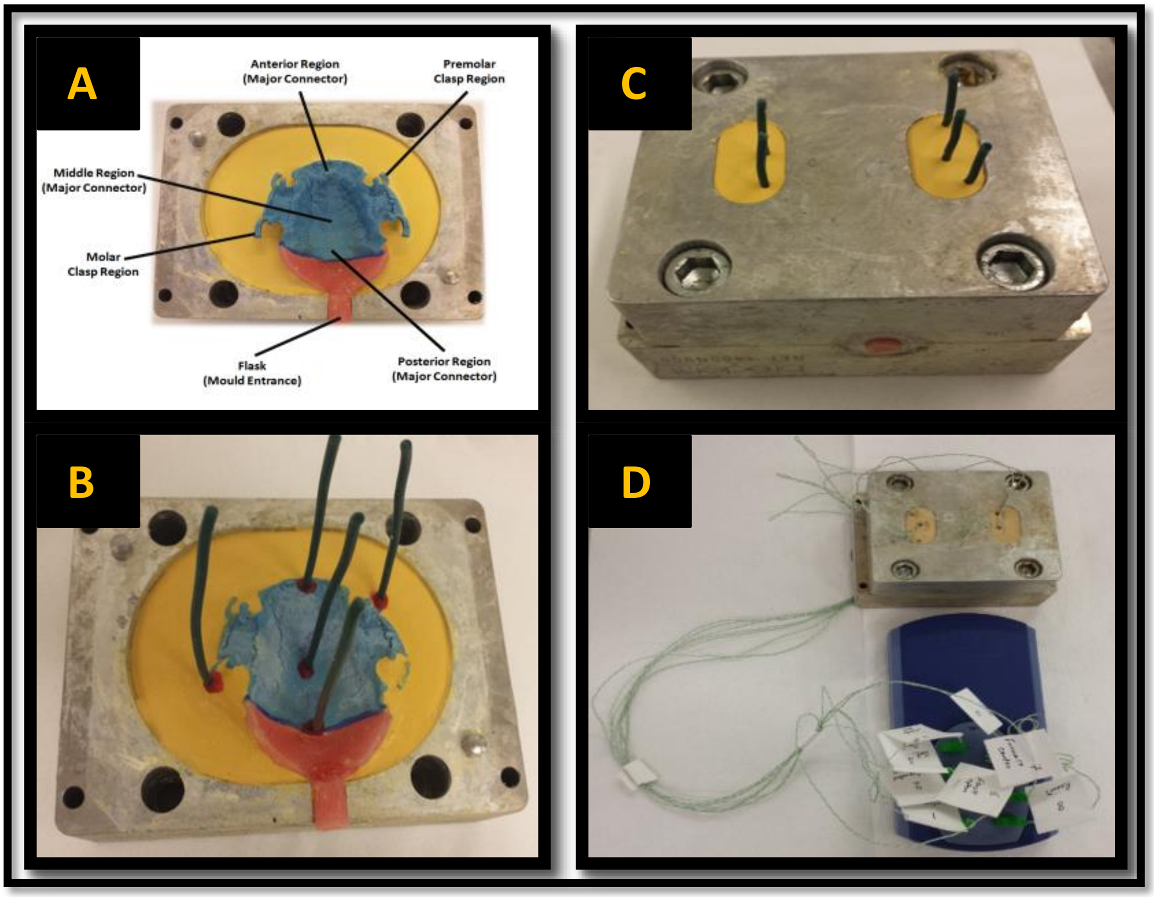


Figure (3-3): Moulded RPD wax framework showing: **A.** location of thermocouples inside the mould cavity; **B.** sprue wax attached to produce the channels; **C.** sprue wax exposed from the moulded flask; and **D.** multi-thermocouples inserted through the hollow channels into the mould cavity at different locations

Flow and Thickness Tests

Flow Test: As no previous studies have reported a suitable technique for measuring the flow of thermo-pressed materials, the current study established a method to estimate the flow behaviour of thermo-pressed PEEK at different mould temperatures by percentage. The flow behaviour of the PEEK specimens fabricated by this denture injection method was estimated using graph paper. For measurement purposes the blue lines represented one millimeter squares. The full wax specimen dimensions of 60 mm X 40 mm width and length respectively were represented by 2400 mm^2 on the graph paper, which reflected 100% of filling. The samples were tested at 0.8 and 1mm depths, and the experimental PEEK specimens were measured within these specific dimensions, figure (3-4).

Thickness Test: It is essential that production of dental prostheses by thermo-pressing method maintains accurate dimension stability. However, in this thermo-pressing method, certain moulding conditions may affect these dimensions and lead to ill-fitting of the dental restoration. Therefore, a method was created to test the thickness of the injected part at different moulding temperatures. The same sample that was used for the flow test was measured by digital micrometer to determine the sample thickness at each level (specimen dimensions of 60 mm X 40 mm width and length respectively). After processing, each specimen of 0.8 and 1 mm thickness was divided into four levels to investigate the effect of mould temperature on thickness. The levels started from the side in contact with the sprue and ended at the free edge; figure (3-5). Each level was subdivided into six square centimeters, and each square centimeter was measured in the centre using an electronic digital micrometer of 0.002 mm accuracy and 0.001 mm resolution. Further detail on these two techniques will be given in chapter (five).

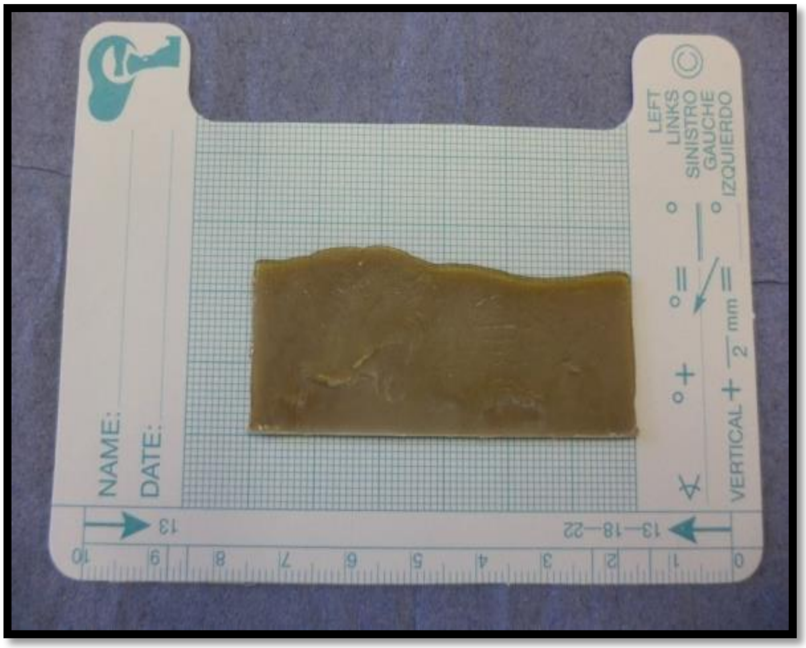


Figure (3-4): PEEK specimen flow measured mechanically using graph paper

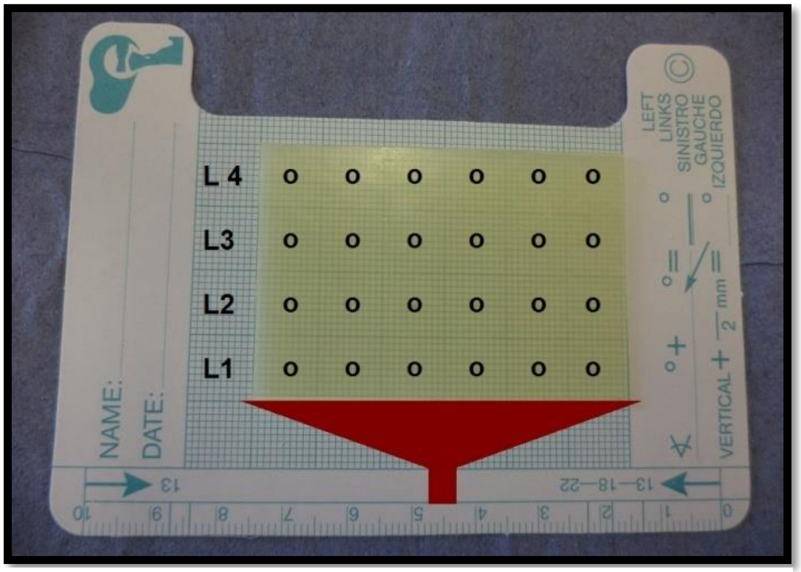


Figure (3-5): The different specimen levels used in the thickness test

Design of Tools for Clasp Retentive and Cycling Tests

The limitations of the various accessories for testing machines available from different companies encouraged us to design and fabricate special tools and jigs for testing purposes. To test the retentive force of the clasp using the tensile jigs, the clasp must be held by a vertical arm to seat on the fixed cast base representing the arch or tooth. The titanium surveyor arm was used to hold the clasp through the clasp pin holder. The surveyor arm was secured by model resin material fixed firmly inside the upper part of the tensile jig and tightened using special slots in the jig. The teeth designed for the test were duplicated and moulded with a base made of modelling material that was fixed inside the lower part of the tensile jig by means of special slots; figure (3-6). The model resin is an alternative modelling material to traditional dental laboratory gypsum stones, and can be poured directly into alginate or silicone impressions to make a model within 30 minutes by hand mixing and bench cure. It produces a clean, bubble and porosity free model with no powder residue, which is dimensionally accurate with no expansion, does not break or chip, but is easy to trim on dental laboratory model trimmers.

For the fatigue cycling test, the clasp specimens had to be held firmly inside the water bath through the cycling period by means of fixed mounting bases. An adjustable sample holder was designed and fabricated for this purpose. A cylinder of hard stainless steel alloy was designed and fabricated with a head ring hole of 4mm in diameter, to hold the clasp and tightened firmly inside the mounting base holder; figure (3-7).

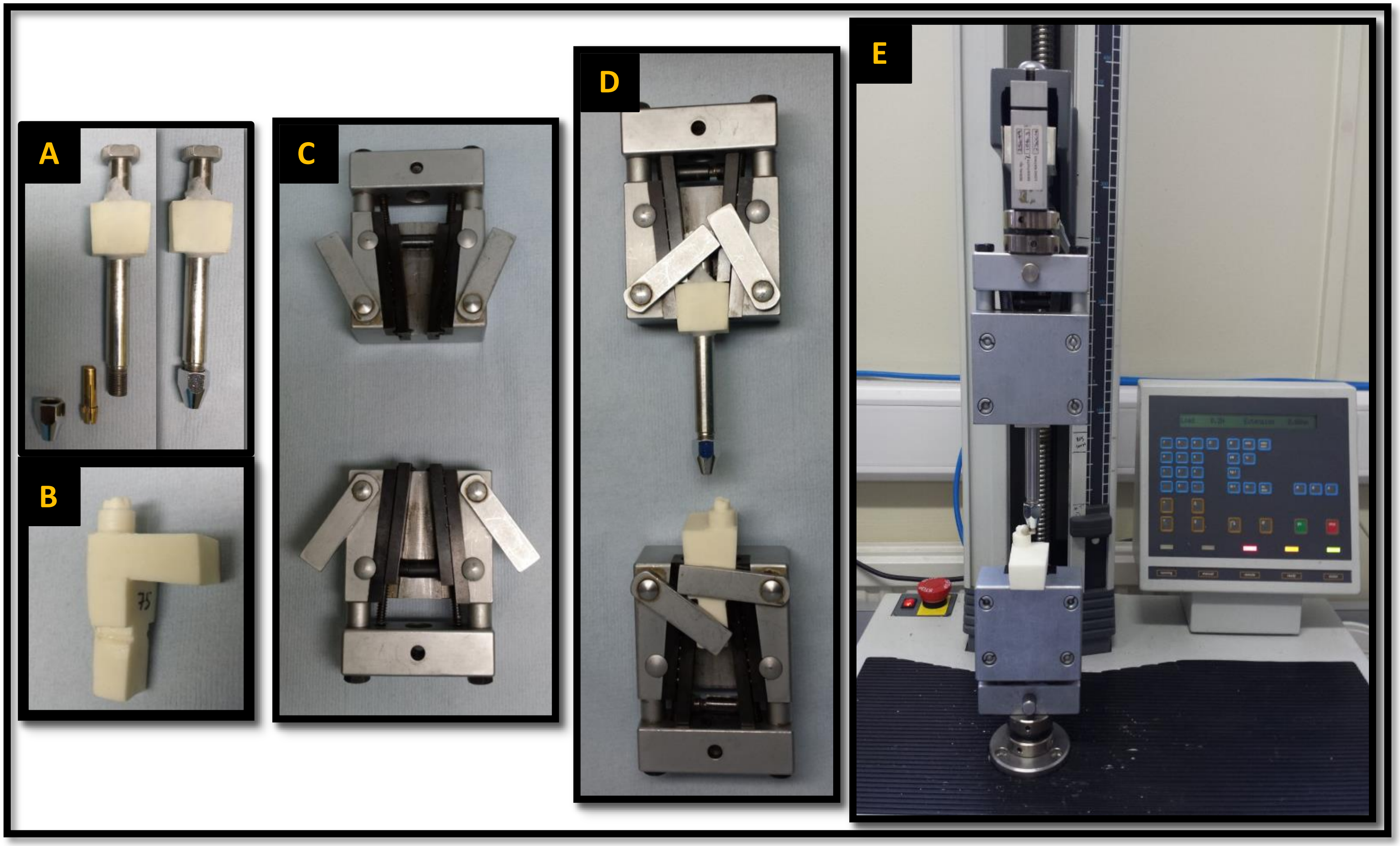


Figure (3-6): Special tools and base fabricated for clasp retentive force test **A.** surveyor arm with a chuck clasp holder; **B**. tooth-base resin; **C**. upper and lower tensile jigs; **D.** test tools secured firmly into jig parts using special slots; **E.** test tools and base-jig under testing procedure

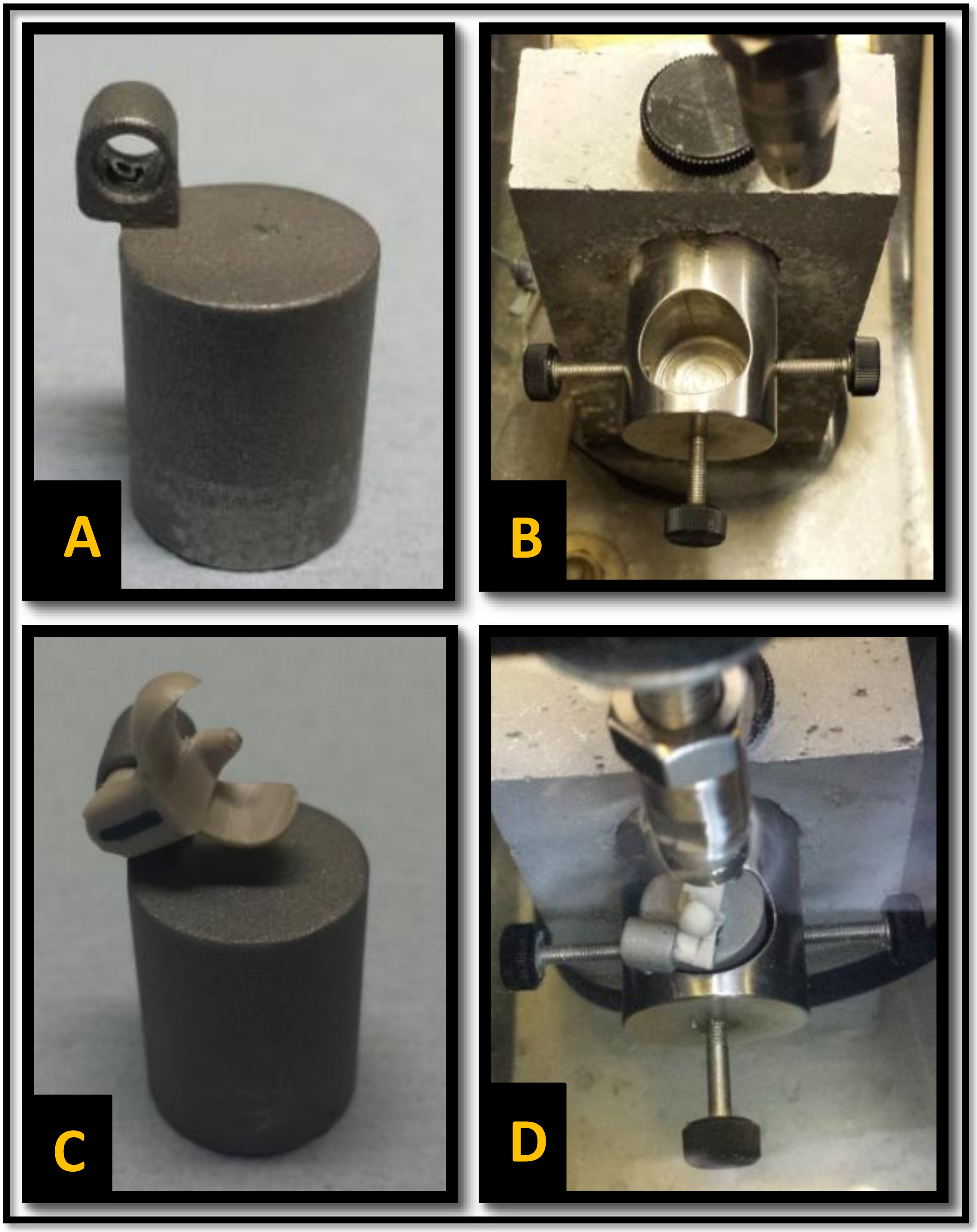


Figure (3-7): A. adjustable clasp holder design; **B.** adjustable sample mounting base fixed on the tank base; **C.** clasp held by adjustable clasp holder; **D.** clasp held by adjustable clasp holder and secured by 3 screws into sample mounting base.

3.2.2. Technical Processing Methods

Different techniques were used in this study to prepare the study samples. However, the specimens were finished and polished using either a machine-polished unit with metallographic grinding papers of 600 or 1200 grits or with medium and fine stone burs (up to 1200 grits) using a micro-motor. This was done to standardise the study sample. Therefore, the finishing and polishing of the study sample specimens will be described briefly in the relevant chapters.

The main processing techniques and methods used in this study are:

Heat-Cured Processing Method

Each sample for study testing of heat-cured PMMA using water bath curing technique followed the conventional dental laboratory procedures. These include preparation of the wax pattern and the mould. For the compression method, after boiling out the wax, a cold mould seal separating medium was applied to the mould surfaces while the mould material was still warm. A water-bath system for heat-cured acrylic resin was used. The mixing of the PMMA powder/liquid ratio followed the manufacturer's instructions (P/L: 100g/10ml). While the mould still warm and after the application of the separating medium the PMMA dough was packed and clamped following the standard procedures. Heat polymerisation was carried out for 9 h [(7h/74°C (±3°C), then 2h/95°C (±3°C)]. The flasks were left after curing to bench-cool overnight, and then deflasked to collect the specimens.

Denture Thermo-Pressing Technique

Injection moulding can be an economical method for manufacturing polymer components. Injection moulding was performed in a commercially available injection moulding machine using material made from high density polyethylene thermoplastic. Experimental variables include injection pressure, speed, and temperature of tools; material quantities and melt temperatures which were standardised. The Thermopress 400 injection moulding system was used for the injection of PEEK and brecrystal PMMA materials; figure (3-8A). The injection system was preheated according to the set programs (bredent, Germany). Each aluminium cartridge was filled with 25g of PEEK-Optima®NI1 or PMMA granules to carry out the denture injection technique. Special thermo-paste grease was used to lubricate the cartridge walls to provide efficient cartridge rejection from the heated chamber. The cartridge was inserted into the heated chamber once the set preheating temperature reached the optimum level. The preheating time for the PEEK material with flask injection mould was 20 minutes, while for the brecrystal PMMA material was 17 minutes. Once the press temperatures were optimized for PEEK polymer at 380 °C and PMMA at 280 °C, the flasks were removed from the furnace and left for 30 seconds to release any steamed air generated inside the mould due to the preheating process. PEEK material injected at 100, 150, 175 and 200 °C mould temperatures, while PMMA was injected as the manufacturer recommended at 40 °C. The PEEK molten material was injected within 60 seconds into the mould cavity with pressing pressure of 150 MPa. However, brecrystal PMMA was pressed at 165 MPa, figure (3-8B). The cooling time for the injected PEEK polymer was 5 to 6 hours, while for the PMMA it was 4 to 5 hours. Nevertheless, the injected moulds were left overnight to allow slow bench-cooling to room temperature. The flask was then deflasked and the specimens were cut from the sprues.

Figure (3-8): A. Thermopress 400 machine used to inject metal-free denture base materials; **B.** The flask was ejected from the heated chamber after injection of the material into the mould cavity

Case Study Design

Kennedy classification Class III modification 1 case study was selected for this experiment stage. The cast model was prepared from a polyvinyl silicone impression material to duplicate the prepared teeth, with trimming of the cast over the saddle areas. The occlusal rest seats of the abutment teeth were prepared according to standard dimensions (Sato *et al*., 2003; Carr and Brown, 2011) and measured under light microscopy; figure (3-9).

The prepared teeth were then replaced in their respectives sockets in the cast model, figure (3-10), and the model duplicated using silicone material. A wax model was then fabricated by melting the base plate wax inside the silicone mould. Next the peripheral dum of 0.5mm was carved carefully in the palatal surface of the wax model, and the saddle area was relieved using 0.5 mm thickness casting wax. Finally, the prepared case study (wax model) was duplicated into the silicone mould, and diestone material (type IV) was poured inside the mould to fabricate the master cast.

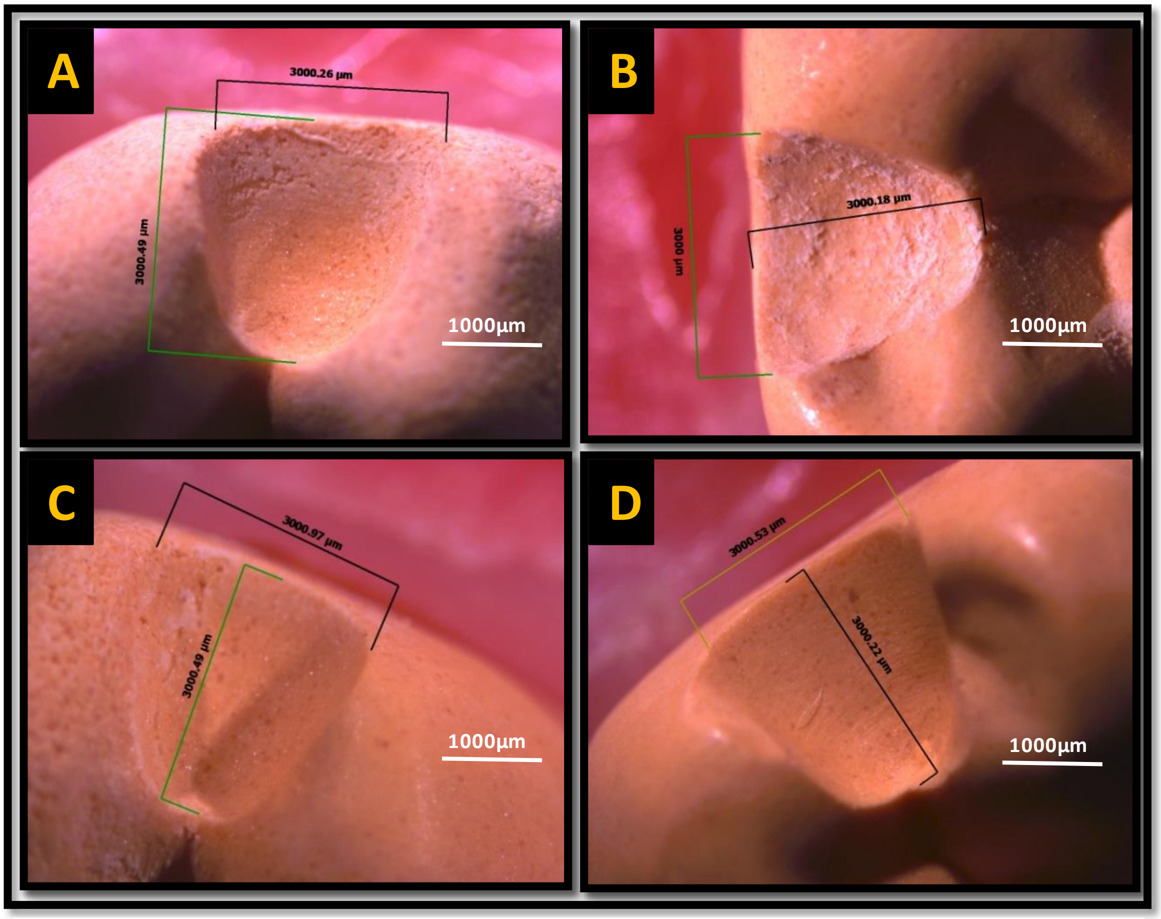


Figure (3-9): Measurement of the dimensions of the ideal occlusal rest under light microscope for the upper, **A.** right 1st premolar; **B.** right 2nd molar; **C.** left 1st premolar; **D.** left 2nd molar

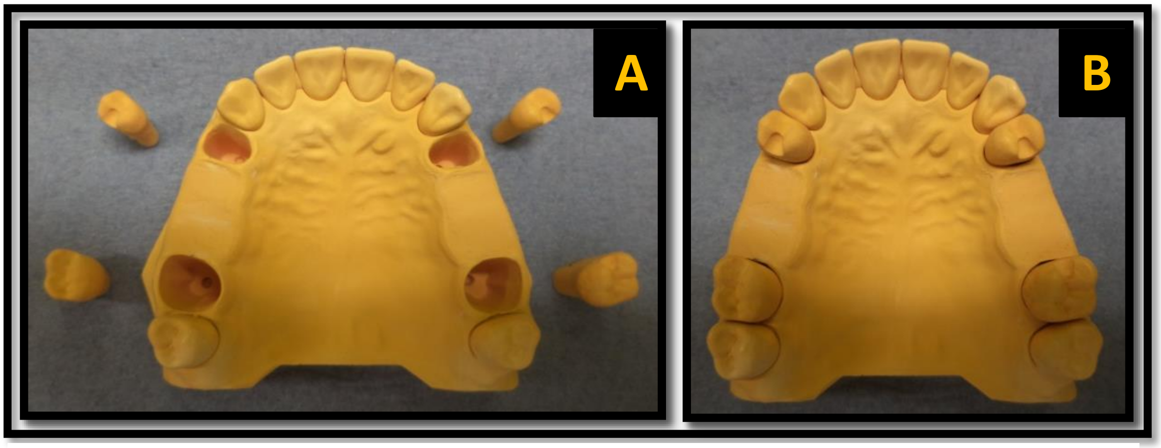


Figure (3-10): A. sample teeth with prepared occlusal rest, **B.** replaced in the cast model

CAD/CAM Production Method

CAD Software

CAD-DWOS

The design of the framework for the RPD and its components was entirely created using the Dental Wings Operating System (DWOS). The master cast was scanned using a lab scanning DWOS 3 unit; figure (3-11). All the icons and information required to use this software designing program for RPD using DWOS are described and illustrated in Appendix (A). However, the RPD framework designed to illustrate this technique was fabricated as a case study to monitor mould/ furnace temperature (Chapter four).

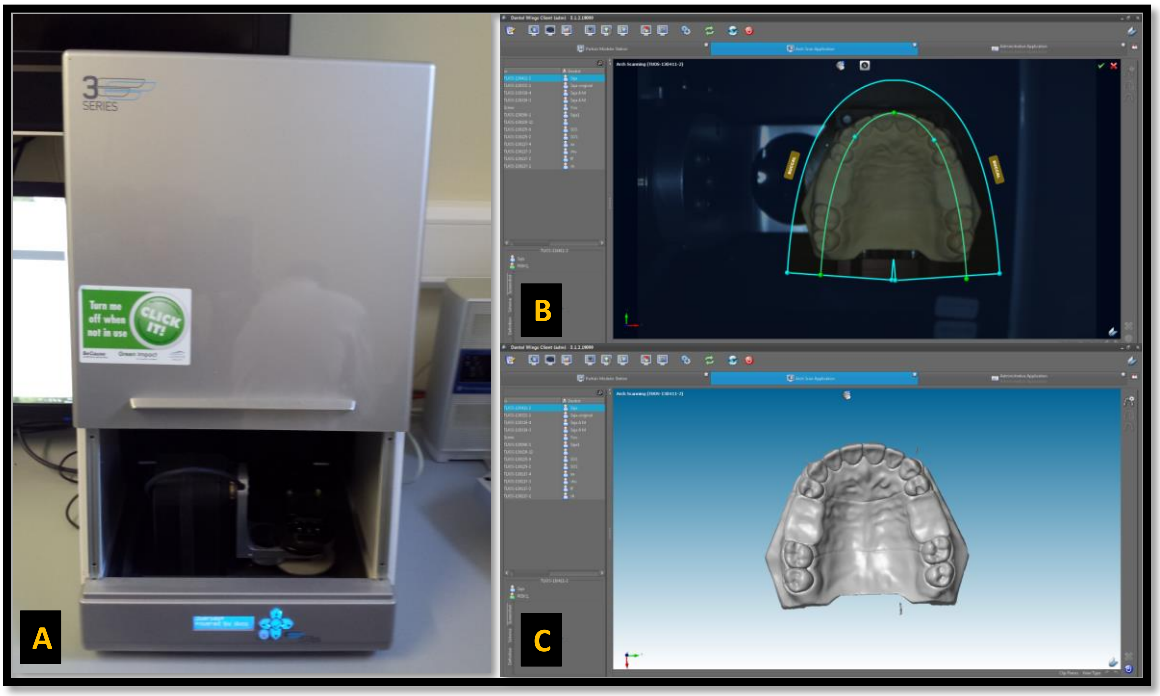
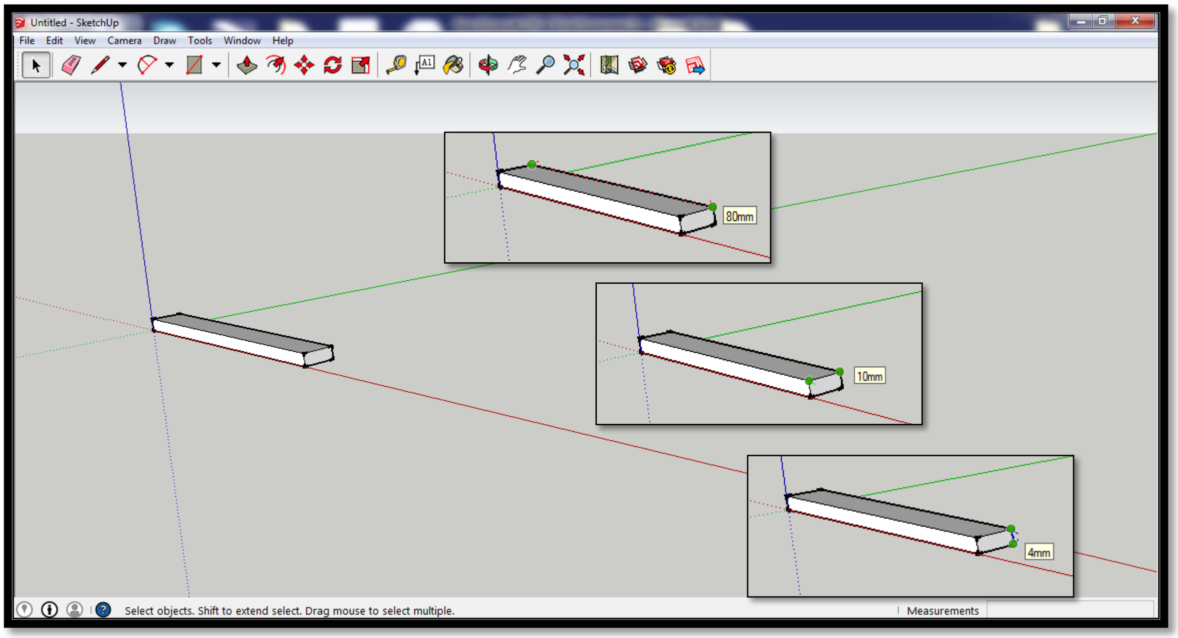


Figure (3-11): A. scanner lab unit with cast chamber; **B.** scanning the master cast (arch) using scanner lab unit; **C.** the scanned cast is displayed in the screen

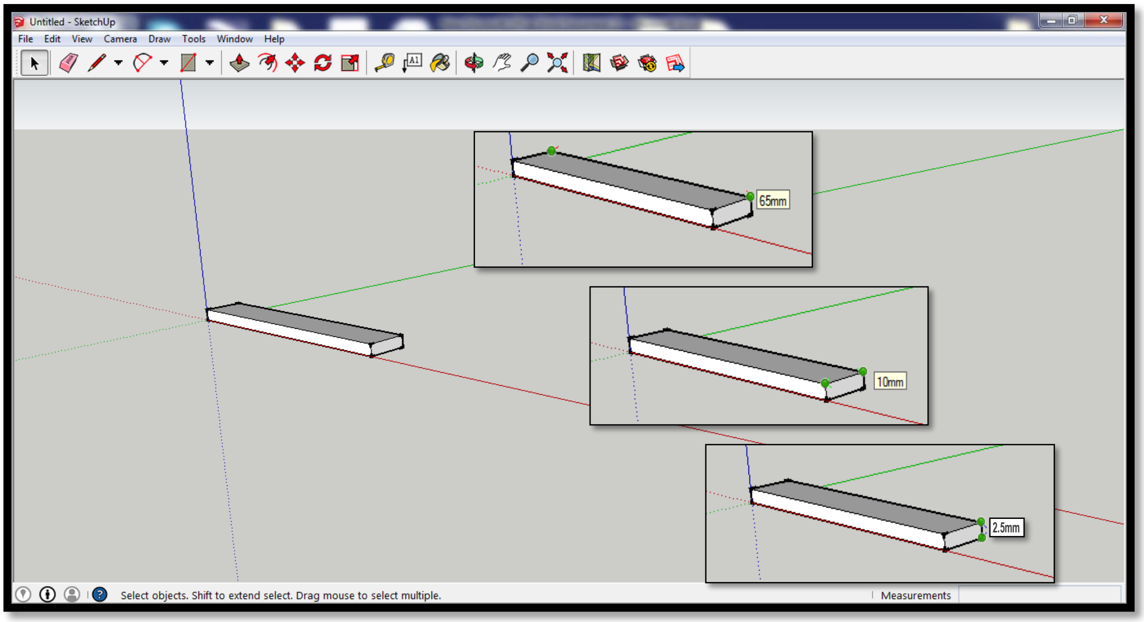
CAD-SketchUp

SketchUp source is a 3D modeling computer program used for a wide range of drawing applications such as architectural and mechanical engineering design. The program is available as a freeware version, and enables the user to design and create shapes in 3D form. In the present study, specimens for impact strength, 4-point bend, and tensile strength tests of different dimensions according to ISO and ASTM standardisation were designed using this program, figures (3-12) to (3-14). The files were then converted to (.Stl) file form and exported for fabrication using machining CAM production method; see chapter seven, sections (1, 2, and 3).



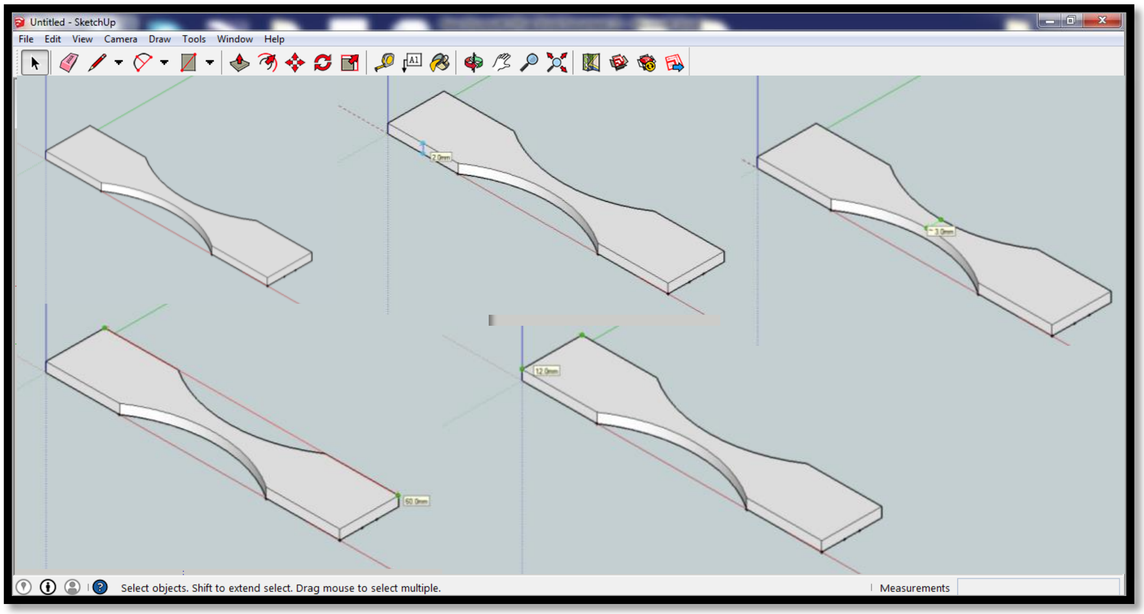
Select objects. Shift to extend select. Drag mouse to select multiple.

Figure (3-12): Impact Izod test sample created using SketchUp 3D modeling program



Select objects. Shift to extend select. Drag mouse to select multiple.

Figure (3-13): 4-Point test sample created using SketchUp 3D modeling program



Select objects. Shift to extend select. Drag mouse to select multiple.

Figure (3-14): Tensile test sample created using SketchUp 3D modeling program

CAM Production Methods

CAM Using 3ZLab Wax Printer Machine

Solidscape 3ZLab printer is a high precision 3D printer used for dental wax-up. It is a desktop-sized AM system that can produce dental wax-up for casting and pressing, figure (3-15). Applications include production of prosthetic devices such as RPD frameworks, crowns, bridges and copings.

The system works with scanned data that can be further improved using the 3Z Works CAD software. The 3ZLab has resolution of 5000 x 5000 dpi (197 x 197 dots/mm), accuracy of up to (±0.0254 mm), and user selectable layer thickness. It is designed to use Solidscape 3Z LabCast material formulated for clean burnout to produce 100% clean castings, with 3Z LabFill support sacrificial material and Dewax liquid solution used to dissolve sacrificial material.

The wax-up technique for casting and pressing produces the most accurate marginal integrity, occlusion, contact, and perfect anatomical fit. 3Z LabCast is the strongest dental wax material available for the building process and allows no material shrinkage. The wax samples produced by this technique can be directly invested, pressed or cast for the highest precision dental restorations. The machine work on 3ZTouch system software, a Windows based program, and 3Z Works software that formats CAD files for 3D printing.

Figure (3-15): 3D wax printer machine (3Zlab)

CAM Using Roland Milling Machine

The DWX-50 is a Roland dental milling machine, developed for the production of dental prosthetics. It provides 5-axis simultaneous machining and a 5-station automatic tool changer. The tool length is managed by a sensor that enhances convenience by fully automating the production process; figure (3-16).

This 5-axis machine simultaneously provides machining on the X, Y, Z axes, and thereby enables the user to run multiple tools for one job. In addition, the material blocks and discs can rotate through 360 degrees in both clockwise and counterclockwise directions and materials can be tilted forward and backward 20 degrees to support complex cuts. Furthermore, this machine enables the user to run the task entirely unattended, and an integrated tool diagnostics feature provides notification of whether the milling was carried out correctly or whether any errors occurred such as a tool breaking prior to completion, which reduces waste. The machine also has an integrated air blower system to keep the cutting area clean and free of debris. The DWX-50 is equipped to mill standard 98 mm discs and block materials, including wax, PMMA, PEEK, zirconia, ceramic, and composite resins. Standard carbide tools for precision milling were used for wax and PEEK discs. The samples that fabricated by this CAM production device are illustrated briefly in the relevant chapters (7 and 8).

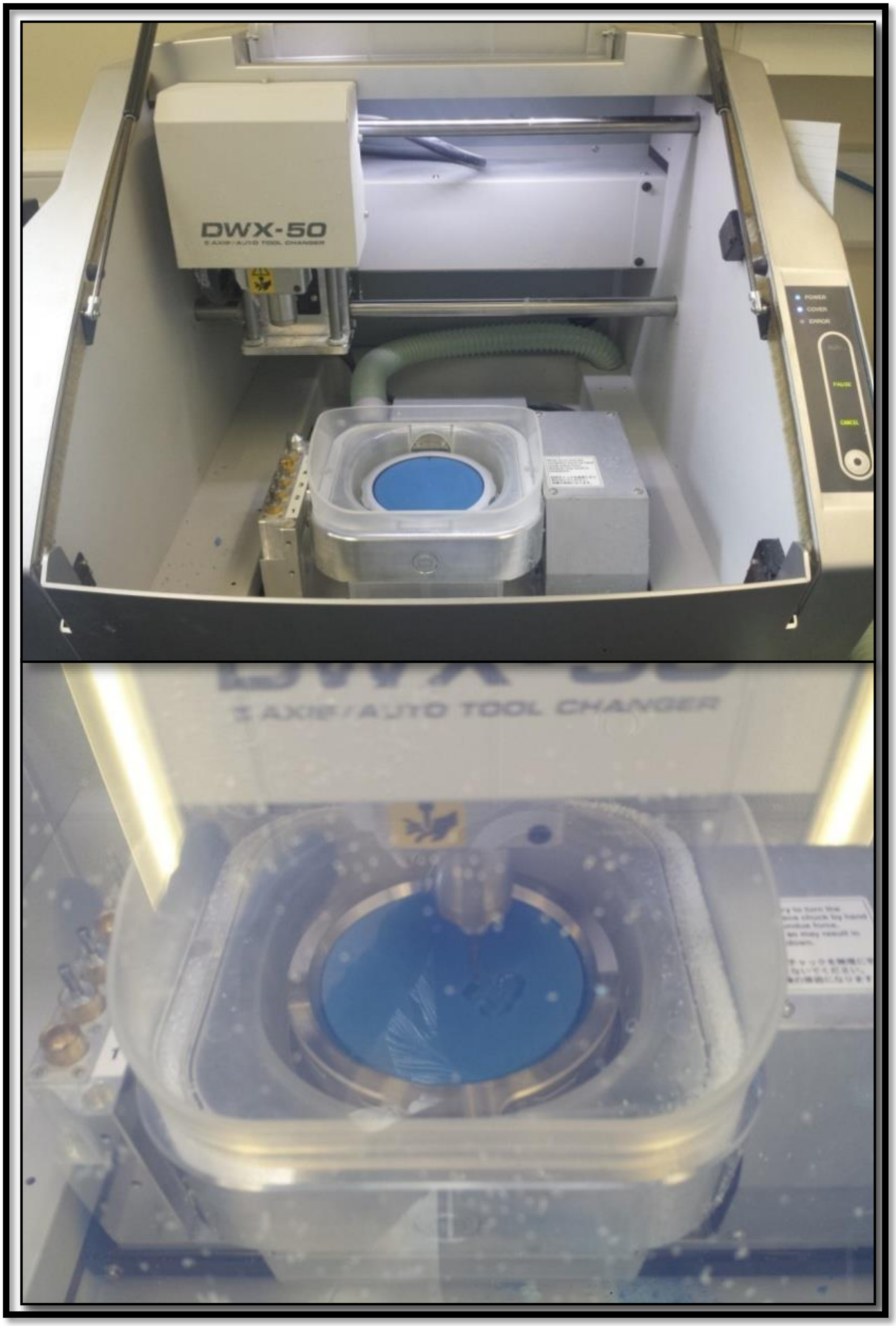


Figure (3-16): Roland milling machine

Casting Technique

All the current study samples and specimens were made from Co-Cr alloy (Co 64 %, Cr 28.6 %, Mo 5 %, Si 1 %, Mn, and C); cast using phosphate bonded investment material, and then left to set, initially for one hour. After the initial set, the casting ring was placed in an oven at 900 ˚C for 2h to burnout the wax pattern. A crucible made of heat-resistant ceramic was used for heating the casting alloy. Successful casting requires management of casting ring burnout, figure (3-17A); melting of the casting alloy; and the manipulation of the casting machine. The molten metal should be able to wet the investment mould material with a low contact angle to produce accurate detailing of the cast prosthesis or framework. In addition, the metal should flow into delicate areas without forming porosity within the surface or subsurface regions. The casting ring is removed from the oven when the alloy is completely molten, and once the casting ring is placed behind the crucible, the crucible ring assembly is spun rapidly. Casting is mostly done in a centrifugal casting machine that operates on the principle of centrifugal force where by rapid spinning driven by a spring or motor accelerates the outward molten alloy. The process of casting takes less than 1 minute since spinning accelerates the molten alloy to flow into the space in the casting ring which was previously occupied by the sprue and wax pattern.

The casting alloy was heated by electrical current at less than 1200 °C, since induction casting would have required processing at higher temperatures; figure (3-17B). Successful casting depends on proper heating of the alloy. Too much heating can lead to damage of the alloy through oxidation of elements, or the investment may break due to thermal shock, whilst too little heating will produce an alloy too viscous to flow freely into all the finest details in the casting ring.

After casting, the casting ring is allowed to cool slowly on top of the bench to produce a harder and stronger alloy. After complete cooling overnight, the casting is divested from the investment material (Wataha, 2002; Powers and Wataha, 2014). However, some base metal alloys tend to form oxides or chemical interaction with the mould wall during the casting process; also, when cooling to room temperature separation from the casting investment becomes more complex. Therefore, extra time will be required for cutting, grinding, finishing the cast metal to achieve a satisfactory finished surface.

It is essential to sandblast the metal restoration to remove the adherent investment material and the green oxide layer coating the surface after the casting procedure (Wataha and Messer, 2004; Powers and Wataha, 2014). Base metal alloys, and particularly Co-Cr types, are very hard, and the greatest expense involved in producing this alloy is consequently the time required for trimming and polishing. The first finishing step was removal of the sprue from the restoration. It was removed carefully with a thin carborundum disc on a handpiece, taking care to avoid scarring of the restoration during this step. Smoothness of the external surface of the final restoration is essential, and therefore electrolytic polishing was carried out to reduce surface roughness. The rough metal surface was connected to an anode in a bath of strongly electrolytic acid. A current is passed between the anode and the cathode, leading to ionizing of the anode which removes any surface film from the metal. The use of an appropriate electrolyte and current density causes the first products of electrolysis to collect in hollows of the rough metal surface and prevents further attack in this area. The contour of the surface is made smooth by means of continuous dissolution of the prominences of the metal surface (McCabe and Walls, 2013; Powers and Wataha, 2014).

Figure (3-17): A. Vecstar furnace used to preheat the casting ring and to burnout the wax pattern; **B.** Electronic induction metal casting machine used to cast the metal alloy

3.3. Statistical Analysis

Analysis of the results of this study was conducted using SPSS software (V-22) (Santoso, 2014). These statistical methods included inferential statistical analysis of variation (ANOVA) and Student T-test. Tests were performed at a confidence level of 95 % and significant P-value of ($P \leq 0.05$).

Chapter Four

Evaluation of Mould Temperature for Denture Injection Method

Chapter Four: Mould Temperature

Introduction

A polymer moulding is produced by introducing molten synthetic thermoplastic polymer into a mould cavity, sufficient to fill completely the mould cavity

For industrial products, the manufacturing company's programmed thermo-pressing guides and methods for moulding polymer were followed using metal moulds. However, in the dental lab it seemed impossible to achieve the same results with different moulding materials considering the size and details of an individual patient's jaw replicas, besides that some parameters such as non-uniform distribution of the mould temperature may affect the properties of the injected material.

Dental gypsum products are materials commonly used to produce dental moulds. Such products need to withstand any processing methods used in construction of a dental prosthesis (Anusavice *et al*., 2013, Van Noort, 2013).

Thermal conductivity of a substance is "the quantity of heat in calories or Joules per second passing through a body of 1 cm thick with a cross section of 1 cm^2 when the temperature difference is 1 °C" (Greig, 2012; Sakaguchi and Powers, 2012). The conductivity of a material changes slightly as the surrounding temperature is altered. However, the differences were generally resulting from temperature changes is much less than the difference that exists between different types of materials. For instance, thermal conductivity for metals such as Iron and Aluminum is approximately 0.163 and 0.50 $Cal/Sec/Cm^2/$ (°C/Cm) respectively, while that of the gypsum product is about

0.0031 Cal/Sec/Cm^2/ (°C/Cm). Therefore, more heat energy may be required to raise the gypsum product moulding temperature comparing to metals (Greig, 2012).

Aim

The present study aims to optimise the mould/furnace temperature at different locations inside the mould cavity for thermo-pressing purposes. This will be achieved using type IV dental hard diestone moulding material and with different furnace temperature settings.

Objectives

The objectives of the present study are as follows:

1. To design and fabricate a RPD study case model using a software designing program (DWOS) and CAM-3Zlap wax printer machine.
2. Monitoring the mould cavity and furnace temperature using a single and multi-thermocouple system at different locations in the mould cavity.
3. To identify the temperature at around 40, 100, 150, 175, and 200 °C at different locations inside the mould cavity for thermo-pressing purposes.

4.1. Materials and Methods

4.1.1. Mould Temperature Study Techniques

To optimise the mould and furnace temperature, a Vecstar furnace was used in this study. The mould temperature of one moulded flask was estimated inside the furnace. The following two techniques were used to test the thermal calibrations in order to optimise the mould/furnace temperatures:

Single thermocouple technique: This is a traditional monitoring method. A digital thermocouple was mounted inside the flat mould cavity, and the same thermocouple was placed in the furnace during the furnace dial set up operation. The furnace was set up for 3 hours at 50, 100, 150, 200, 250 and 300 °C. The data were collected at hourly intervals.

Multi-thermocouple technique: Eight digital thermocouples were mounted during the furnace dial set up operation in different parts inside the mould cavity of the designed framework, in the furnace, and at room temperature. The furnace was set up for 4 hours at 150, 200 and 250 °C. The data were monitored digitally, and the temperature was recorded at one minute intervals for 4 hours (240 min).

4.1.2. Mould Preparation

The denture injection flasking technique was used in this study. The lower part of the dental flask was filled with hard dental stone investment material (Type IV), mixed according to the manufacturer's instructions (W/P: 20ml/100g). The diestone moulding material used in this study was Esthetic base® gold (type IV hard diestone), it has the hardness of approximately 210/280 N/mm² (30/60 min) and more than 300 N/mm² after 24h; compressive strength after 1h of about 85MPa and after 24h more than 120 MPa; and expansion DIN less than 0.08 %. The mechanical mixing time is 60 Sec with an approximate processing time of 9-10 min, and an approximate setting time of 13-14 min. The first stone mix layer was prepared using a vacuum mixture unit and this was poured into the lower half of the flask. Silicone moulds were prepared to standardise the sprue design for both study levels. Prefabricated sprue wax of 5 mm thickness was connected to the wax pattern; the sprue end was 10 mm in diameter to allow contact with the samples through the main entrance hole in the flask.

Single thermocouple technique: A casting sheet of wax with the dimensions of 60 mm x 40 mm x 0.8 mm was used for this study level to simulate the RPD framework dimensions, figure (4-1). Special flasks suitable for thermo-pressing technique were used that had one opening entrance for the injected material. The wax pattern and the sprue were placed in position horizontally after coating one side with vacuumed creamy consistency stone material to avoid trapping of air. After 45 minutes, when the stone material had set, figure (4-2), the coated soft paraffin separating medium was applied. The two halves of the flask were then secured by fully tightening the screws. Another vacuumed stone mixture layer was poured into the upper half of the flask using the vibrator to avoid trapping any air. The stone investment material was allowed to harden for 60 minutes, and then the flask was placed in a wax extraction unit for 5 minutes. Subsequently, the flask was opened and all the wax was flushed out with detergent agents and boiling water. The mould surfaces were left to dry for 30 seconds. Since this sample was prepared for temperature monitoring purposes, no separating medium was used to coat the mould, and it was left overnight to dry completely at room temperature.

Multi-thermocouple technique: the RPD framework wax pattern for this study level was designed by DWOS and printed using a 3D wax printer to create a mould cavity and to monitor the temperature at different locations inside the mould cavity.

4.1.3. Wax Pattern Preparation

RPD Design Using CAD

The wax pattern was designed using the CAD technique. The case study cast of Class III mod.1 Kennedy classification was scanned and surveyed as described previously in chapter three. A rough RPD design of 3mm thickness was created with full palatal coverage and clasp arms on the premolar and molar abutment teeth, figure (4-3). This was done to provide enough space inside the mould cavity to monitor the temperature at different locations. In addition, it allowed the thermocouple sensors to be inserted easily inside the mould cavity without any contact with the moulding material. The design was then finished and exported into the (.Stl) file ready for fabrication of the RPD wax sample by CAM.

Fabrication of RPD Design Using CAM

The wax pattern was fabricated using a 3Zlab 3D wax printer for dental wax-up. The RPD framework was printed on to the solid wax cast material and wax fill support material, figure (4-4). Then, the wax sample was immersed in special dissolving petroleum solution to remove the supporting wax material, leaving the solid wax RPD pattern design, figure (4-5). Then the RPD wax pattern was moulded using one of the dental moulding materials.

4.1.4. Moulding Process

The RPD wax pattern was invested using type IV diestone moulding material and special flasks for the thermo-pressing technique, and the sprue was attached to the wax framework design as described with the single thermocouple technique. When the stone material had set, a coating of soft paraffin separating medium was applied. The thermocouple channels were produced using 2.5 mm sprue wax and fixed by applying drops of wax to selected points on the framework pattern. Figures (4-6) and (4-7A) show the different points and locations that were selected to monitor the mould and furnace temperature:

1. Room
2. Furnace
3. Flask (mould entrance)
4. Posterior region (major connector)
5. Middle region (major connector)
6. Anterior region (major connector)
7. Premolar clasp region
8. Molar clasp region

The two halves of the flask were then secured by fully tightening the screws to expose the channeled free sprue ends through the top openings of the flask. The upper half of the flask was then filled with vacuumed stone mixture, figure (4-7B), and the moulding material allowed hardening, after which the wax was boiled out and the mould left overnight to dry and cool as with single thermo-couple technique.

4.1.5. Mould/Furnace Monitoring Technique

Single thermocouple monitoring technique: a one-channel digital thermometer with one thermocouple sensor end was used in this technique, (n=3). One end of the thermocouple sensor was placed in the centre region of the mould cavity, and later was placed in the centre of the furnace during the preheating procedures. Hourly readings were collected from the digital thermometer at each step.

Multi-thermocouples monitoring technique: a multi-channel LCD digital thermometer with eight thermocouple sensors was used in this technique, (n=5). They were named, numbered and inserted inside the channels into the mould cavity. Each thermocouple sensor end was inserted through the hollow channel that remained after wax elimination, leaving the sensor tips free from contact with the surface of the mould material. This was done in order to measure the temperature of the mould cavity at this point without interfering with the temperature of the mould surface. They were positioned at different locations inside the mould cavity, and the furnace chamber during the preheating procedure. One of these sensitive thermocouples was left outside the furnace at room temperature, and the others were inserted through the channels so that they were exposed at the channel ends in the following locations: the flask mould entrance, posterior, middle and anterior regions of the major connector, and the premolar and molar clasp regions, figure (4-8). The data were recorded at one minute intervals throughout the four hours of testing, and the readings were recorded and collected by PLW recording program, figure (4-9).

Figure (4-1): Full palatal coverage wax pattern

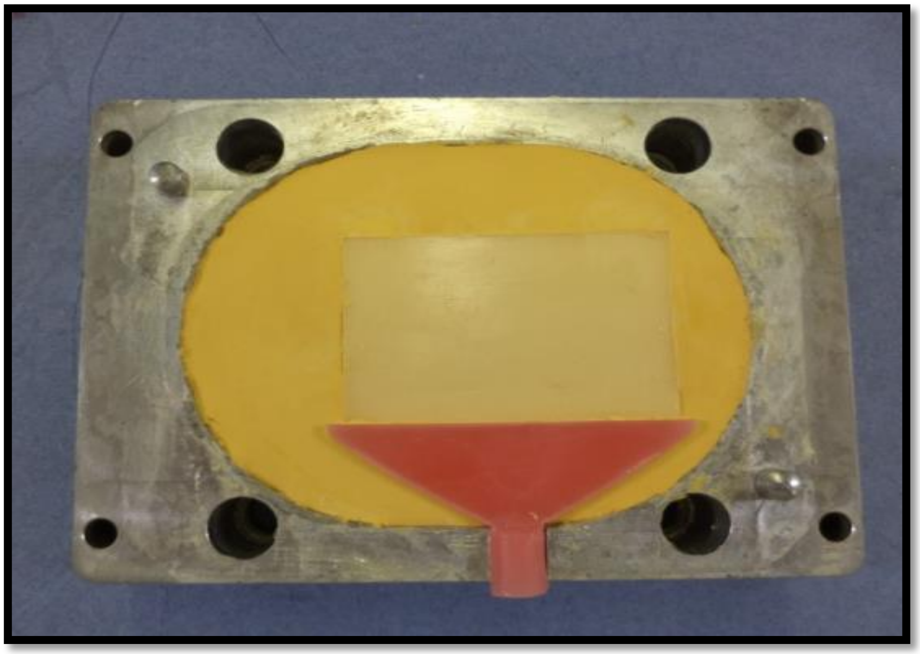


Figure (4-2): The flasking of wax pattern with fan sprue design for one thermocouple technique

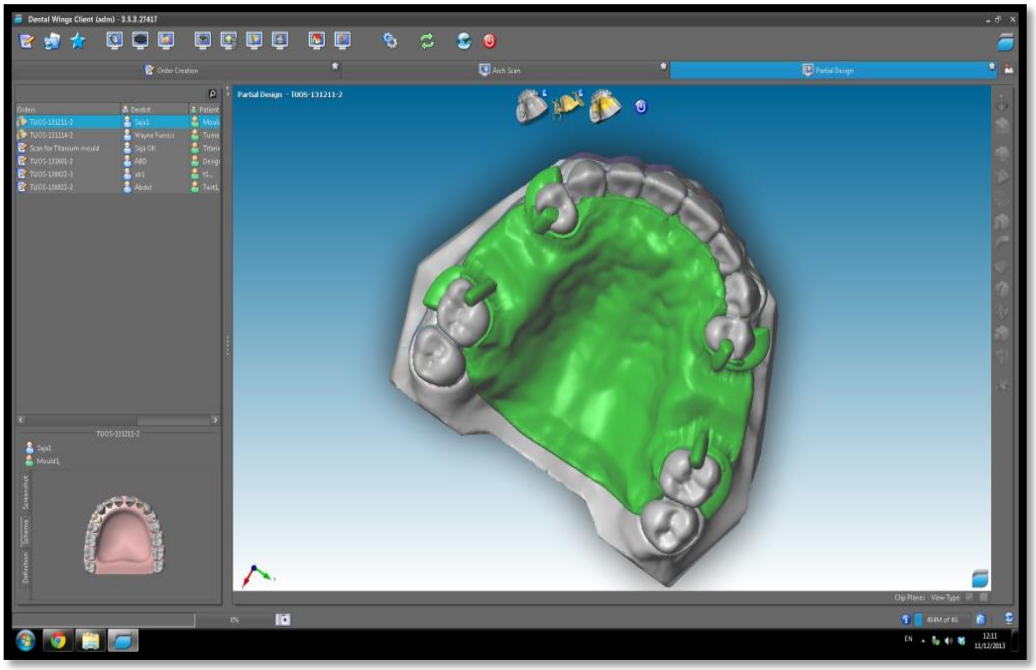


Figure (4-3): RPD framework designed by CAD-DWOS

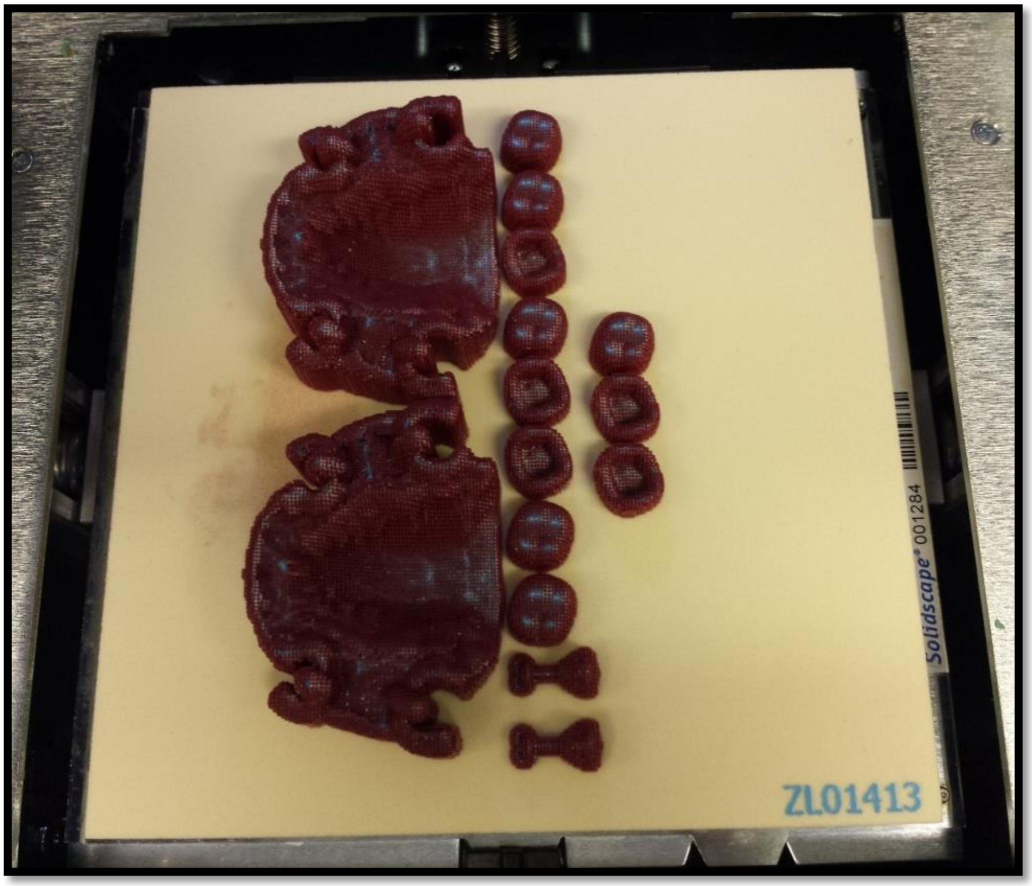


Figure (4-4): RPD framework printing using 3Zlab wax printer

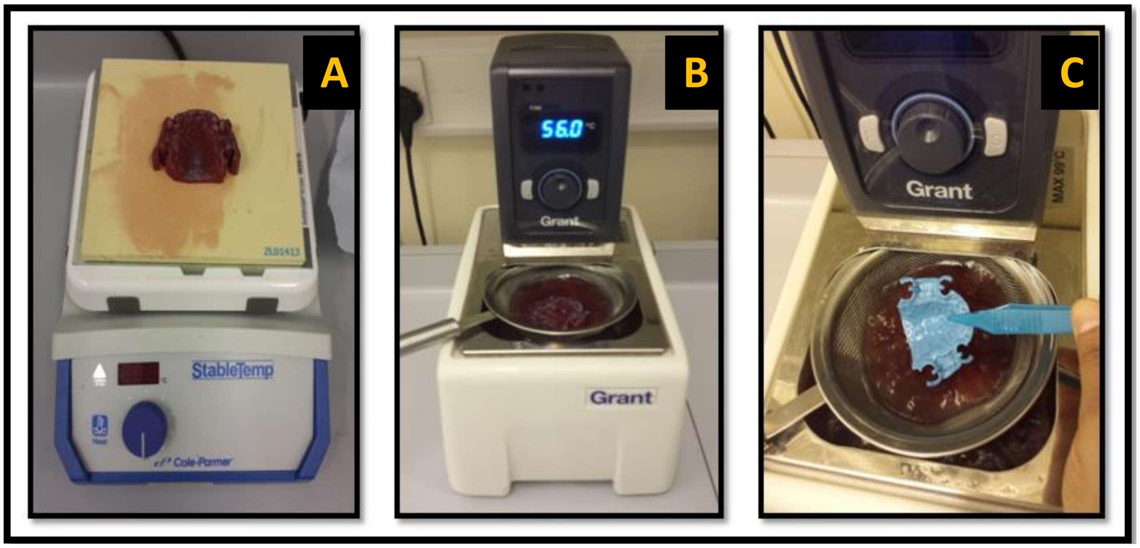


Figure (4-5): A. RPD wax framework separated from platform base; **B.** Special dissolving petroleum solution used to remove the supporting wax material from the RPD framework design; and **C.** RPD framework wax design ready for moulding

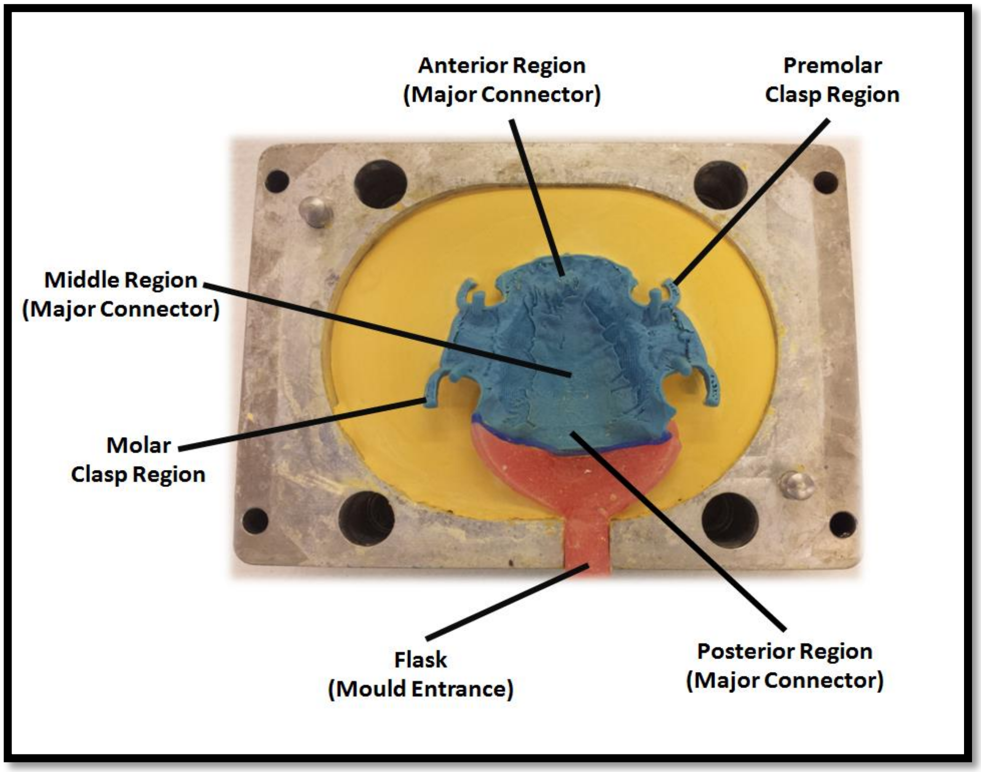


Figure (4-6): Moulded RPD wax framework showing the location of the different thermocouples inside the mould cavity

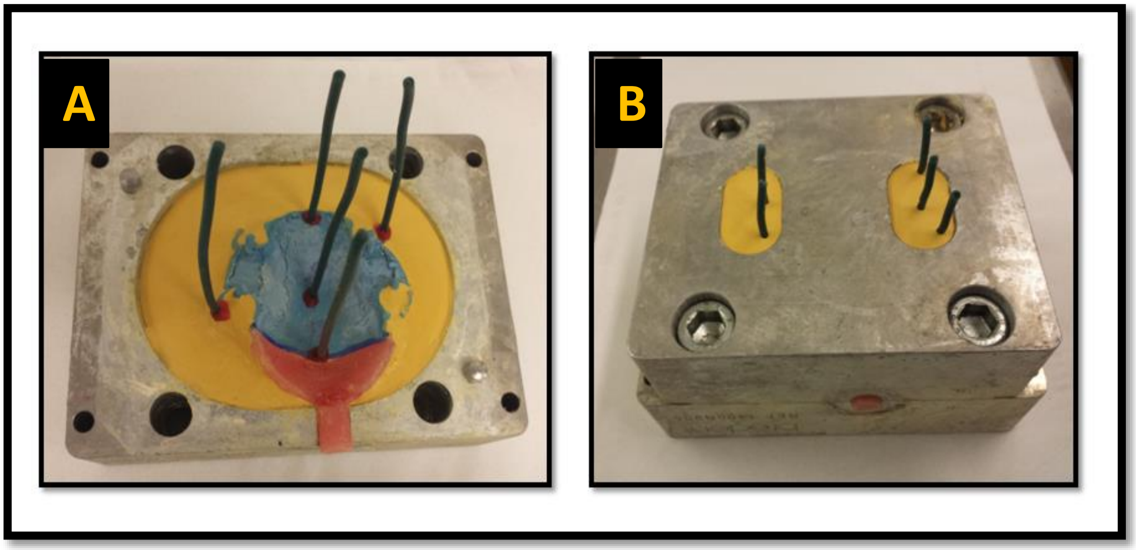


Figure (4-7): Flasking the RPD framework by attachment of 2.5 mm sprue wax to produce the channels for the thermocouple sensors: **A.** before moulding the upper half of the flask; **B.** after moulding the upper half of the flask

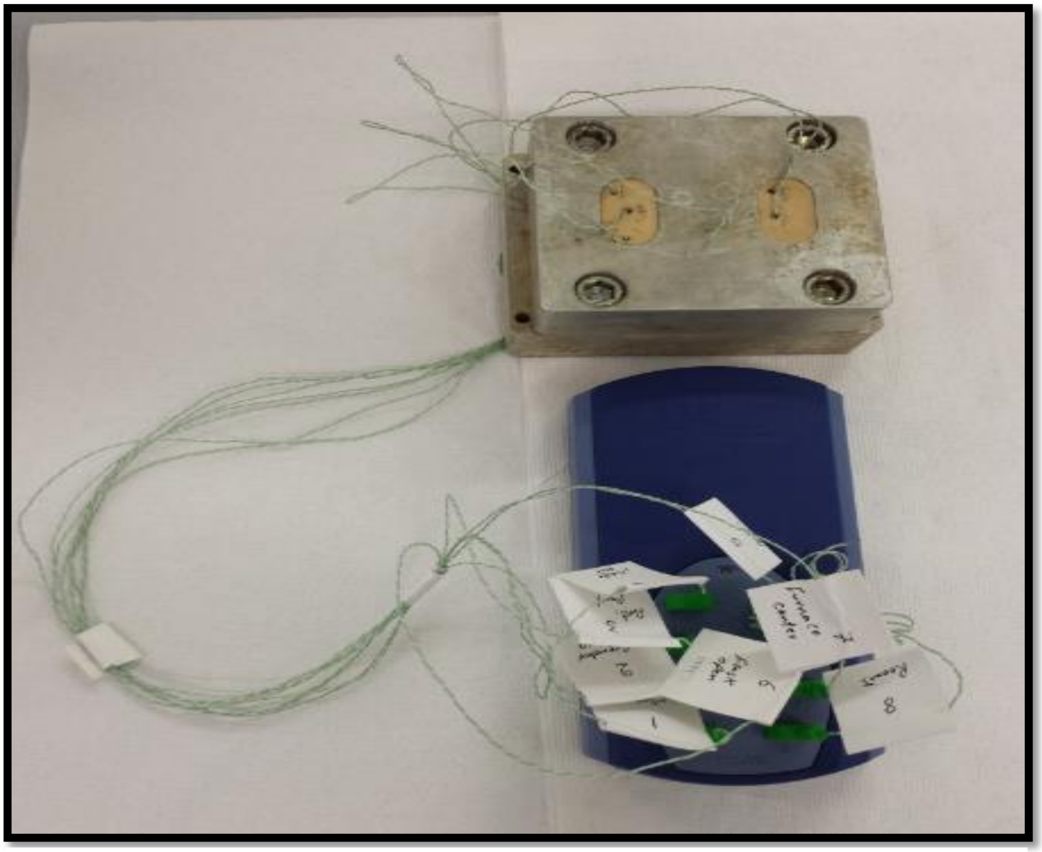
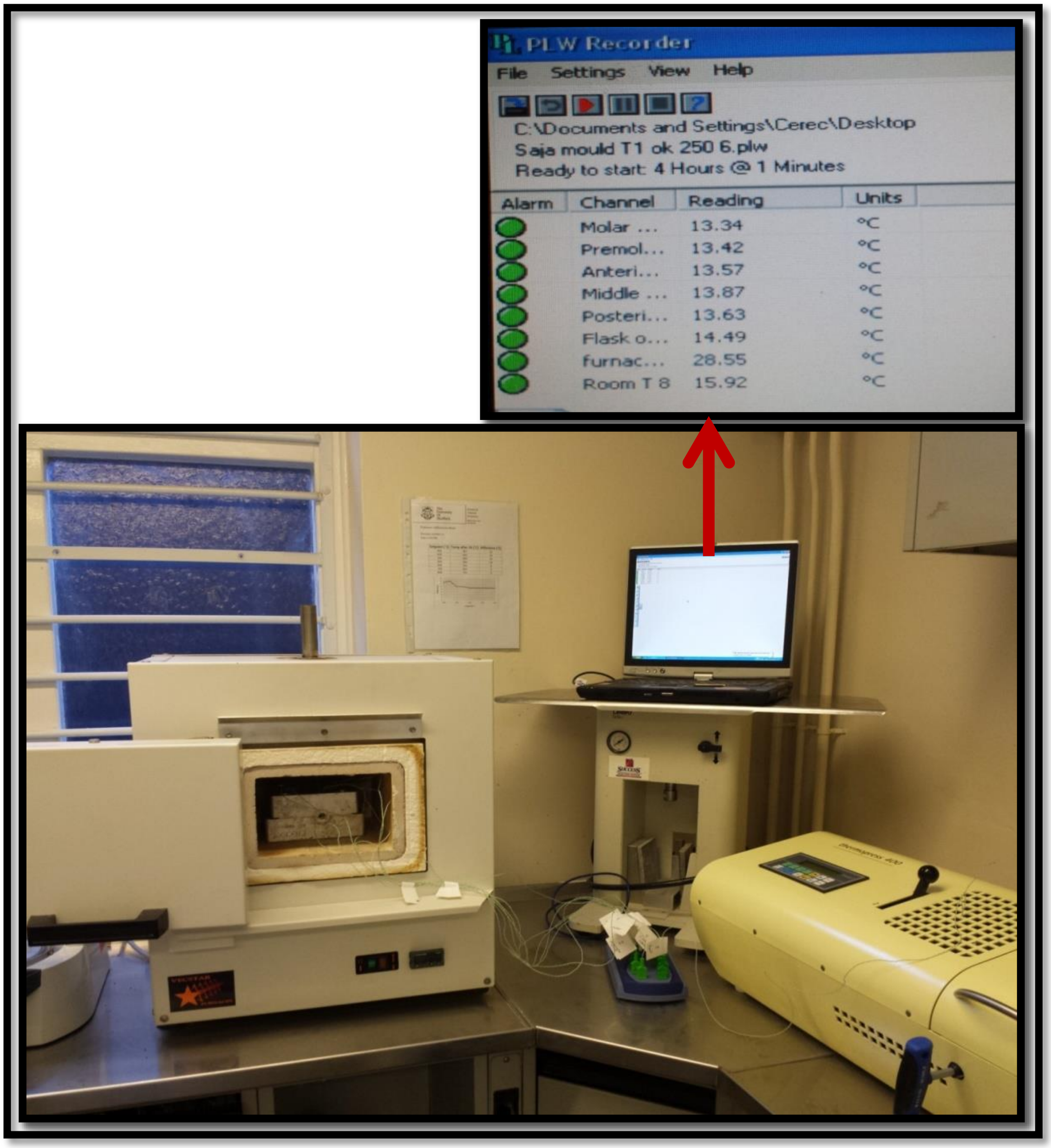


Figure (4-8): Multi-channel digital thermometer with multi-thermocouples of sensitive sensors inserted inside the mould cavity at different locations



C:\Documents and Settings\Cerec\Desktop
Saja mould T1 ok 250 6.plw
Ready to start: 4 Hours @ 1 Minutes

Alarm	Channel	Reading	Units
●	Molar ...	13.34	°C
●	Premol...	13.42	°C
●	Anteri...	13.57	°C
●	Middle ...	13.87	°C
●	Posteri...	13.63	°C
●	Flask o...	14.49	°C
●	furnac...	28.55	°C
●	Room T 8	15.92	°C

Figure (4-9): The moulded flask with thermocouple sensors inside the furnace connected to computer system to collect the data at one minute intervals using the PLW recording program

4.2. Results

Analysis of results was conducted using appropriate statistical methods. The data were compared using T-test for the single thermocouple test and analysis of variance (ANOVA) for the multi-thermocouple testing technique. The tests performed at a confidence level of 95 % and significant P-value of (P≤0.05); see appendix part (B).

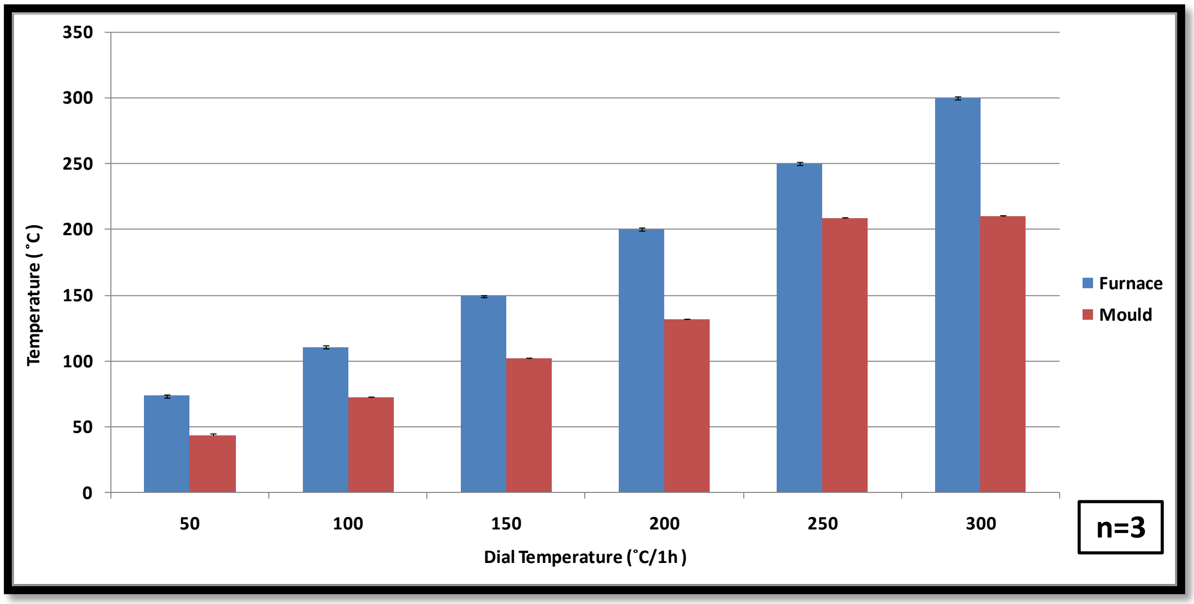


Figure (4-10): Mould/ furnace temperatures (1 hour after setting the furnace temperature)

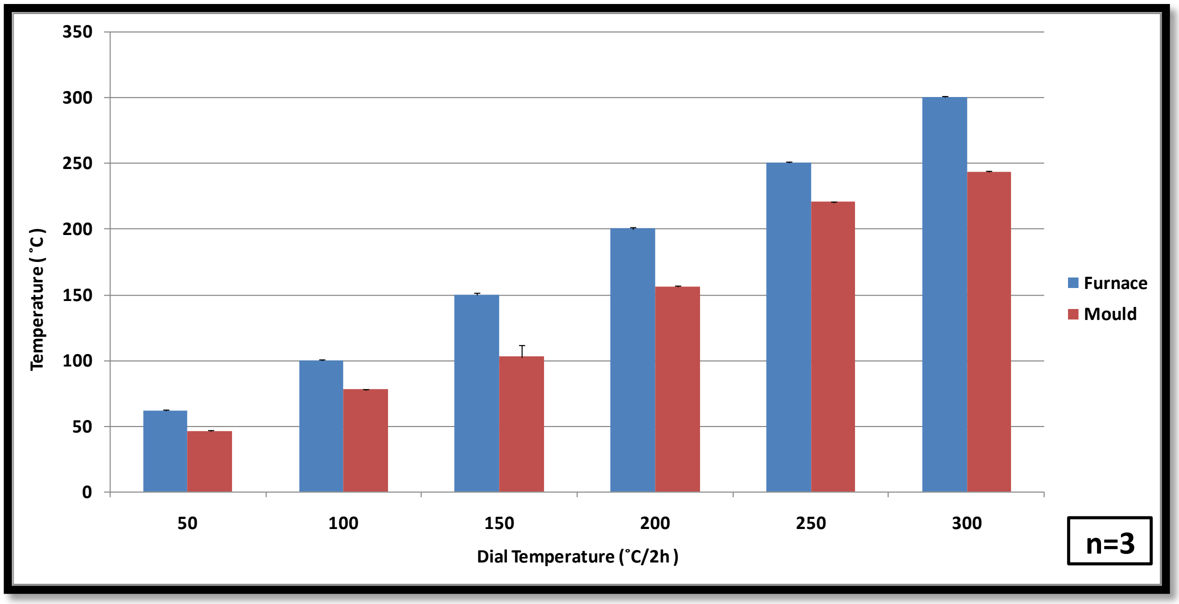


Figure (4-11): Mould/ furnace temperatures (2 hours after setting the furnace temperature)

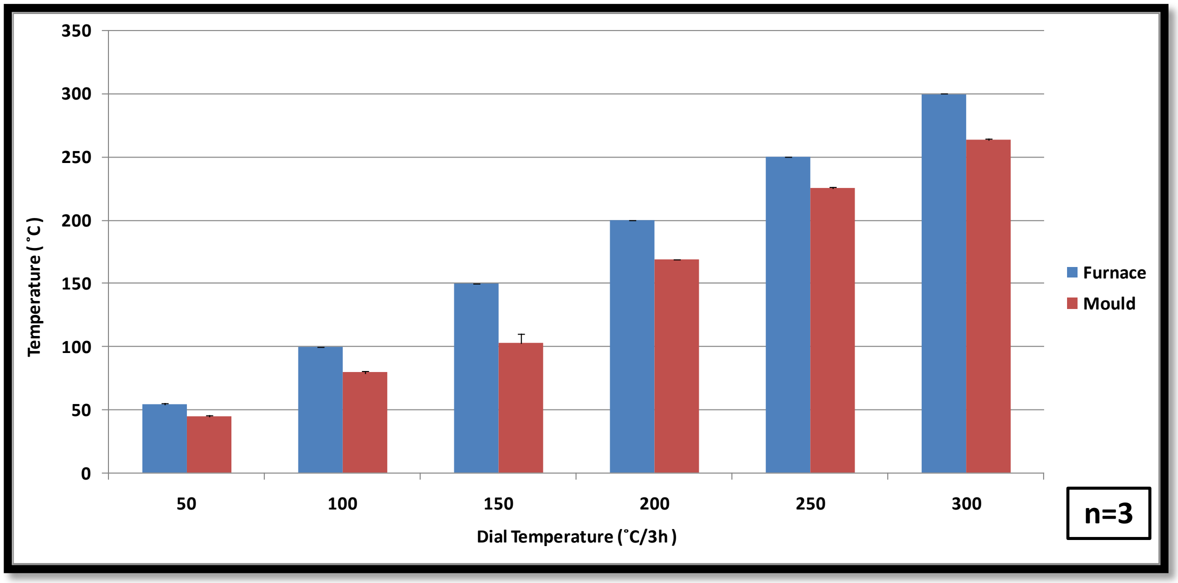


Figure (4-12): Mould/ furnace temperatures (3 hours after setting the furnace temperature)

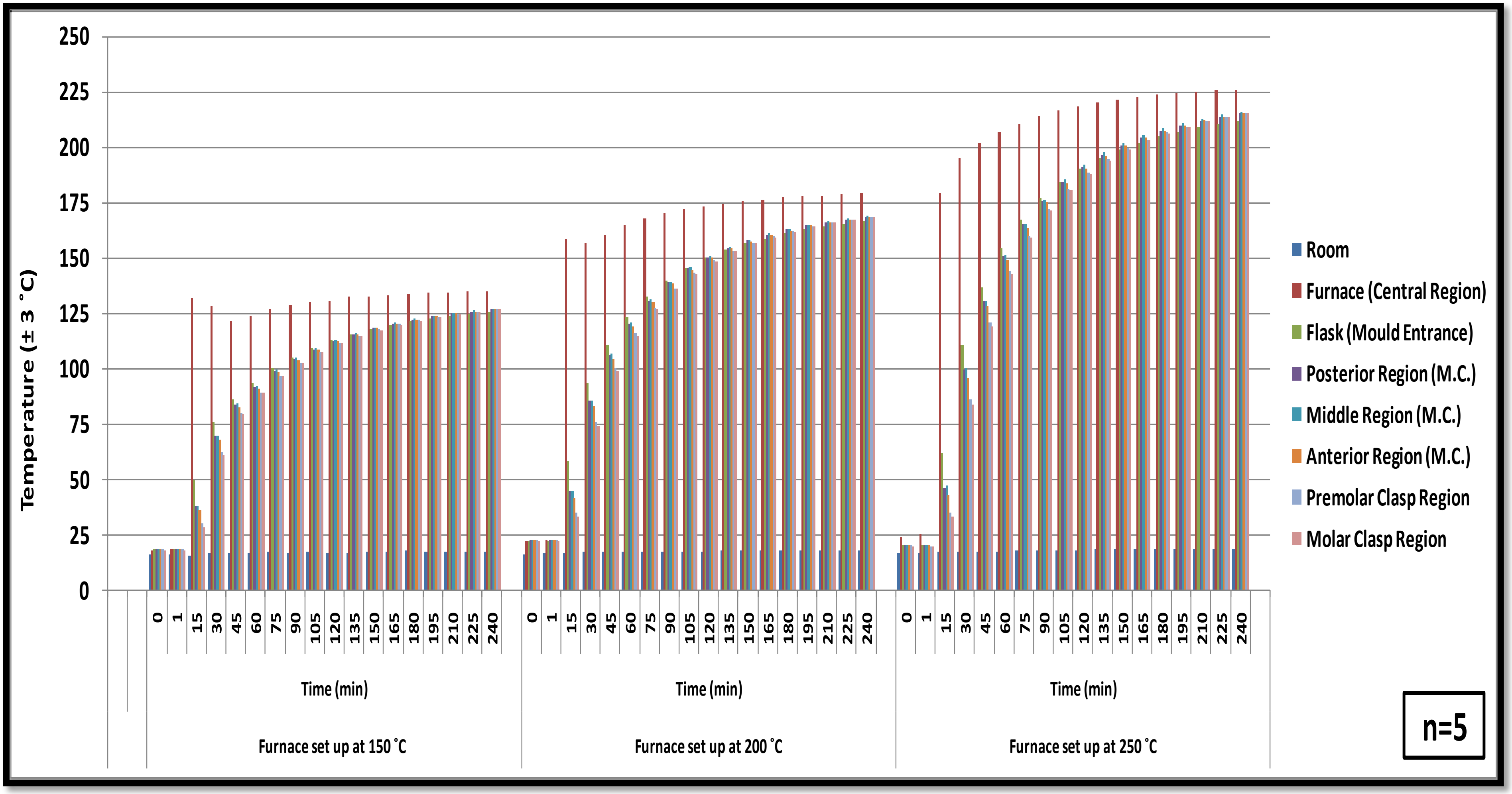


Figure (4-13): Diagram showing the mean distribution of mould/furnace temperature using multi-thermocouple technique

Table (4-1): Selected mould temperatures at particular time points using single thermocouple technique

Furnace (Dial set up)	No.	Suggested T (°C)	Mould T (±°C) (single location)	Time (h ± 5 min)
50 °C	3	40-50	46 (±1)	2
			45 (±1)	3
150 °C	3	100	102 (±7)	1
			103(±9)	2
			103(±7)	3
200 °C	3	150	156 (±1)	2
200 °C	3	175	169 (±0.3)	3
250 °C	3	200	208 (±1)	1
300 °C	3	200	210 (±1)	1

Table (4-2): The four selected mould temperatures at particular time points using multi-thermocouple technique

Furnace (Dial set up)	No.	Suggested mould T (°C)	Mould T (±°C) at 5 selected locations	Time (±2min)
150 °C	5	100 (PEEK)	104 (±2)	90
200 °C	5	150 (PEEK)	150 (±2)	120
250 °C	5	40-50 (PMMA)	41 (±8)	15
	5	175 (PEEK)	174 (±3)	90
	5	200 (PEEK)	201 (±3)	150

The experimental results were as follows:

Single thermocouple monitoring technique: The mould/furnace calibration data for the Vecstar furnace in this study were evaluated according to the results presented below. Generally, there were statistically significant differences between the mould and furnace temperatures among the studied groups (P<0.05). This was detected by using the same thermocouple inside the mould cavity and in the furnace. Figures (4-10) to (4-12), and table (4-1) show the critical mould temperatures identified and selected for the present study on the basis of the results for this test method.

Multi-thermocouples monitoring technique: The data for the mould/furnace temperature at different locations inside the mould as recorded with multi digital thermocouple sensors were analysed over the 4 hour testing period (240 min) when the furnace was set up at 150, 200, and 250 °C. The outcomes were estimated on the basis of the presented data.

Generally, significant statistical differences (P<0.05) were identified between the mould and the furnace temperature, and within the mould temperature at different points during the monitored period. However, at selected mean values of the suggested mould temperature for this study, the temperatures of around 100, 150, 175, and 200 °C showed a non-significant difference (P>0.05) at particular timings. Statistical analysis showed that the temperature was the same in the posterior region, middle region, anterior region of the major connector, premolar clasp region, and molar clasp region inside the moulded framework cavity. There were non-significant differences (P>0.05) at these locations at temperatures of 100 °C at 90 min, 150 °C at 120 min, 175 °C at 90 min, and 200 °C at 150 min after set up the furnace temperature at 150, 200, and 250 °C respectively, figure (4-13) and table (4-2).

4.3. Discussion

Since this study adopted injection moulding technique to fabricate thermoplastic products, it was possible that the injection moulding conditions might influence the processing parameters. The injection moulding system is one of the most commonly used processing technologies in the plastics industry, and the temperature of the mould is an important factor in determining the final quality of the injected product. Unfortunately, non-uniform distribution of mould temperature is problem that can affect injection moulding (Chen *et al*., 2006). The mould temperature has perhaps a less obvious but often more dominant effect on final product properties. In semi-crystalline materials such as PEEK the mould temperature is an important factor in determining the degree of crystallinity in the polymer, which may affect the performance parameters of the injected product in use. According to Wilfong (1989), using a typical mould temperature of 180-220 °C for PEEK polymer provides a crystalline surface with no quenched or amorphous characteristics (Wilfong, 1989). In addition, the Invibio processing guide for injected PEEK polymer recommends that the moulding temperature should range from 175-205 °C to ensure uniform crystallinity of the moulded parts (Invibio, 2004a). However, their recommendations may rely on their system using metal platforms to process PEEK in industry.

Elevating the temperature of the mould above the injected material glass-transition temperature (T*g*) could prevent premature freezing of the mould. On the other hand, the cold mould may increase the risk of premature freezing of the melt front, resulting in incomplete mould filling (Despa *et al.*, 1999). Therefore, heating the mould to a temperature around the melting point of the injected polymer may ensure complete penetration into the mould cavity. Thus, the mould has to be heated to ease penetration into the depths of the cavity. Crystals can only form at temperatures below melting point but above the T*g* of the polymer. When moulding semi-crystalline materials such as PEEK, the ideal mould temperature will be above the T*g* in order to give the polymer adequate time to crystallise.

The present study found a lack of uniformity in temperature across different locations inside and outside the mould cavity. Cavity temperature is a complex function of static and dynamic parameters and should be kept constant during the injection procedure. There is an extensive explanation for heat transfer inside the furnace. The heat could be affected by the environment, and between the flask and the mould cavity (Čatić, 1979).

This demands a new way of regulating the temperature. The influence of mould temperature on production rate and stability of the injection moulding process, as well as on the quality of injected materials, has been largely underestimated. Therefore, the main objective of this study was to optimise the mould temperature for thermo-pressing denture injection method.

The preliminary test using single thermocouple sensor provided limited data. The moulded flask preheating procedure was carried out using the same sensitive sensor twice, by placing inside the centre of the mould cavity and the furnace. This could reflect only the approximate mould temperature at one location each time. The results of this study were considered to be of insufficient accuracy. Therefore, multiple thermocouple technology should be used for the entire temperature monitoring system in order to provide a more accurate set of data for consequent data processing. In addition, this system has the advantages of detecting specific temperatures in different places at the same time throughout long-term test periods.

Despite the fact that the sensitive sensor located inside the furnace indicated higher temperatures at different studied levels, those located inside the diestone moulded design cavity demonstrated lower temperatures at different positions. The lower heat produced within the moulded diestone material may be related to the lower thermal conductivity of the investment material. According to (O'Brien, 2008) each material substance has specific heat which is represented by the capacity of that material to absorb energy while also changing temperature. This is calculated as the energy required to raise the temperature of one unit of mass of the substance by one degree. The material thermal conductivity depends on the availability of “free electrons”, since metals are bounded by many free electrons. They are good conductors of heat and electricity as compared to non metals. in contrast, cooling a substance causes contraction (Whaites and Drage, 2013). Therefore, more energy and heat were needed to elevate the temperature of the gypsum moulding material into suggested temperatures.

The thermal properties of dental diestone material at high temperatures are not well known, as is the case with many investment moulding materials. The properties are difficult to measure, subject to transient effects and the method of measurement often appears to have a significant effect on the results produced. Values can also be affected by the rate of temperature change and it is not realistic to determine appropriate values for every temperature variation. Furthermore specific heat is affected substantially by the driving off of both free and chemically bound water. Evaporation and subsequent condensation of water in cooler parts of the invested sample substantially affect the apparent thermal conductivity. The composition of dental investment material and hence the properties vary slightly between manufacturers and countries of origin. However, leaving the mould material overnight can improve these properties and can help it to withstand preheating and the force generated during the injecting procedures. Modern injection moulds are high technology tools used for mass production. Typically, dental products fabricated by this method have to meet stringent quality demands because they are often directly visible to the user. The production of high quality parts depends on maintaining the temperature of the mould at an appropriate level and with equal temperature distribution. Whilst the moulds fabricated in the dental lab were made from gypsum bonded products, hard stone (type IV) investment materials were used in this study to simulate the production conditions of other denture base materials. In the present study, optimisation of the gypsum mould temperatures was investigated using a Vecstar furnace with 1100 °C maximum temperature. In theory, the temperature of the heated furnace is very difficult to control due to its complex characteristics. In practice, mould temperature was detected using a digital thermocouple with a USB sensor inside the invested mould cavity. The use of this sensor over the three different periods showed less temperature difference inside the mould than demonstrated by the furnace thermocouple readings for all studied groups. This may be related to the type of gypsum product material, which is not a refractory high-temperature resistant material (Van Noort, 2013) or it could reflect the steam temperature generated due to the heating process.

The Invibio thermo-pressing instruction guide recommends that the temperature of moulds used to thermo-press PEEK should range between 175-205 °C to produce a stable product with superior mechanical properties (Invibio, 2004a). This is recommended when using metal moulds to thermo-press molten PEEK for industrial purposes. However, using of gypsum products to create the mould is the only commonly used method to fabricate a positive reproduction for patients' arches and associated structures. As yet, further experiments are needed to investigate how mould temperature could affect the properties of the injected PEEK when using dental moulding materials. Therefore, to study further the effects of mould temperature on the properties of injected PEEK the mould temperatures selected were 100 °C which was below the PEEK T*g*, and three temperatures, 150, 175, and 200 °C, above the PEEK T*g*.

4.4. Conclusion

The present study draws the following conclusions:

1. The single thermocouple provides limited data results, while multiple thermocouples technology for the entire temperature monitoring process provides a more accurate set of data at different locations and across the same preheating treatment time.

2. The uniform mould temperatures were identified at the posterior, middle, anterior regions of the major connector, premolar and molar clasp regions when:

a. the furnace was set up at 150 °C for 90 min to achieve around 100 °C mould temperature.

b. the furnace was set up at 200 °C for 120 min to achieve around 150 °C mould temperature.

c. the furnace was set up at 250 °C for 90 min to achieve around 175 °C mould temperature.

d. the furnace was set up at 250 °C for 150 min to achieve around 200 °C mould temperature.

To sum up, the mould/furnace recorded data achieved by this study identified differences in the mould temperature at different locations inside the cavity compared to furnace temperature. However, the mould temperature was lower than that of the actual Vecstar furnace temperature when monitored by both single and multiple thermocouples. Therefore, more heated energy was needed to elevate the gypsum mould temperature.

Chapter Five

The Effect of Mould Temperature on PEEK Flow and Thickness Behavior Using Denture Injection Method

Chapter Five: Flow and Thickness

Introduction

Since the uniform distribution of the mould temperature at different regions was achieved at 100, 150, 175, and 200 °C below and above the PEEK T*g*, more studies were needed to investigate the effect of these mould temperatures on the physical and mechanical properties of thermo-pressed PEEK polymer.

In the past, thermo-pressing technique could only be employed in combination with very large industrial machines. Nevertheless, continuous development has led to the launch of very powerful injection moulding machines into the market. Few companies have succeeded in developing an injection moulding system for dental laboratories which can be operated without any external pressure source.

The production of dental restorations involves different processing methods therefore; moulding materials should withstand any processing conditions in construction of a dental prosthesis such as design application, heating, fracture risk and produce a smooth precision moulding cavity shaped by the lost wax method (Anusavice *et al*., 2013; Van Noort, 2013). Regardless of the particular ingredients, proportions and treatment of the moulding materials, the material should be easy to manipulate and have sufficient strength and accuracy at elevated temperatures (McCabe and Walls, 2013). No studies have investigated the effect of mould temperature on the flow and thickness accuracy behaviour of thermo-pressed PEEK polymer in relation to its use with a dental moulding material.

Aim

This study aims to determine the flow and thickness behaviour of PEEK polymer as a denture base using PEEK-Optima®NI1 prepared by thermo-pressing technique at different mould temperatures below and above the PEEK T*g*.

Objectives

The objectives of this present study are:

1. Measuring the flow behaviour of 0.8 and 1mm depth PEEK-Optima® samples at different mould temperatures, and comparing with conventional PMMA.
2. Investigating the effect of different mould temperatures on the sample thickness behaviour of thermo-pressed PEEK-Optima® samples of 0.8 mm and 1 mm depth, and comparing with conventional PMMA denture material.

5.1. Materials and Methods

5.1.1. Mould Preparation

This study proposed to make comparisons of properties using specimens with simple shape instead of dentures and denture shaped specimens. Use of rectangular specimens enabled variables such as shape, size, and thickness of the samples to be controlled and the physical properties to be directly related to the material itself.

For the flow and thickness tests a wax pattern with dimensions of 60 mm width and 40 mm length was tested to reflect the dimensions of full palate coverage and depths of 0.8 and 1 mm was used for test purposes. A fan shape sprue wax was suggested for use in this test. In this study, different mould temperatures of 100, 150, 175 and 200 °C were optimised for examining for the PEEK-Optima®NI1 polymer.

A silicone mould with internal dimensions of 60 x 40 x 0.8 mm was produced for the wax pattern. The sprue design and the heat-cured and thermo-pressing techniques used to process the PMMA and PEEK-Optima® materials have been described previously. The PEEK-Optima® was thermo-pressed using denture injection method. A special flask was used for injection purpose, and the hard dental diestone (Type-IV) used as moulding material was mixed according to the manufacturer’s instructions (W/P: 20ml/100g).

5.1.2. Processing Methods

The processing method for the heat-cured PMMA, thermo-pressed PMMA and PEEK-Optima®NI1 was described previously. A Thermopress 400 injection moulding system was used in this study. The system was preheated according to the set programs. The preheating time, injection time and pressure for the PMMA were according to the manufacturer's instructions while the mould temperature to thermo-press the PEEK polymer was selected by the present study. However, the injection time and pressure to thermo-press the PEEK polymer were according to the instructions for the Thermopress 400 injection machine.

The sprue design, flasking, packing, water-bath curing for the PMMA and the thermo-pressed PEEK-Optima® followed the methods and techniques mentioned previously in chapter three.

5.1.3. Deflasking and Sprue Removal

The cold flasks were deflasked by releasing the tightened screws, and the specimens were removed from the investment stone material. The sprue was then cut off using a disc bur with hand piece speed of 300 rpm. The PEEK specimen edge which was connected to the sprue was finished using sand paper of 140 grit size and a speed of 400 rpm on the grinder polisher machine. To remove any investment material from the sample surfaces, they were immersed in plaster cleaning solution for 15 minutes with the aid of an ultrasonic cleaner unit.

5.1.4. Sample Measurement

Flow Test

The flow behaviour of the PEEK specimens fabricated by denture injection method was estimated using graph paper. For measurement purposes the blue lines represented one millimeter squares. The full wax specimen dimensions of 60 mm X 40 mm width and length respectively were represented by 2400 mm^2 on the graph paper, which reflected 100 % filling. Hence, the experimental PEEK specimens were measured within these specific dimensions, figure (5-1) and (5-2).

Thickness Test

After processing by denture injection method, the specimens of 0.8 and 1 mm thickness were divided into four levels to investigate the effect of the mould temperature on thickness. The levels started from the side in contact with the sprue and ended at the free edge. Each level was subdivided into six square centimeters, and each square centimeter was measured in the centre using an electronic digital micrometer of 0.002 mm accuracy and 0.001 mm resolution, figure (5-3).

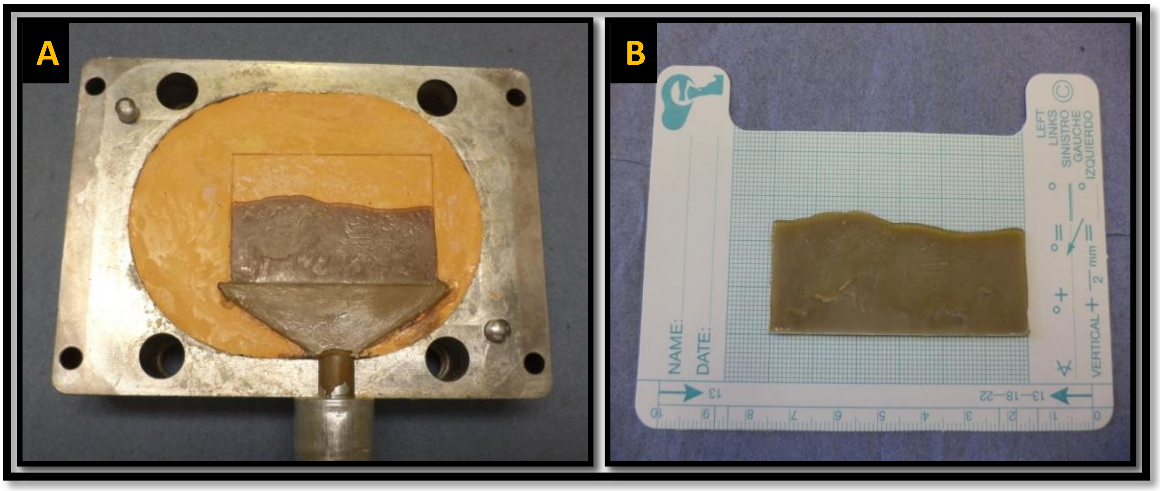


Figure (5-1): A. The PEEK flow with the sprue after cooling and deflasking; **B.** PEEK specimen flow behaviour measured using graph paper

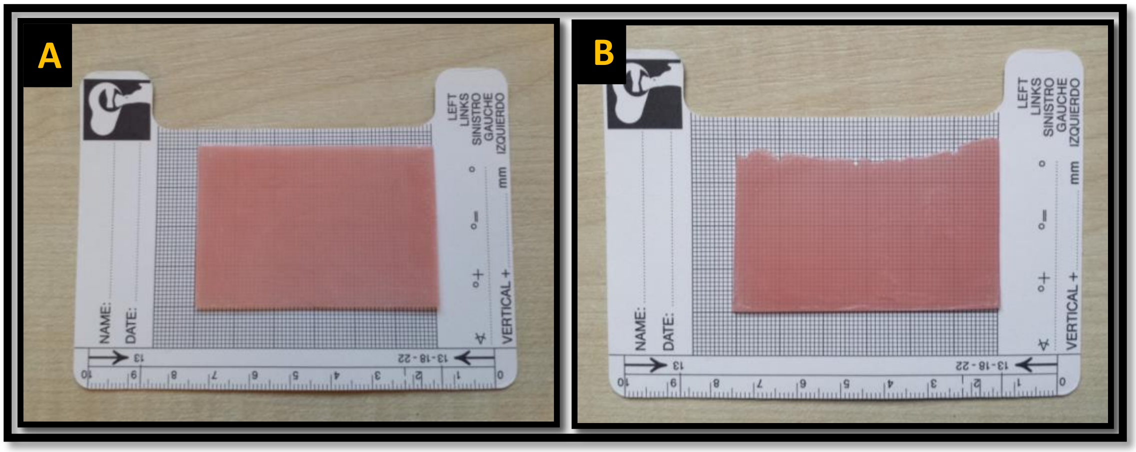


Figure (5-2): The specimen flow behaviour measured using graph paper **A.** heat-cured PMMA; **B.** thermo-pressed PMMA

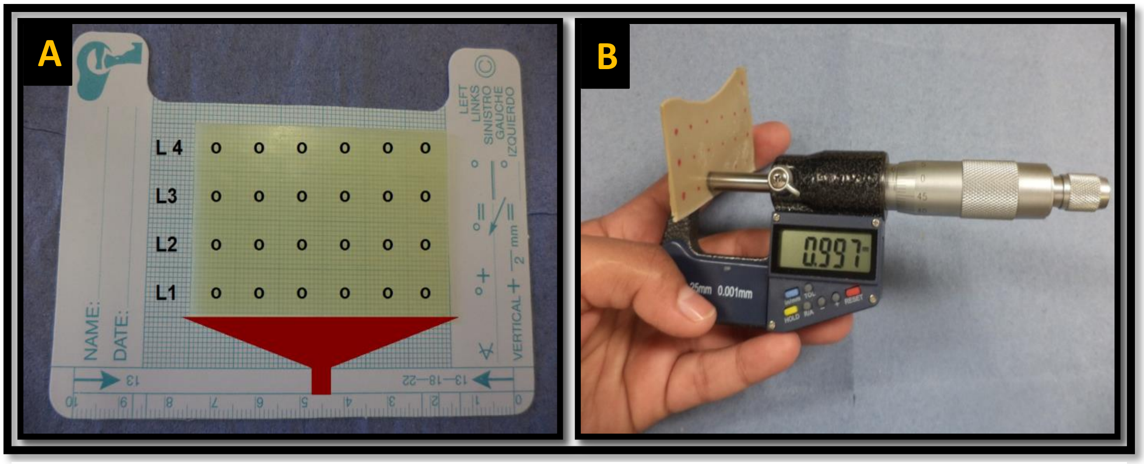


Figure (5-3): A. the four tested levels of the study specimen, ranging from L1 at the sprue edge level to L4, the free end level; **B.** digital micrometer of 0.002 mm accuracy was used to measure the sample thickness at selected points

5.2. Results

The statistical methods used to analyse the results included analysis of variation (ANOVA).The test performed at a confidence level of 95 % and significant P-value of ($P \leq 0.05$).

Exploratory analysis was conducted in a series of steps whereby the flow and thickness test data of the conventional PMMA, PEEK-Optima® that were injected at 100, 150, 175 and 200 °C mould temperature were compared through analysis of variance (ANOVA); see appendix part (C).

5.2.1 Flow Behavior

The following results clarify the flow percentage mean values of thermo-pressed PEEK-Optima® polymer at different mould temperatures when compared with the conventional PMMA denture material.

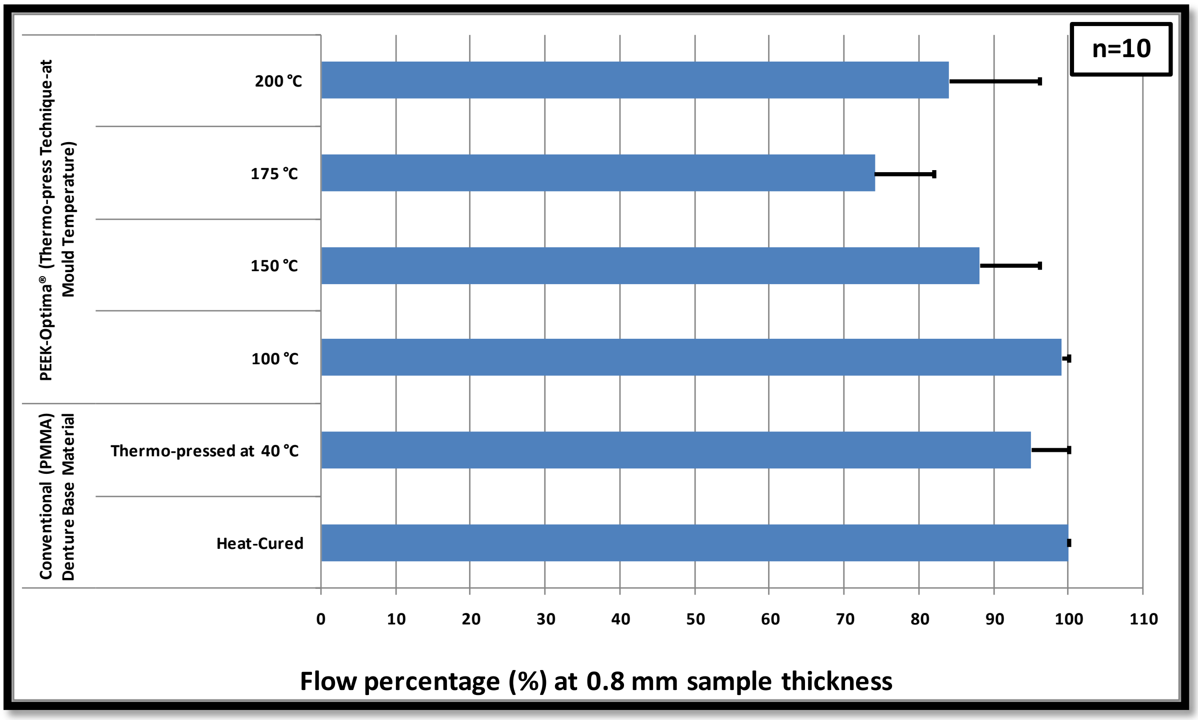


Figure (5-4): Diagram showing the mean distribution of PMMA and PEEK flow behaviour at sample depth of 0.8 mm

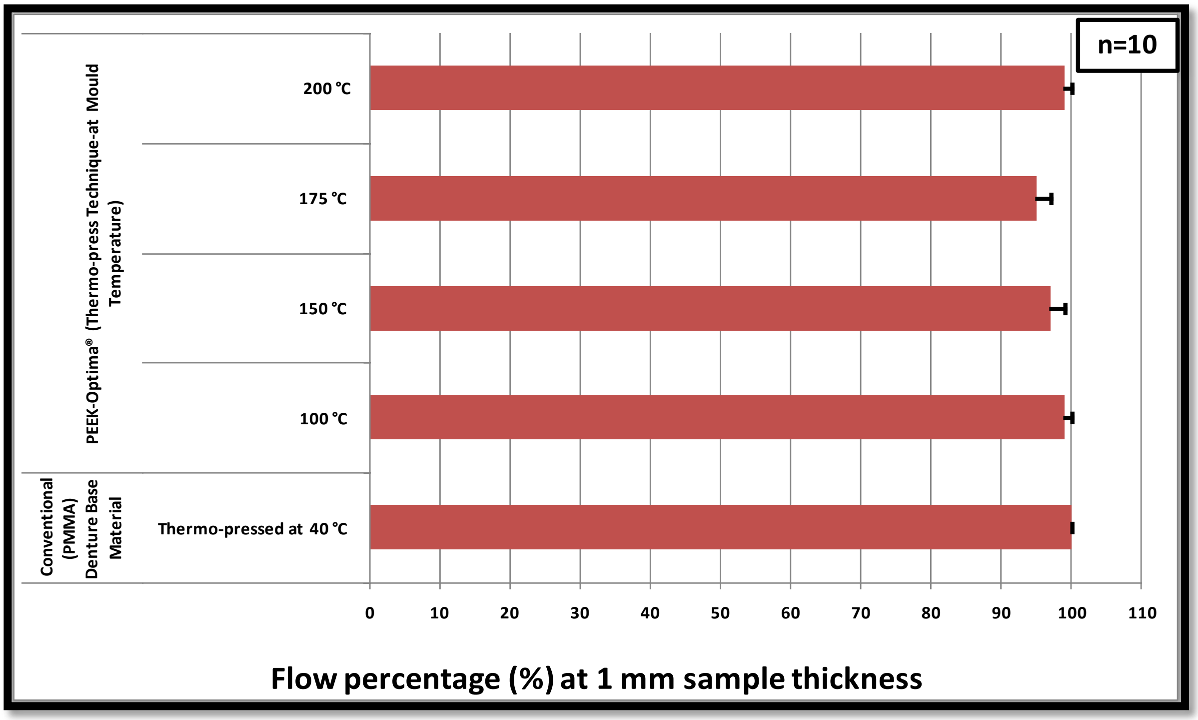


Figure (5-5): Diagram showing the mean distribution of PMMA and PEEK flow behaviour at sample depth of 1 mm

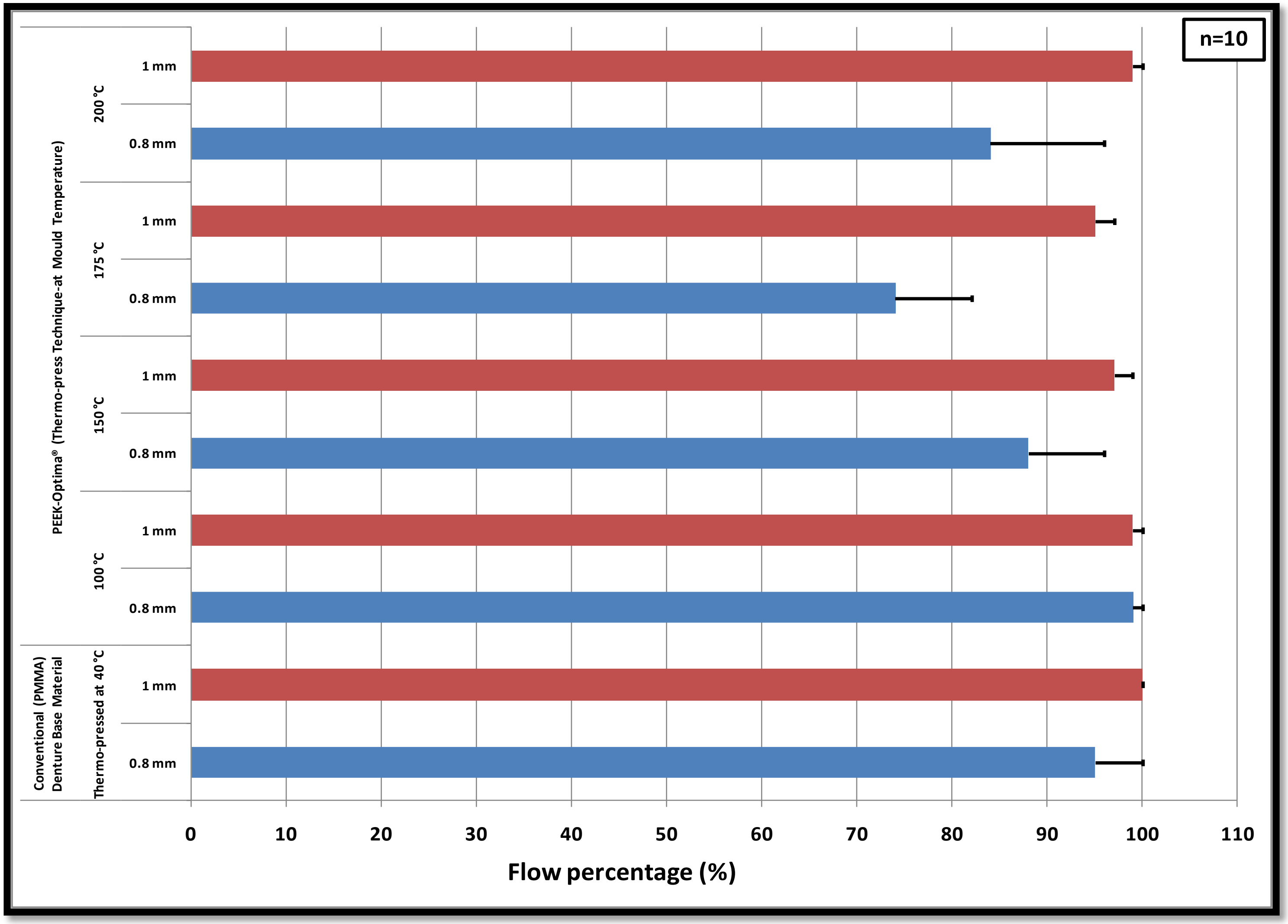


Figure (5-6): Diagram showing the mean flow distribution in percentages of the tested material at sample depths of 0.8 and 1 mm

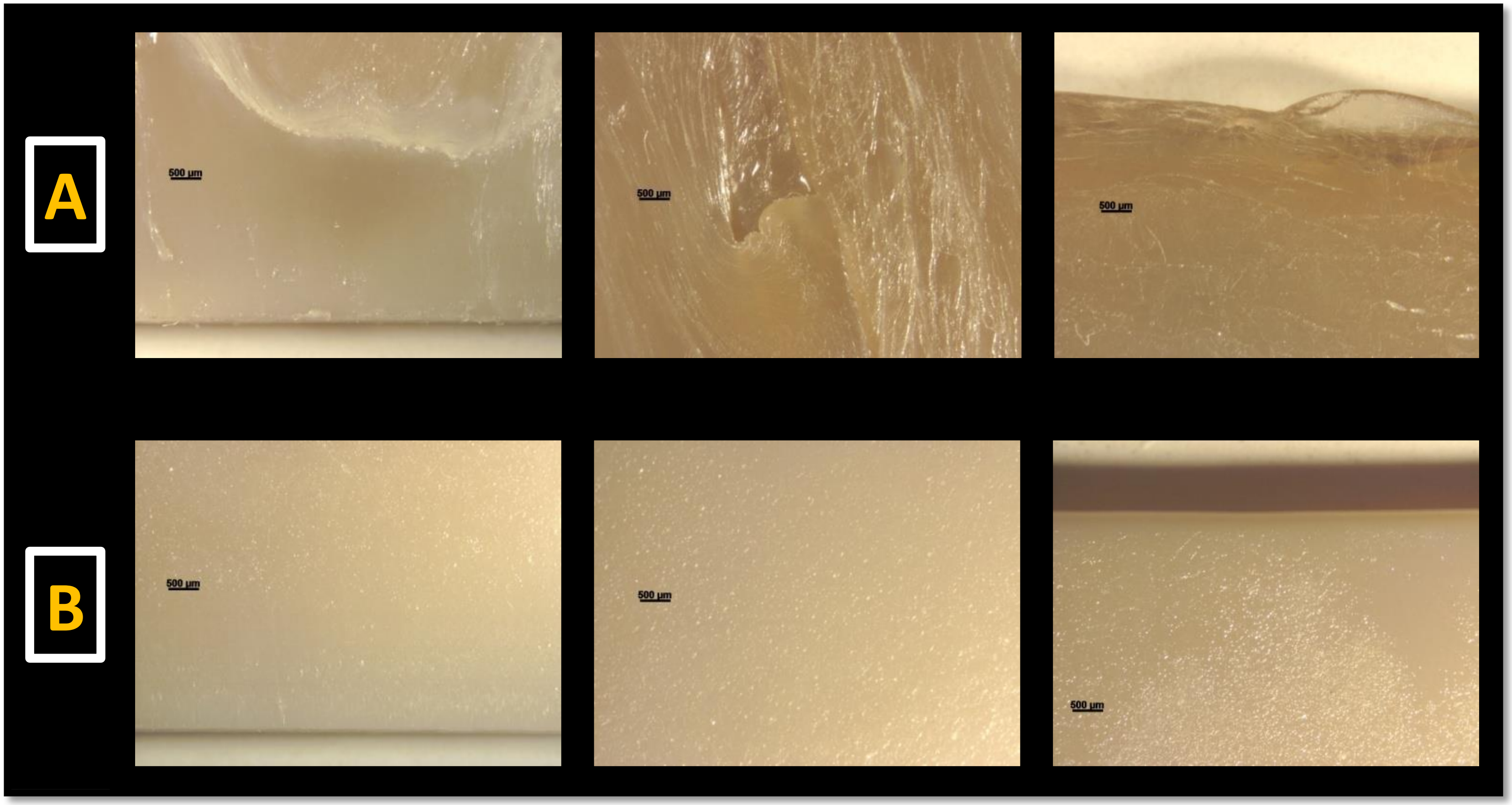


Figure (5-7): Examination under light microscope of the PEEK-Optima® specimens thermo-pressed at different mould temperatures (left: edge in contact with the sprue; centre: the specimen centres; right: the free edge). The PEEK was thermo-pressed at **A.** 100 °C; and **B.** 150 °C

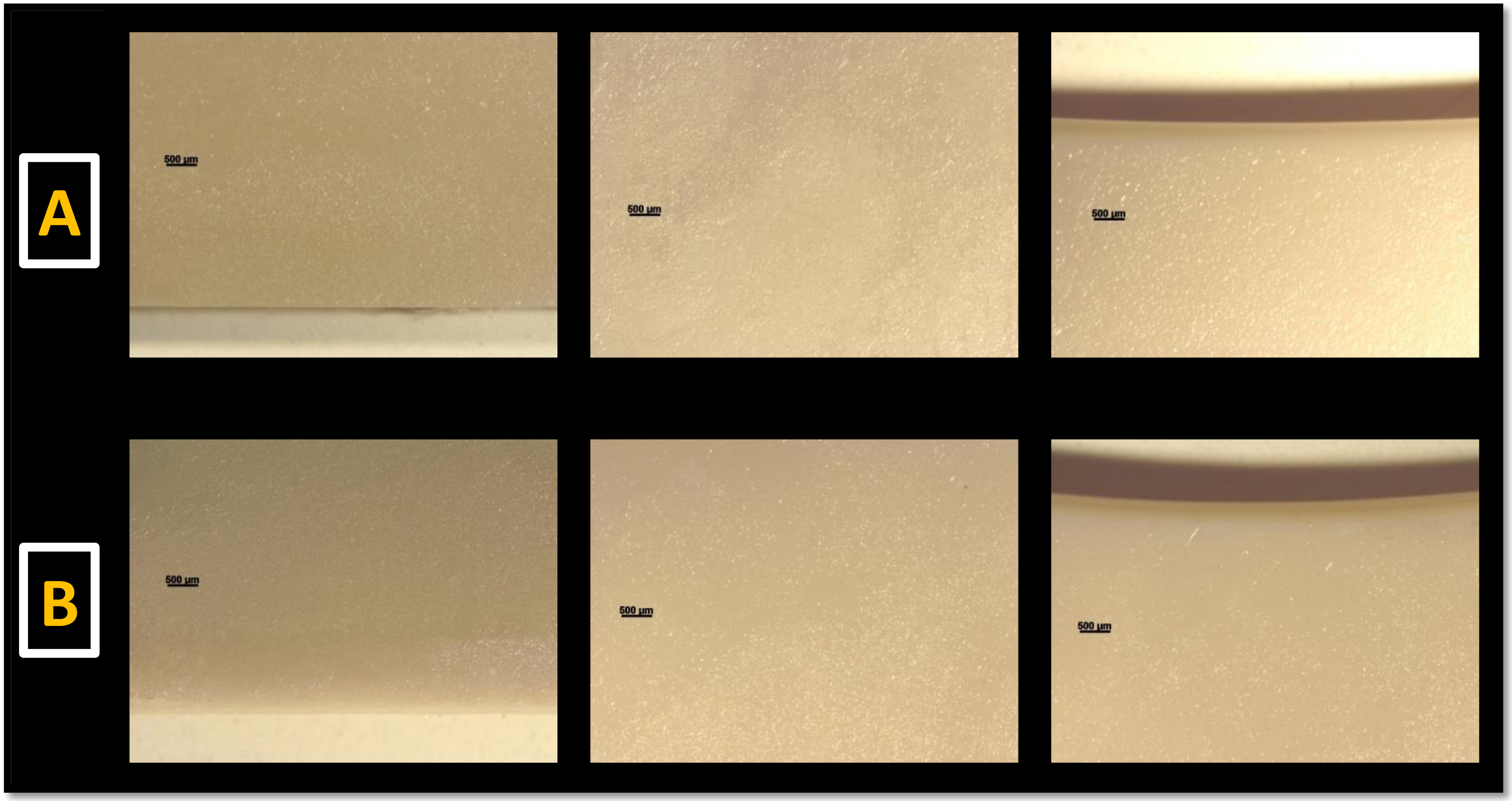


Figure (5-8): Examination under light microscope of the PEEK-Optima® specimens thermo-pressed at different mould temperatures (left: edge in contact with the sprue; centre: the specimen centres; right: the free edge). The PEEK was thermo-pressed at **A.** 175 °C; and **B.** 200 °C

In 0.8 mm depth samples: Figure (5-4), there was no statistically significant difference (P>0.05) between the flow percentage of the PMMA sample that was processed by heat-cured water-bath, with a mean value of 100%, and that processed by thermo-press technique of 95(±5) %. Meanwhile, there was a statistically significant difference (P<0.05) between the flow percentage of the heat-cured PMMA and that of the PEEK-Optima® thermo-processed at different mould temperature above the PEEK T*g*. On the other hand, there was a statistically non-significant difference (P>0.05) between the flow percentage of the thermo-pressed PMMA and that of the PEEK-Optima® thermo-processed at different mould temperature below and above the PEEK T*g* except in the case of 175 °C mould temperature (P<0.001).

There was a statistically significant difference (P<0.05) between PEEK thermo-pressed at mould temperature of 100 °C below the PEEK T*g*, with mean value of 99 (±1) %, compared to PEEK-Optima® thermo-pressed at mould temperatures above the PEEK T*g* at 150, 175, and 200 °C, with mean values of 88(±8) %, 74 (±8) %, and 84(±12) % respectively. However, there was no statistically significant difference (P>0.05) between different mould temperature below and above the PEEK T*g* except in the case of 150 and 175 °C mould temperatures (P<0.05).

In 1 mm depth samples: Figure (5-5), there was no statistically significant difference (P>0.05) between the 100 % flow of the thermo-processed PMMA sample and that of PEEK-Optima® thermo-processed at 100 °C and 200 °C, with a mean value of 99 (±1) %. However, there was a statistically significant difference (P<0.05) in percentage between the thermo-processed PMMA flow and that of the PEEK-Optima® thermo-processed at 150 and 175 °C, of 97 (±2) % and 95 (±2) % respectively.

There was a statistically significant difference ($P<0.001$) between PEEK thermo-pressed at mould temperature of 100 °C below the PEEK T*g*, with mean value of 99 (±1) %, compared to PEEK-Optima® thermo-pressed at mould temperatures of 175 °C, with mean value of 95 (±2) %. However, there was no statistically significant difference ($P>0.05$) in the cases of samples thermo-pressed at 100 °C and those processed at 150 and 200 °C mould temperature ($P<0.05$). Moreover, there was a statistically non-significant difference ($P>0.05$) between the flow percentage of the PEEK-Optima® thermo-processed at different mould temperature above the PEEK T*g* except in cases of 175 °C and 200 °C mould temperatures ($P<0.001$).

Comparisons of 0.8 mm and 1 mm depth samples: Generally, there was statistically no significant difference ($P>0.05$) between the flow percentage of the thermo-press PMMA sample processed at 0.8 mm depth with a mean value of 95 (±5) and that of the sample of 1mm depth, at 100 % flow, figure (5-6).

There was a statistically significant difference ($P<0.05$) between the flow percentage for the 0.8 mm depth PEEK-Optima® samples thermo-processed at 150 °C [88 (±8) %] and at 175 °C [74 (±8) %] mould temperature and that thermo-processed at 1mm depth, with mean values of 97 (±2) and 95 (±2) % respectively. However, statistically there was no significant difference ($P>0.05$) between the flow percentage of 0.8mm depth PEEK-Optima® samples thermo-processed at 100 °C and 200 °C mould temperature of 99

(±1)% and 84 (±12) % flow and that thermo-processed at 1 mm depth, with both mean values at 99 (±1) %.

Each group of specimens investigated under light microscope revealed different crystalline behaviours and flow texture at the surface and in different locations within the specimen. This was noticed when the temperature was increased steadily inside the mould cavity from 100 °C to 200 °C. The different crystalline behaviours were examined in three different areas within each group of specimens, figures (5-7) and (5-8).

5.2.2. Thickness Behaviour

The following results present the sample thickness data estimated for the PEEK material based on the denture injection method at 0.8 and 1 mm sample depths and processing at different mould temperatures.

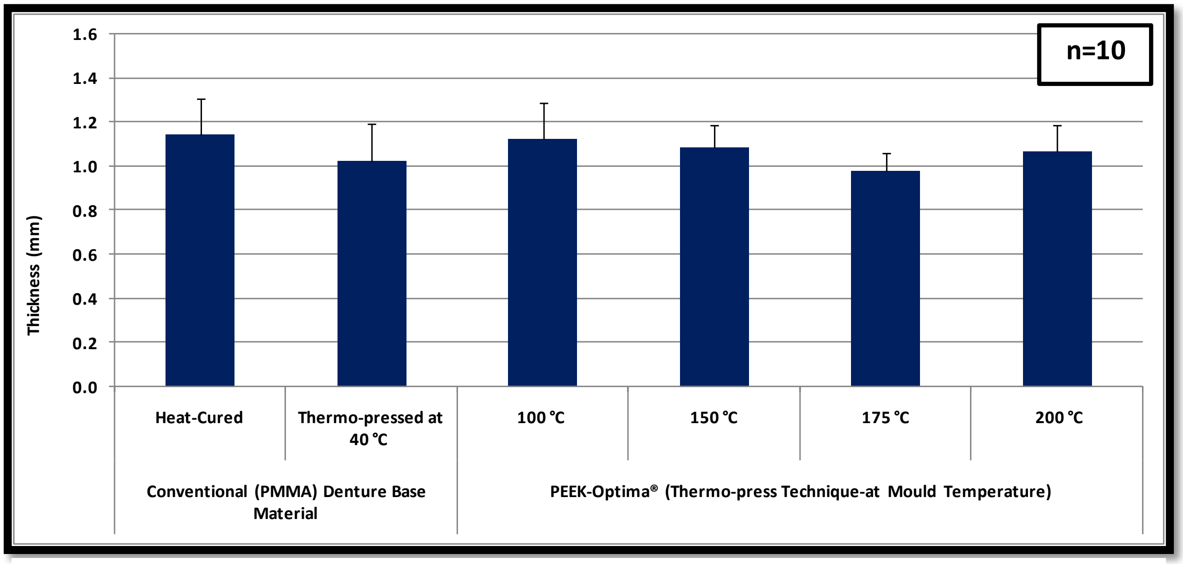


Figure (5-9): Diagram showing the mean distribution of sample thickness at 0.8 mm sample depth

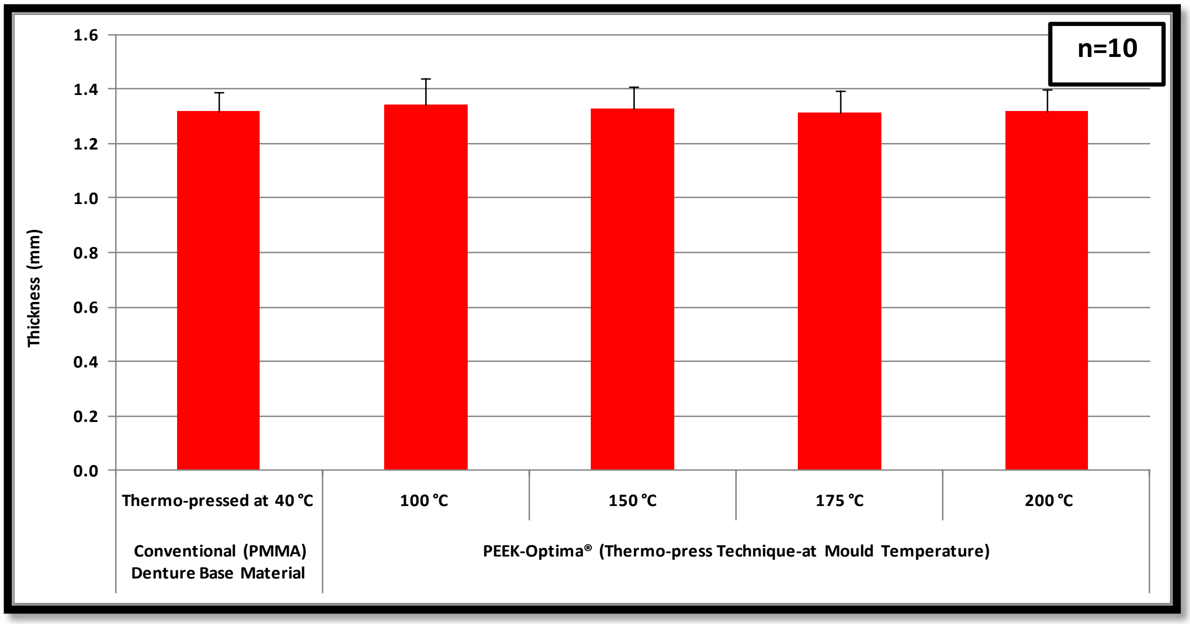


Figure (5-10): Diagram showing the mean distribution of sample thickness at 1 mm sample depth

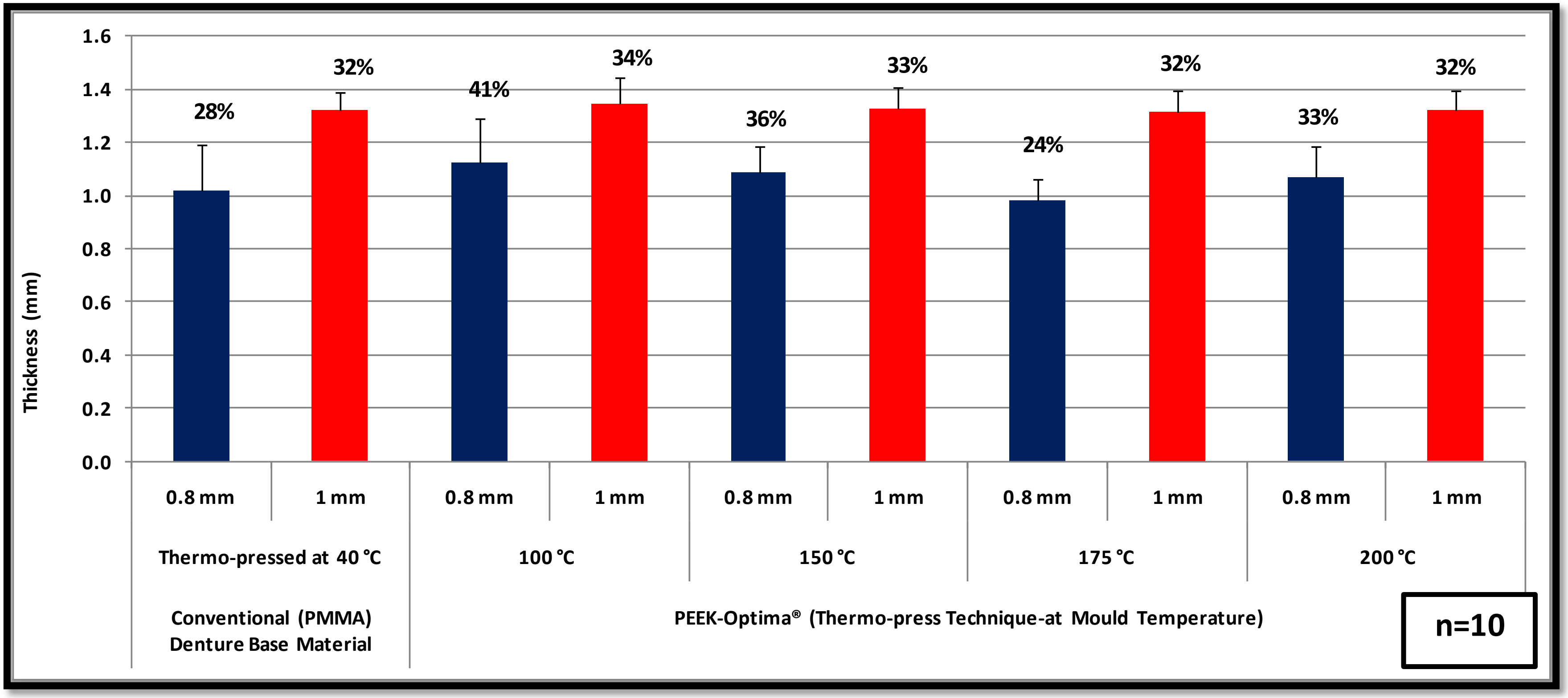


Figure (5-11): Diagram showing the mean distribution of sample thickness in 0.8 and 1mm depth samples and increase in thickness percentage compared to the original depth

In 0.8 mm depth samples: Figure (5-9), there was a statistically significant increase in specimens thickness in the PMMA sample ($P<0.001$) processed by heat-cured water-bath, with a mean value of 1.14(±0.17) mm, in comparison to that processed by thermo-press technique, with a mean value of 1.02(±0.17) mm. In the PMMA sample processed by heat-curing there were significant differences ($P\leq0.001$) in specimen thickness in comparison to the PEEK-Optima® thermo-pressed at 150, 175, and 200 °C mould temperature above the PEEK T*g*, with mean values of 1.09(±0.10), 0.98(±0.08), and 1.12 (±0.16) mm respectively. However, it was non-significant ($P>0.05$) compared to that thermo-pressed at 100 °C mould temperature of 1.07 (±0.12) mm below the PEEK T*g*. On the other hand, statistically significant differences ($P<0.05$) were found in the mean thickness value of the thermo-pressed PMMA compared to that of the PEEK-Optima® thermo-pressed at different mould temperatures.

Statistically there were significant differences ($P\leq0.001$) in the mean thickness of the PEEK-Optima® samples that were thermo-processed at different mould temperatures except in the case of that thermo-pressed at 150 °C and those processed at mould temperatures of 100 and 200 °C ($P>0.05$).

In 1 mm depth samples: Figure (5-10), there were statistically non-significant differences in specimen thickness between the thermo-pressed PMMA sample ($P>0.05$), of 1.32 (±0.07) mm, and the PEEK-Optima® samples thermo-pressed at 150, 175, and 200 °C mould temperatures above the PEEK T*g*, with mean values of 1.33 (±0.08), 1.32 (±0.08), and 1.32 (±0.08) mm respectively. However, the differences were statistically significant (P<0.05) when compared to PEEK-Optima® thermo-pressed at 100 °C mould temperatures below the PEEK T*g*, with a mean value of 1.34 (±0.10) mm.

Statistically there was no significant difference (P>0.05) in the mean thickness of the PEEK-Optima® samples that were thermo-processed at different mould temperature except between that thermo-pressed at 100 °C and those processed at 175 and 200 °C mould temperatures (P<0.05).

Comparison of 0.8 mm and 1 mm depth samples: Generally, statistically significant differences in thickness (P<0.001) were found between 0.8 and 1 mm depth specimens across all the tested samples, figure (5-11).

There were statistically significant differences in specimen thickness of the thermo-pressed PMMA sample at 0.8 and 1mm depth (P<0.001) compared to thermo-pressed PEEK-Optima® samples of different mould temperatures and depths. However, the only statistically non-significant difference (P>0.05) identified was between the PMMA at 0.8mm and the thermo-pressed PEEK-Optima at 1mm depth at 175 °C and 200 °C. Also, statistically non-significant differences were found between PMMA of 1 mm depth and PEEK-Optima® of 1mm depth that was thermo-pressed at mould temperatures of 100, 150, 175, and 200 °C below and above the PEEK T*g*.

Statistically significant differences in thickness percentage were identified in comparison to the original specimen depth (P≤0.001). The thermo-pressed PMMA of original depth of 0.8mm increased in thickness by about 28 %, and that of 1 mm depth increased by about 32 %. The thickness of the PEEK-Optima® that was thermo-pressed below the PEEK T*g* at 100 °C increased by about 41 % compared to the original depth of 0.8mm, and the 1 mm sample increased by about 34%. Meanwhile, the PEEK-Optima® of original depth of 0.8 mm that was thermo-pressed above the PEEK T*g* at 150, 175, and 200 °C increased in thickness by about 36 %, 24 %, and 33 %, and that of the original depth of 1 mm increased by about 33 %, 32 %, and 32 % respectively.

5.3. Discussion

In industry thermo-pressing and moulding production methods are controlled by computer and metal moulding platforms are used. However, from the scientific point of view, conditions inside the dental lab for the construction of accurate replicas for patients' arches and the associated structures are very different. Moreover, it is either impossible or too expensive to provide a metal mould for every patient who requires a dental prosthesis. Hence, with the available dental lab facilities, materials, and equipment investigation of PEEK polymer as a denture base material and optimization of its physical properties compared to those of conventional denture base materials is extremely important. Therefore, the specimens were prepared using hard diestone moulding material and denture injection method. The Thermopress 400 machine was used in this study, due to its suitability for injecting metal-free denture base materials.

5.3.1. Flow Test

In 0.8 mm thickness specimens, no differences were identified between the flow percentages of PMMA samples processed by heat-cured water-bath and thermo-press techniques. Nevertheless, differences in flow percentage were noticed between the heat-cured PMMA and the PEEK-Optima® thermo-processed at different mould temperatures above the PEEK T*g*. This may be related to the different processing techniques used to prepare the sample (Salim *et al.*, 1992; Baydas *et al.*, 2003). This may support this study's observation of no differences between the thermo-pressed PMMA and the PEEK-Optima® thermo-processed at different mould temperatures below and above the PEEK T*g* when the same processing technique was used, except at 175 °C mould temperature. This may be due to the shortage in the flow percentage of this sample at this mould temperature for some unknown reason or may be due to the sample's small depth of 0.8 mm. The PEEK-Optima® samples thermo-pressed at mould temperatures above the PEEK T*g* at 150, 175, and 200 °C exhibited a lower flow percentage than that thermo-pressed at 100 °C below the PEEK T*g*. This could be correlated to the specimen depth of 0.8 mm, since features such as design and geometry of the mould may influence the injected product (Kurtz, 2011b), or it could be due to a greater amount of steam being released from the heated mould into the mould cavity during the injection process and slightly blocking the flow.

In 1 mm depth specimens, higher flow percentages were identified in the thermo-pressed PEEK-Optima® samples that were thermo-processed at 100 °C and 200 °C. This may be related to the easy flow characteristic of the amorphous and lower density PEEK polymer at 100 °C mould temperature below the PEEK T*g*, and the ease and gentle flow of the molten PEEK material into the wider and warmer mould surfaces at 200 °C above the PEEK T*g* (Kurtz, 2011b). Also, no difference was noticed between these two PEEK mould temperatures and that of the PMMA using the same processing technique.

Generally, as the sample depth increased from 0.8mm to 1mm, the flow percentage of the PEEK-Optima® improved. This may be related to the gentle flow of the molten PEEK material into the wider mould cavity as opposed to the material shrinkage that occurred at the lower depth. However, no effect was observed on the flow percentage when sample depth of the PMMA was increased from 0.8mm to 1mm. This may be related to the composition of this PMMA material, which has low viscosity and density (Van Noort, 2013) compared to PEEK-Optima® polymer (Reitman *et al.*, 2011).

Under light microscopy examination, the specimens revealed different surface flow behaviour and texture as the mould temperature increased. The specimens exhibited more uniform amorphous-crystalline structure and parts when thermo-pressed at mould temperatures above the PEEK T*g*. However, at 100 °C mould temperature thermo-pressed below the PEEK T*g* the sample demonstrated amorphous texture characterized by transparency, lower density and with less crystalline counterparts (Atkinson *et al.*, 2002). This might support the conclusion drawn by Kurtz that the failure of the PEEK material to achieve the required mould temperature results in rapid cooling and insufficient time for crystallisation of the injected part to take place.

Wilfong's conclusions might also supported by the study's finding that moulding conditions may reveal different levels of crystallinity in different parts of the polymer, additionally to the diverse effects on the material's properties, since the polymer cooling rate varies depending on its thickness (Wilfong, 1989). Moreover, Invibio recommends in its PEEK processing guide that surface temperature for injected PEEK material should be in the range of 175-205 °C (Invibio, 2004b; Kurtz, 2011b). However, this study used a gypsum product to produce the mould rather than the recommended metal moulds.

5.3.2. Thickness Test

In 0.8 mm thickness samples, an increase in specimen thickness was noticed in the heat-cured PMMA specimen using water-bath technique compared to the PMMA sample processed using thermo-press technique. In addition, an increase in the average thickness was observed in the heat-cured PMMA compared to the PEEK-Optima® thermo-pressed at 150, 175, and 200 °C mould temperatures above the PEEK T*g*. According to Salim *et al.,* and Baydas *et al.,* this could be related to the different processing techniques potentially affecting the accuracy of the processed parts (Salim *et al*., 1992; Baydas *et al*., 2003).

The thickness of PEEK-Optima® thermo-pressed above the PEEK T*g* had less effect as the mould temperature increased compared to that of 100 °C mould temperature thermo-pressed below the PEEK T*g*. The wavy and folding surface of the PEEK-Optima® at 100 °C mould temperature revealed un-uniform texture which may have enhanced the surface thickness when measured by the digital micrometer. Meanwhile, it remained uniform and consistent as the mould temperature increased above the PEEK T*g*.

With 1 mm depth samples, the thermo-pressed technique was used for both the PMMA and PEEK polymer at different mould temperatures. No differences were identified in the thickness of the thermo-pressed PMMA specimens compared to the PEEK-Optima® specimens thermo-pressed at mould temperatures above the PEEK T*g*. But, differences were noticeable when they were compared to PEEK-Optima® specimens thermo-pressed at 100 °C mould temperatures thermo-pressed below the PEEK T*g*. A higher increase in the thickness average was noticed with the PEEK-Optima® thermo-pressed at

100 °C, while the samples thermo-pressed at 175 and 200 °C mould temperatures were less affected. This may be related to the high crystalline surfaces associated with PEEK's thermal behaviour when it is processed at high temperatures and above the PEEK T*g* (Wilfong, 1989).

Regardless of the type of materials used for thermo-pressing by denture injection method and the moulding conditions, the material should provide dimensional accuracy under different processing methods. Although the processing conditions in this study were standardised and controlled and the only variable was the specimen depth, all the tested materials showed variation in thickness percentage as the specimen depth increased. Remarkable increases and decreases in specimen thickness were observed between the 0.8 and 1 mm depth samples of the tested materials. Compared to the original depths of 0.8 mm and 1 mm, the PEEK-Optima® samples that were thermo-pressed at 200 °C mould temperature revealed constant increases in thickness percentage of 33 % and 32 % respectively. However, according to the Invibio processing guide, PEEK-Optima® can produce consistent parts with dimensional tolerances as low as 0.05 % (Invibio, 2004a) if the operation is carried out under the recommended injection moulding temperature of 355 °C at the rear; 365 °C at the middle; 370 °C at the front; and 375 °C at the nozzle (Kurtz, 2011b). It is possible that this dimensional tolerance only be achieved through using the recommended metal platforms as a moulding material rather than gypsum products.

All materials have their own rate and amount of expansion and contraction during heating and cooling (Whaites and Drage, 2013). For instance metals such as Aluminum has about 22.2 linear thermal expansion which is higher than that of pure Iron (12) and cast Iron (10.4) and that of steel of 11 (10^{-6}m/mk). According to Greig (2012), gypsum bounded investment materials should not have linear thermal expansion vary more than 20 % of expansion claimed by the manufacturer (Greig, 2012; Sakaguchi and Powers, 2012). However, according to the manufacturer, the hard distone moulding material used in this study has setting expansion (DIN) less than 0.08 %. Yet, no thermal expansion has been recorded; therefore, more studies should be established to evaluate the using of these materials at high temperatures.

5.4. Conclusion

The present study draws the following conclusions:

1. As the sample depth increased from 0.8 mm to 1 mm, the flow percentage of the PEEK-Optima® NI1, using thermo-pressing technique, improved.

2. Under light microscope, the PEEK-Optima° NI1 thermo-processed at 100 °C mould temperature below the PEEK T*g* illustrated a transparent amorphous texture, while that thermo-processed at different mould temperatures above the PEEK T*g* revealed more crystalline counterparts.

3. The thermo-pressed polymer materials of 0.8 mm and 1 mm depths showed an increase in thickness values of more than 30 % compared to the original depths.

To sum up, it seems that certain features of the injection moulding conditions for PEEK polymer processing such as the parts' geometry, may influence the flow ability of the injected PEEK polymer. In addition, gypsum moulding material may show high thermal expansion as the mould heated at high temperatures for thermo-pressing purposes.

Chapter Six

Investigating the Surface Roughness of Thermo-pressed PEEK as a Denture Base Material

Chapter Six: Surface Roughness

Introduction

As the mould temperature has an effect on PEEK flowability and dimensional accuracy, this parameter may influence the surface topography of thermo-pressed PEEK polymer as a denture material. The surface roughness of dental prostheses is a significantly important issue in relation to denture base materials as it may affect the oral health of tissues that are in direct contact. Thereafter, surface roughness could promote microbial colonisation and plaque accumulation

The denture base commonly has a hard, non-shedding surface, and this may accumulate plaque and biofilm. The surface topography could contribute to biofilm formation and microbial colonisation on the denture base.

In terms of health considerations, higher concentrations of bacterial colonisation could occur in some denture base materials when the surface roughness value is greater than 2.0 µm (Bollenl *et al*., 1997; Radford *et al*., 1999). Polishing of the denture fitting surface is not possible as it may significantly affect adjacent non-machined areas unless a very precise polishing technique is adopted.

PEEK thermoplastic polymer has recently been suggested for use for dental purposes. However, no studies have investigated the surface roughness of thermo-pressed PEEK polymer as a denture base material compared to that of conventional PMMA denture material.

Aim

This study aims to assess the un-polished surface topography of PEEK-Optima®NI1 as a denture base material processed by thermo-pressing technique and at different mould temperatures.

Objectives

The objectives of the present study are:

1. To test the surface roughness of the diestone moulding materials before and after heat treatment at different mould temperatures.
2. To investigate the effect of mould temperature on the surface roughness of PEEK-Optima®NI1 processed at different mould temperatures, and compare with its effect on the surface roughness of conventional PMMA.

6.1. Materials and Methods

6.1.1. Mould Preparation

Mould Preparation for Diestone Specimens

In this study a silicone mould was prepared to duplicate the stone moulded cavity to test the effect of selected mould temperatures on the surface roughness of diestone moulding material. Stone specimens (n=10) of internal cut dimensions of 60x40x0.8mm were constructed to simulate the dimensions of the mould cavity that would receive the melted PEEK material, figure (6-1). Dental diestone moulding material (Type IV) was mixed according to the manufacturer’s instructions (W/P: 20 ml /100 g) and poured into the silicone mould, using a vibrator to avoid trapping any air. After 60 minutes, when the stone material had set, and to simulate the injection processing, the specimens were placed in a wax extraction unit for 5 minutes, and then detergent agents and boiling water were applied. The mould surfaces were left to dry for 30 seconds and then one layer of acrylic separating medium was used to coat the mould surfaces while the mould material was still warm. The mould was left overnight to dry in preparation for the next step.

Mould Preparation for PEEK and PMMA Specimens

The sample design, mould preparation, heat-cured PMMA samples, heating times, and the injection moulded process for both the PMMA and PEEK-Optima®NI1 samples all followed the same procedures described previously in chapter five.

6.1.2. Diestone Preheating Process

To assess the effect of heated mould temperature on the surface roughness of diestone moulding material, the diestone specimens were preheated at different selected temperatures. A Vecstar furnace was set up at different temperatures according to the results achieved in chapter four, see table (6-1). The specimens were placed inside the furnace at room temperature 25 (±1 °C) and the temperatures were elevated steadily. Once the test time was complete, the specimens were removed from the furnace to cool on the bench overnight, ready for measuring of surface roughness the next day.

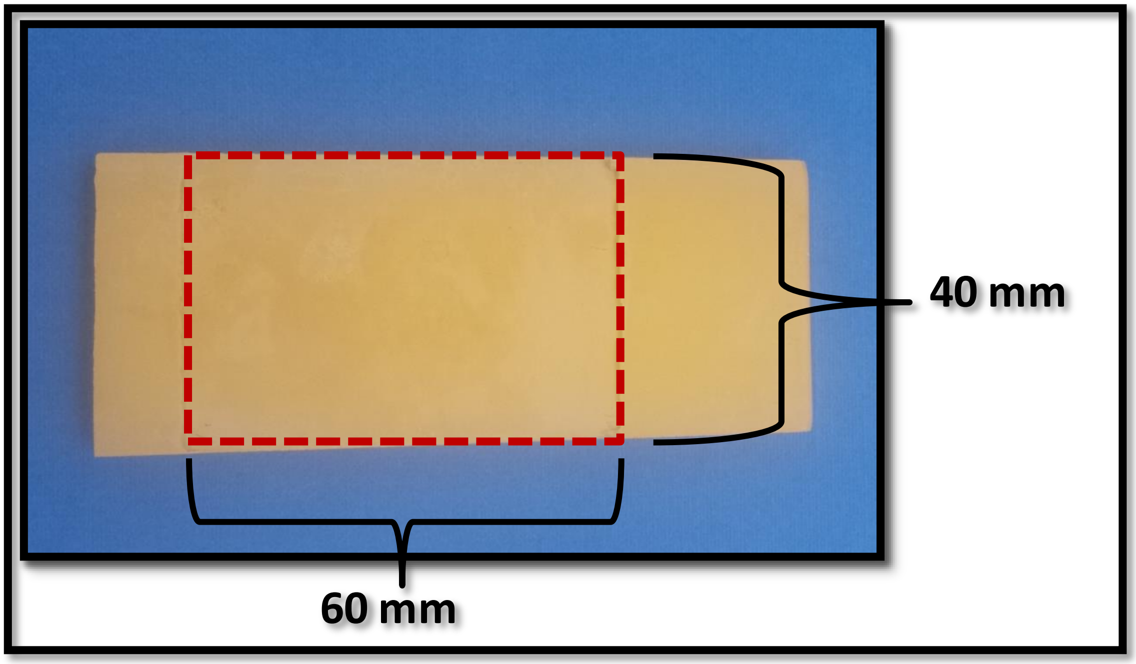


Figure (6-1): dimensions of the diestone moulding specimens

Table (6-1): Select moulding temperatures and times for testing material

Furnace set up T (°C)	Mould T (°C)	Time (min)
150	100	90
200	150	120
250	~ 40	15
250	175	90
250	200	150

6.1.3. Sample measurement

Surface Roughness of Diestone Moulding Material

Specimens (n=10) were tested before and after heat treatments using a profilometer surface roughness testing machine (TR200, USA). Each diestone mould specimen surface was measured vertically and horizontally within a distance of 5mm. Measurements for each specimen surface numbered 22 in total (11 vertical and 11 horizontal readings), figure (6-2).

PEEK and PMMA Surface Roughness

The surface roughness of the PMMA processed by heat-cured water bath and denture injection technique, and PEEK specimens thermo-pressed at different mould temperatures was estimated using a profilometer testing machine. Each surface was measured in a similar way to those of the diestone samples (22 readings), figure (6-3).

Figure (6-2): Measuring diestone type IV specimen by profilometer surface roughness testing machine

Figure (6-3): Measuring PEEK specimen surface by profilometer surface roughness testing machine

6.2 Results

Suitable statistical methods were used to analyse the surface roughness results. The data for the conventional PMMA, PEEK-Optima®NI1 injected at 100, 150, 175 and 200 °C mould temperatures were compared via analysis of variance (ANOVA) and 2-tailed student T-test at a confidence level of 95 % and significant P-value of ($P \leq 0.05$), see appendix part (D).

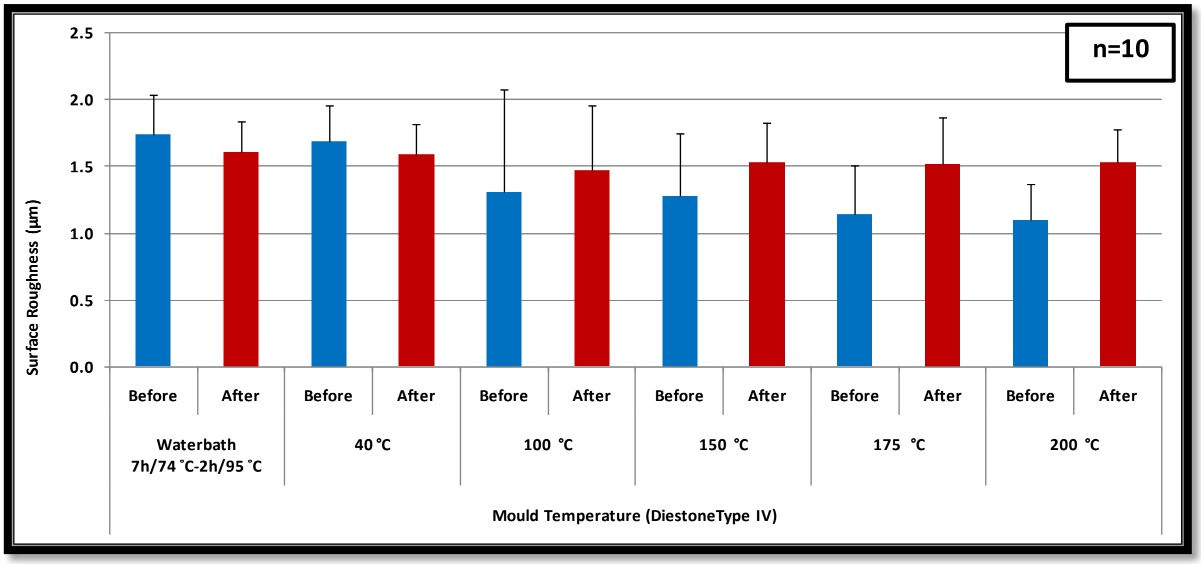


Figure (6-4): Diagram showing the mean distribution of surface roughness of the diestone moulding material before and after heat treatment at different mould temperatures

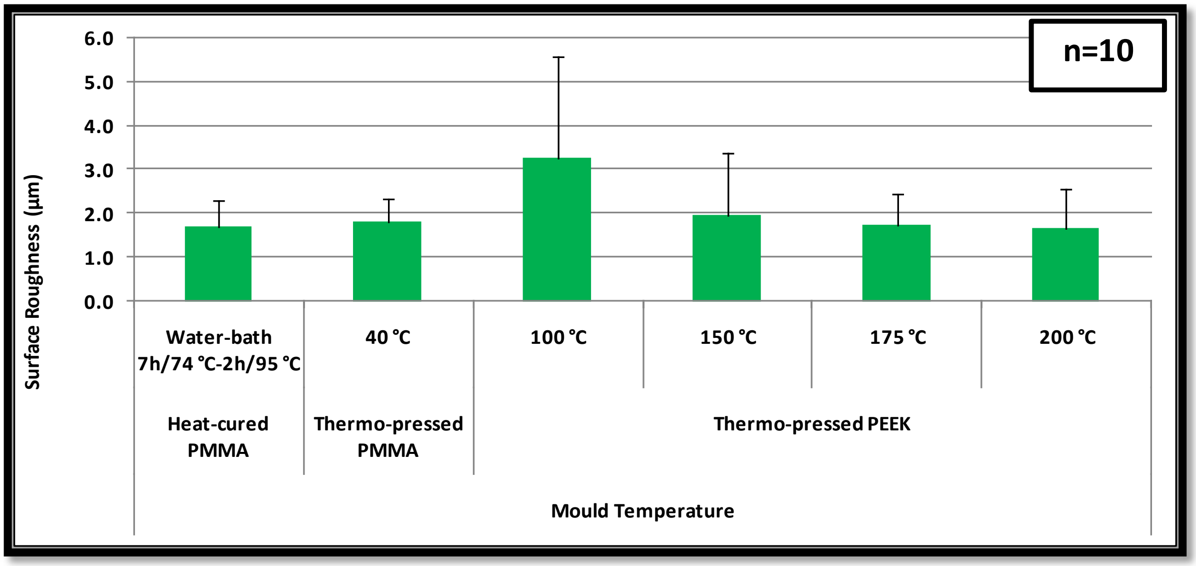


Figure (6-5): Diagram showing the mean distribution of surface roughness among the tested polymer materials

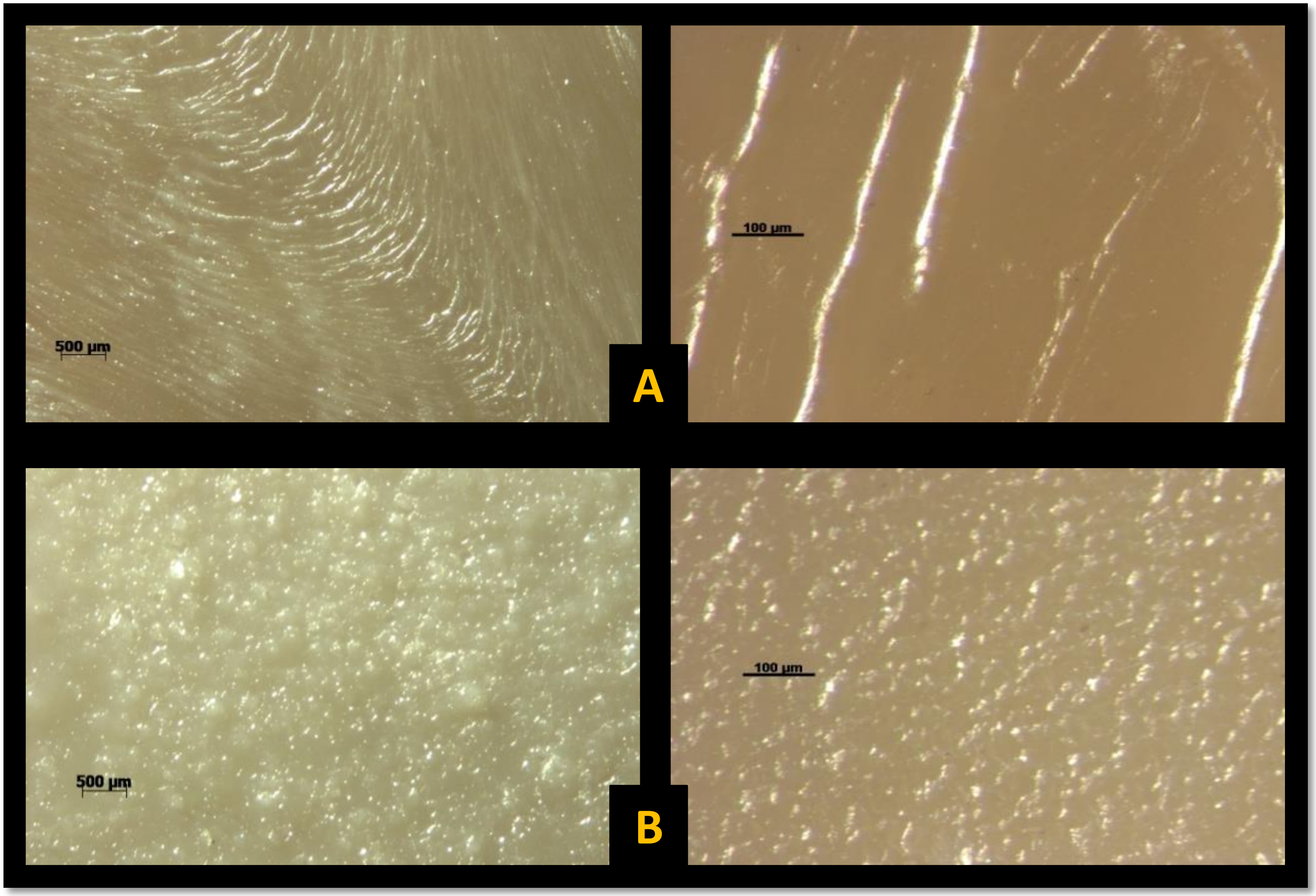


Figure (6-6): Examination under light microscope of PEEK specimens processed at mould temperatures of **A.** 100 °C; and **B.** 150 °C (right images under high magnification)

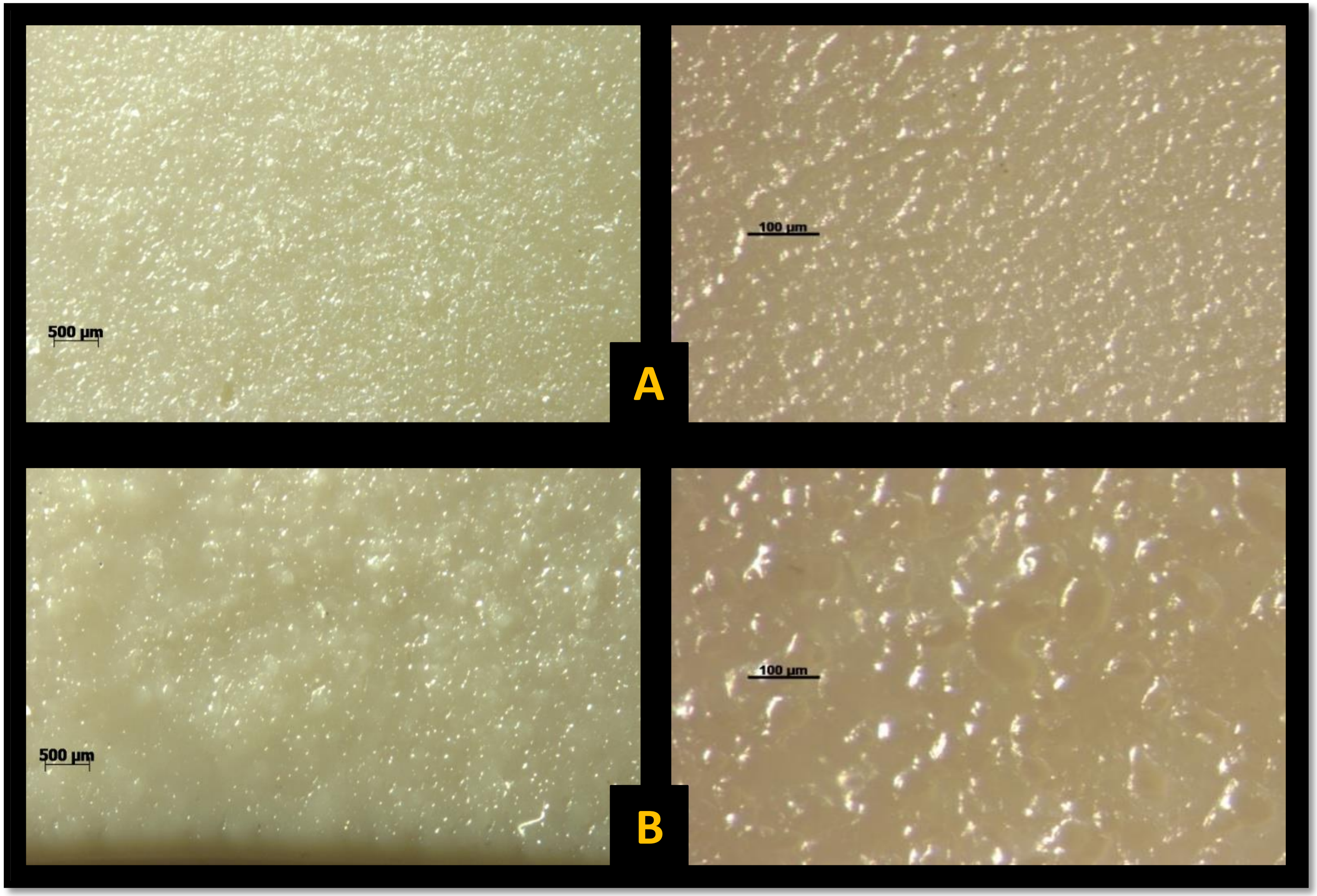


Figure (6-7): Examination under light microscope of PEEK specimens processed at mould temperatures of **A.** 175 °C; and **B.** 200 °C (right images under high magnification)

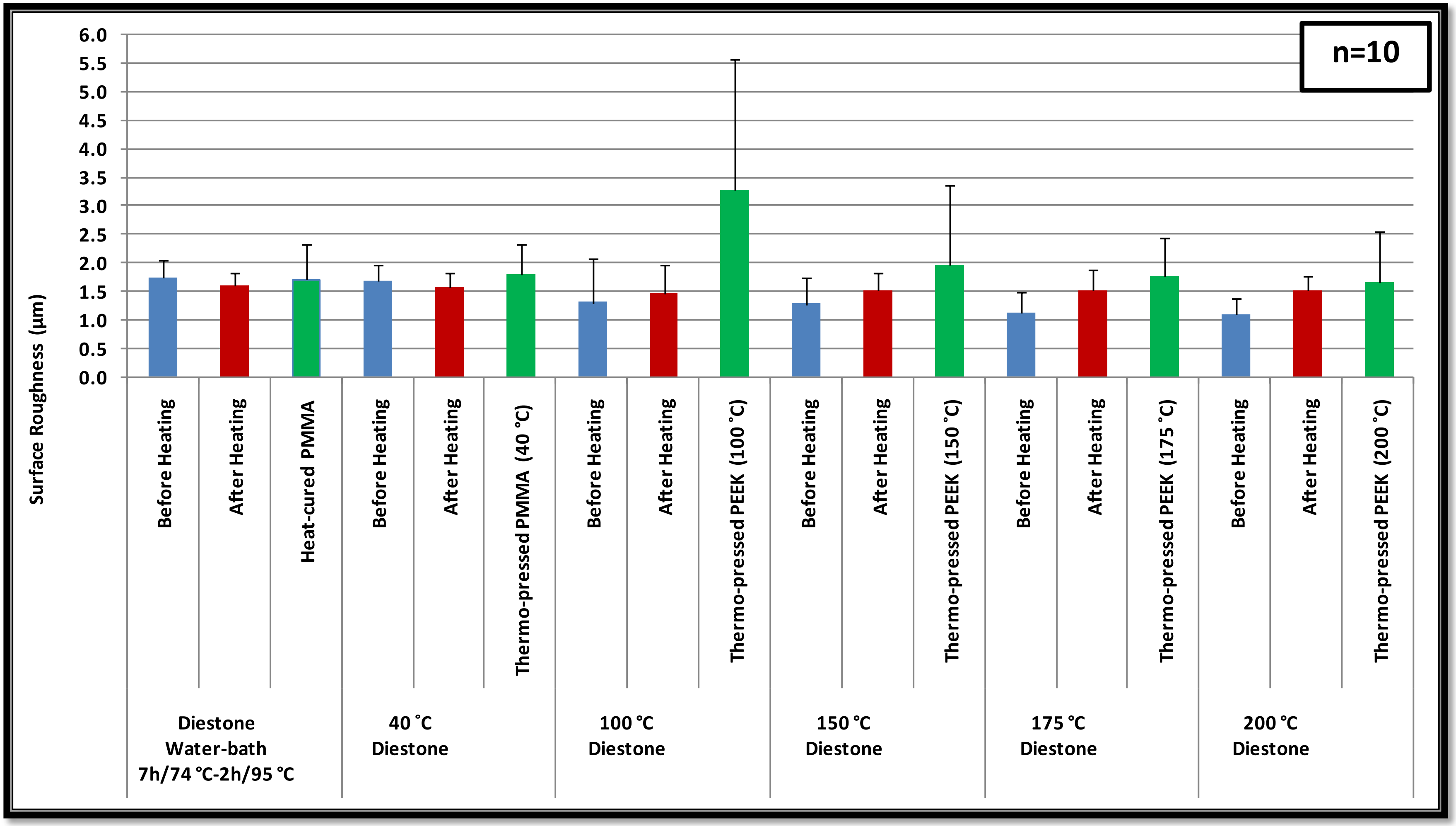


Figure (6-8): Diagram showing the mean distribution of surface roughness among the studied diestone moulding material and tested polymer materials

Diestone moulding material: Generally, there were statistically significant differences (P<0.001) between the surface roughness of the diestone moulding material before and after the heat treatment for all the tested materials, figure (6-4). There was significant increase in surface roughness of the diestone moulding material after the heating treatment carried out for processing purposes (P<0.001).

Processed polymer materials: there was a statistically non-significant difference (P>0.05) between the surface roughness of PMMA that processed by both heat-cured water-bath, with a mean value of 1.7 (±0.6) µm, and that processed by thermo-pressing technique, at 1.8 (±0.5) µm. However, there was a statistically significant difference (P<0.001) between the surface roughness of the PMMA that processed by both techniques and that of the PEEK-Optima®NI1 thermo-pressed at 100 °C mould temperature, figure (6-5). The PEEK-Optima®NI1 thermo-pressed at 100 °C mould temperature below the PEEK T*g* exhibited an increase in surface roughness of 3.3 (±2.3) µm compared to the PMMA. Also, it exhibited a significant increase (P<0.001) in surface roughness compared to the PEEK-Optima®NI1 thermo-pressed at mould temperatures above the PEEK T*g*. Statistically there were non-significant differences (P>0.05) between the surface roughness of all the PEEK-Optima®NI1 material, thermo-pressed at different mould temperatures, with mean values of 2 (±1.4) µm, 1.8 (±0.7) µm, and 1.7 (±0.9) µm above the PEEK T*g* at mould temperatures of 150, 175, and 200 °C respectively. However, the lowest surface roughness mean value, of 1.7 (±0.9) µm was noticed with the PEEK-Optima®NI1 thermo-pressed at 200 °C mould temperature. Under light microscopy, the PEEK specimens showed diverse crystalline-amorphous texture at different mould temperatures, figures (6-6) and (6-7).

Comparison of the diestone after heating and the tested polymer materials: there were statistically significant differences ($P<0.05$) between the surface roughness of the diestone moulding material after heat treatment and that of the processed polymer materials, figure (6-8). There was a significant increase in the surface roughness of the tested polymer materials compared to that of the diestone moulding material after heating treatment ($P<0.05$) in the PMMA processed by both techniques, and the PEEK-Optima®NI1 thermo-pressed at different mould temperatures.

6.3. Discussion

To carry out the surface roughness test specimen dimensions of 60 mm width and 40 mm length were used to reflect the dimensions of full palate coverage of a RPD base, while the thickness selected for study purposes was 0.8 mm. Different mould temperatures of 100, and 150, 175 °C and 200 ˚C were estimated in this study. The surface roughness of the diestone moulding material was also tested before and after the heat treatment.

The diestone moulding material exhibited an increase in surface roughness after heat treatment at the tested temperatures. This may be related to dehydration of the moulding material during the heating procedures. The elevation of the mould temperature in dry atmosphere may lead to evaporation of some or all of the mixture liquid to produce a rough surface. As the heating temperature increases, more liquid evaporates leaving an increasingly rougher surface.

Regarding the tested PMMA polymer materials there were no differences in surface roughness between the two heat-cured water-bath PMMA samples, of 1.7 (±0.6) µm, and that of the thermo-pressed PMMA, of 1.8 (±0.5) µm. In addition, the surface roughness of PMMA samples processed by both techniques was the same as that of the PEEK-Optima®NI1 material sample thermo-pressed at mould temperature above the PEEK T*g*, at 2 (±1.4), µm1.8 (±0.7) µm, and 1.7 (±0.9) µm at 150, 175, and 200 °C respectively. All of these figures were lower than that for the PEEK-Optima®NI1 material sample thermo-pressed at 100 °C mould temperature, with 3.3 (±2.3) µm surface roughness.

PEEK-Optima®NI1 as an injected denture base material without polishing procedures seems to have variable surface roughness values related to mould temperatures above the PEEK T*g*. However, the PEEK material that was injected above the glass transition temperature at 200 °C mould temperatures exhibited lower mean surface roughness. This may be related to the polymer cooling rate within thin sections, while additionally the typical warm mould temperatures of 180-220 ˚C could provide a highly crystalline surface with no quenched or amorphous characteristics (Wilfong, 1989; Kurtz, 2011b). This feature of PEEK material might be essential to reducing the formation of rough surfaces that can encourage microbial adherence and colonisation during functional performance.

Under light microscopy, the PEEK surface topography of the specimen thermo-pressed at 100 °C mould temperature below the PEEK T*g* showed a wavy flow with more amorphous-less crystalline texture. This may affect the PEEK surface by leading to high irregularities and increased roughness. However, as the mould temperature increased above the PEEK T*g*, the PEEK sample surfaces showed consistency in crystal particles and this may lead to less surface roughness at elevated mould temperatures.

The lack of information about the behavoiur of PEEK crystals at different processing mould temperatures makes it difficult to draw inferences about the causes of the differences found. In addition, the lack of literature concerning acceptable denture surface roughness values raises the question of whether these statistical differences in the surface topography of the conventional PMMA and biocompatible PEEK polymer material are clinically meaningful.

6.4. Conclusion

The present study draws the following conclusions:

1. The diestone moulded material had lower surface roughness after water-bath heat-cured PMMA resin and furnace heating at 40 °C to thermo-press the PMMA polymer.
2. The diestone moulded material had higher surface roughness after furnace heating at 100, 150, 175, and 200 °C to thermo-press the PEEK-Optima®NI1 polymer.
3. The diestone moulded material that was furnace heated at 100, 150, 175, and 200 °C exhibited lower surface roughness than that of the thermo-pressed PEEK-Optima®NI1 specimens at the same processed heated mould temperature.
4. The PEEK-Optima®NI1 specimens that were thermo-pressed at 100 °C mould temperature had higher surface roughness than that at 150, 175, and 200 °C.
5. Under light microscopy the PEEK-Optima®NI1 specimens thermo-pressed at 100 °C mould temperature lower than the PEEK T*g* exhibited non-uniform amorphous-crystalline structure. Meanwhile, those thermo-pressed at elevated mould temperatures had more uniform amorphous-crystalline structure.

To sum up, it can be seen that although the diestone mould demonstrated increased in surface roughness after preheating, the mean surface roughness value of PEEK material injected at 200 ˚C mould temperature was lower compared to the other experimental groups. Hence, PEEK-Optima®NI1 may offer promises as an alternative denture base material to PMMA with fewer opportunities for microbial colonisation.

Chapter Seven

Mechanical Properties of PEEK as a Denture Material

Chapter Seven: Mechanical Properties

Introduction

The inadequate performance of the mechanical properties of available traditional denture base material such as PMMA and Co-Cr appears to indicate the need for their replacement by new denture materials. PEEK thermoplastic polymer has recently developed for use for dental purposes. However, no studies have investigated the mechanical properties of PEEK polymer as a denture base material. Since the mould temperatures could affect the physical properties of the injected PEEK, it could also influence its mechanical properties.

Aim

Evaluation of thermo-pressed and machined PEEK's mechanical properties as a non-metal denture base material

7.1. Izod Impact Strength

Aim

This study aims to determine PEEK's impact strength as a notch weakening denture material compared to conventional PMMA denture base material.

Objectives

The objectives of this present study are as follow:

1. To evaluate the impact strength of:
    a. PEEK-Optima®NI1 thermo-pressed by denture injection method with different mould temperatures
    b. PEEK-Juvora™ machined by CAM
    c. PEEK materials to compare with that of conventional PMMA
2. To examine the sample fractured surfaces under SEM

7.1.1. Materials and Methods

Mould and Sample Preparation

The Izod test samples (n=10) were prepared according to the dimensions recommended by (ASTM D 256, ISO 180) (Keener *et al*., 2004; da Costa *et al*., 2007; Chen and Evans, 2009; Ozcelik *et al*., 2010), table (7-1). Ten rectangular wax blocks of 12.00 mm X 5.00 mm X 82.00 mm depth, width, and length respectively were used to create uniform silicone mould spaces.

Processing Procedure

Heat-Cured PMMA

Mould preparation for the heat-cured PMMA followed the conventional dental laboratory procedures for water-bath curing by compression method. The water-bath system was used for heat curing the acrylic resin. Mixing of the PMMA powder/liquid ratio followed the manufacturer's instructions. Heat polymerization of the material was carried out for 9 h. The flasks were kept after curing to bench-cool overnight and the sample was then deflasked, figure (7-1A).

Denture Injection Method

The wax specimens were prepared for moulding by using type IV diestone gypsum investment material. The stone was allowed to harden for 60 minutes, the wax was soften in a wax extraction unit for 5 minutes, and then the flasks were opened and cleaned with detergent agents and boiling water. The mould surfaces were left to dry for 30 seconds. One layer of acrylic separating medium was used to coat the mould surfaces while the mould material was still warm. An acrylic-plaster separating liquid specially designed for separating thermo-press resins was used during the pressing and injection process. The moulds were then left overnight to dry in preparation for the injection process.

The mould was preheated by setting up the furnace temperature for the particular time period required for optimization of the mould temperature for the injection process, table (7-2).

A Thermopress 400 injection moulding system was used for the PEEK and PMMA thermo-pressed materials. The PEEK material used in this study was PEEK-Optima® NI1, which is an unfilled PEEK formulation. The injection system was preheated according to the manufacturer's set programs and as mentioned previously. The PEEK material was injected at different mould temperatures of 100, 150, 175 and 200 °C, while the PMMA granules were thermo-pressed at 40 °C. The injected moulds were left overnight to allow slow bench-cooling to room temperature. The flasks were then deflasked and the specimens were cut from the sprues, figures (7-1B and C).

Table (7-1): ASTM D-256, ISO 180 method designations, specimen types, notch types and notch dimensions (mm)

Method designation ^{a,b}	Specimen	Notch type	Notch base radius (^{r}N)	Remaining width, b_N, at notch base
ISO 180/ U	Length *l* = 80± 2	Unnotched	—	—
ISO 180/ A	Depth *b* =10.0 ± 0.2	A	0.25 ± 0.05	
ISO 180/ B	Thickness *h* =4.0 ± 0.2	B	1,00 ± 0.05	8.0 ± 0.2

Table (7-2): The optimised mould temperatures selected for thermo-pressing the PEEK-Optima® by denture injection method

	Mould Temperature (°C)			
	100	150	175	200
Dial set up (Furnace) (°C / min)	150/90	200/120	250/90	250/150

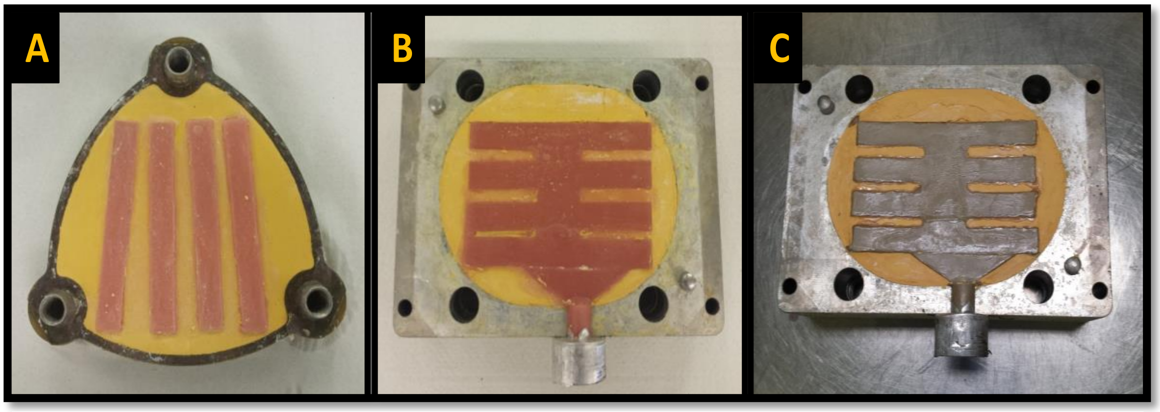
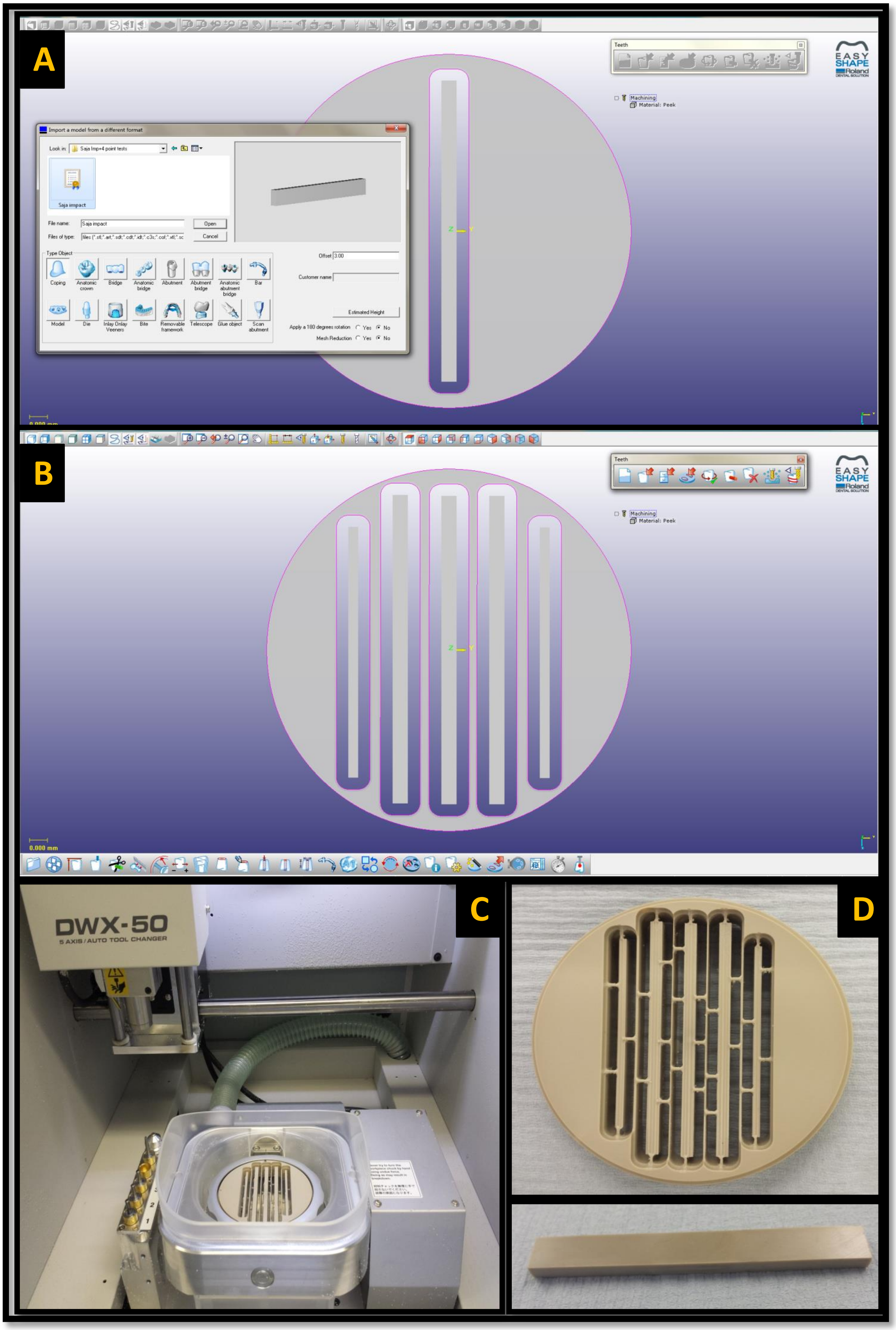


Figure (7-1): Impact sample prepared using **A.** heat-cured PMMA; **B.** thermo-pressed PMMA; **C.** thermo-pressed PEEK-Optima®

CAD/CAM Technique

An impact specimen file designed and created using the SketchUp 3D modeling program was exported to the milling machine for manufacture of the PEEK specimens, figure (7-2). A Roland milling machine was used for the CAM technique, and the PEEK polymer used in this study technique was PEEK-Juvora™, which is unfilled PEEK in disc form.



Look in: Saja Imp+4 point tests

File name: Saja impact

Files of type: files (*.stl;*.art;*.sdt;*.cdt;*.idt;*.c3s;*.col;*.xtl;*.sc

Offset 3.00

Customer name

Apply a 180 degrees rotation ○ Yes ● No

Mesh Reduction ○ Yes ● No

Figure (7-2): Impact and 4-point bending test samples prepared using **A&B.** design milling program; **C.** fabricated using milling machine; and **D.** milled PEEK samples

Finishing and Polishing

The entire sample was finally machine-polished using 600 and 1200 grit metallographic grinding papers. According to (ASTM D 256-ISO 180), the recommended dimensions were 10.00 (±0.2) mm depth, 4.00 (±0.2) mm width, and 80.00 (±2) mm length; however, for the final test sample a length of 79 (±0.4) mm was used in this study, figure (7-3).

Notching Procedure

Since the impact absorbed energy of PEEK was to be tested in breaking notched specimens, the notch preparation for Izod test was accomplished by sample machining. This was done to investigate the effect of mould temperature on PEEK's impact strength with notch weakening.

A notching cutting machine with a radius cutter of 0.25 mm was used to notch the sample. The specimens were cut with a notch base radius of 0.25 (±0.05) mm and depth of 2 mm. The specimens' dimensions were then measured using a digital micrometer of 0.02 mm accuracy to determine the remaining depth of the test specimens after notching. The test specimens were prepared and tested at 23 (±2) °C. Prior to mechanical testing, the specimens were stored in water at a temperature of 37 (±1) °C for 50 (±2) h (ISO-1567), figure (7-4A).

Testing Procedure

Impact Strength

To calculate the Izod impact strength of notched specimens (a_{iN}), the IT 503 impact tester machine was used to compute the absorbed energy of the breaking specimens (E_c) based on the following equation:

$$a_{iN} = \frac{E_c}{h \cdot b_N} \times 10^3$$

Where

E_c is the impact energy absorbed by breaking the test specimen (mm).

h is the width or thickness of the test specimen (mm).

b_N is the remaining depth of the test specimens (mm).

The readings were reported in kJ/m^2:

The machine was calibrated before testing the sample to establish the free hanging or zero potential energy position of the pendulum. This procedure enables the IT 503 tester to automatically correct the breaking energy and strength values for all the tests for windage and friction losses. The unit mode selected for the test energy was Joules while the strength was measured in kJ/m^2. Since the strength was based on a cross-sectional area, the specimens’ width and depth needed to be displayed to ensure the results were calculated.

The vice was loosened for insertion the specimen, with the notch facing toward the striking direction. Once the notch was centred and level with the top of the vice, the specimen was clamped in position. Then, the safety doors were closed and the specimens ID and dimensions (width and depth) were entered before runing the test. To release the pendulum and impact the specimen, the test key was pressed; figure (7-4B). After completion of the impact on the specimen, the data displaying the break energy were recorded from the machine screen. The safety door was then opened and the pendulum carefully released from its return swing and re-latched back in position. The broken and clamped tested pieces were removed from inside the box ready for loading of the next specimen.

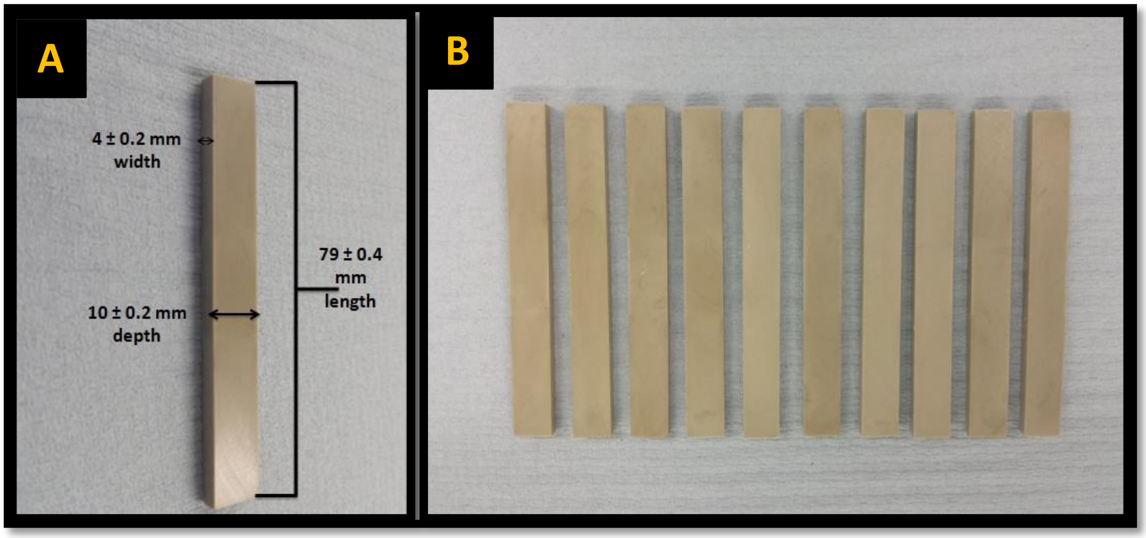


Figure (7-3): A. Impact sample dimensions; **B.** specimens prepared for notching procedure

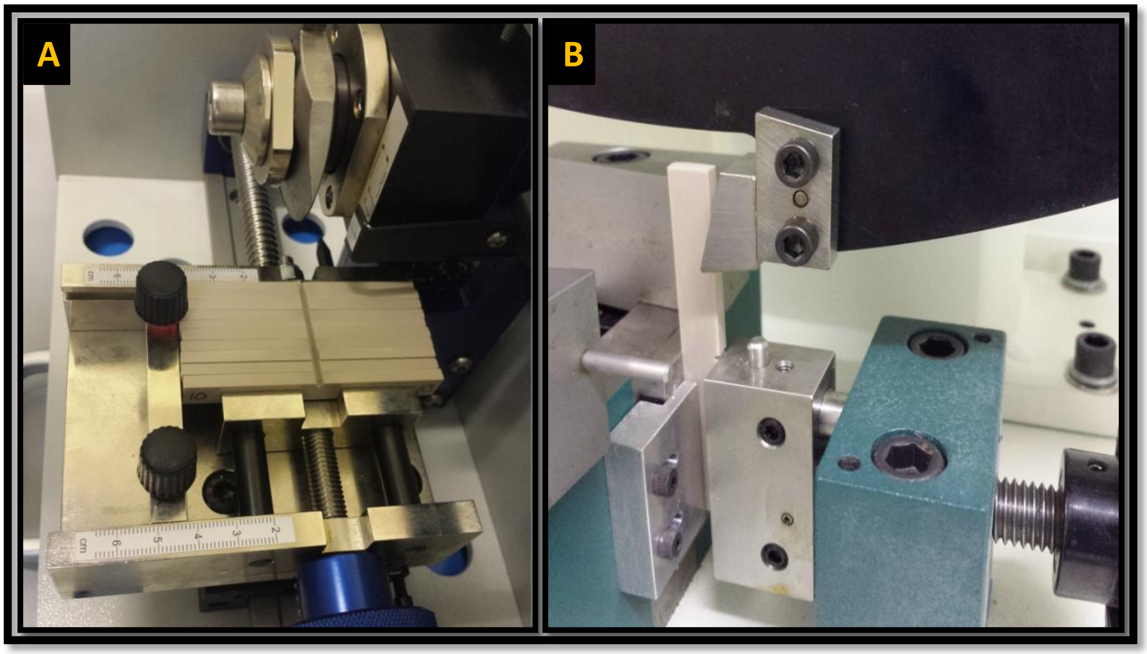


Figure (7-4): A. sample after notching; **B.** specimens under impact testing

Scanning Electronic Microscope (SEM)

The scanning electronic microscope (SEM) is a type of electron microscope that produces images of a sample by scanning it with a focused beam of electrons. For non-conductive materials like polymer, a gold coating is needed to make the specimen conductive. The main purpose of this coating is to prevent the surface charging and to increase the emission of secondary electrons. A sputtering device was used for gold coating; figure (7-5A). In this technique gold ions are ejected from the cathode plate into an argon atmosphere to form plasma that deposits metal onto the specimen, figure (7-5B). After being coated, the specimen was fixed inside the specimen chamber of the electron optical column unit; figure (7-5C). In the operation PC unit, a set of icons is used for switching between the scan modes, starting the auto-function, or opening an operation window. The image is displayed on the screen, so that specimen shift and stage movement can be monitored. Data such as accelerating voltage and magnification become visible when the image is in freeze mode.

Figure (7-5): A. sputtering device for gold coating; **B.** specimen prepared with gold coating for SEM; and **C.** electron optical column unit

7.1.2. Results

The statistical methods used in order to analyse the results included analysis of variation (ANOVA), and the test performed at a confidence level of 95 % and significant P-value of ($P \leq 0.05$).

Exploratory analysis was conducted in a series steps, and the impact strength data of the conventional PMMA, PEEK-Optima® injected at 100, 150, 175 and 200 °C mould temperature, and PEEK-Juvora™ were compared by means of analysis of variance (ANOVA), see appendix part (E)

Figures (7-6), (7-7), and table (7-3) illustrate the statistically significant differences ($P<0.05$) in values of impact strength and absorbed energy for the PEEK polymer when compared with the conventional heat-cured and thermo-pressed Polymethylmethacrylate (PMMA).

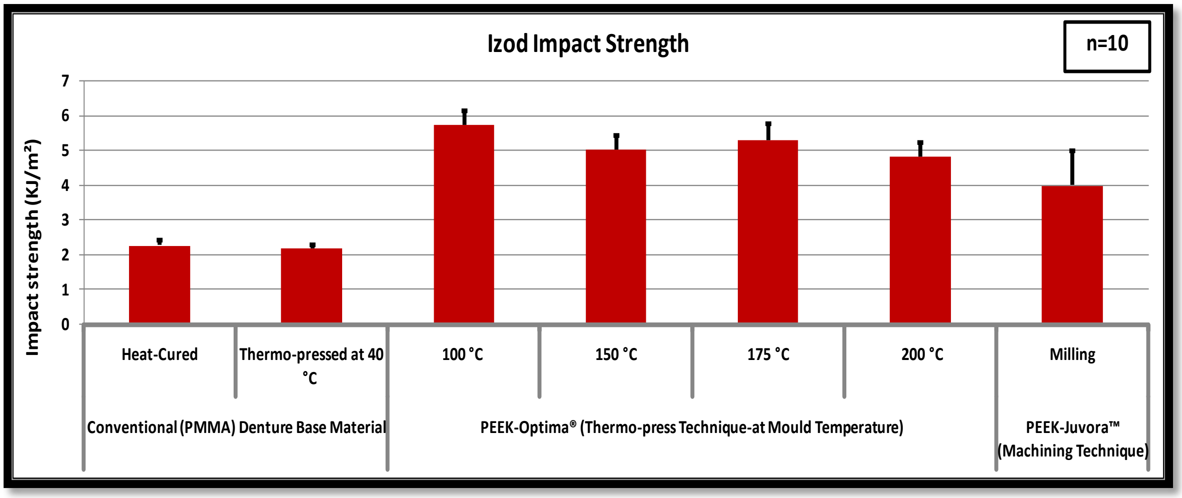


Figure (7-6): Mean distribution of the notched Izod impact strength of the tested material

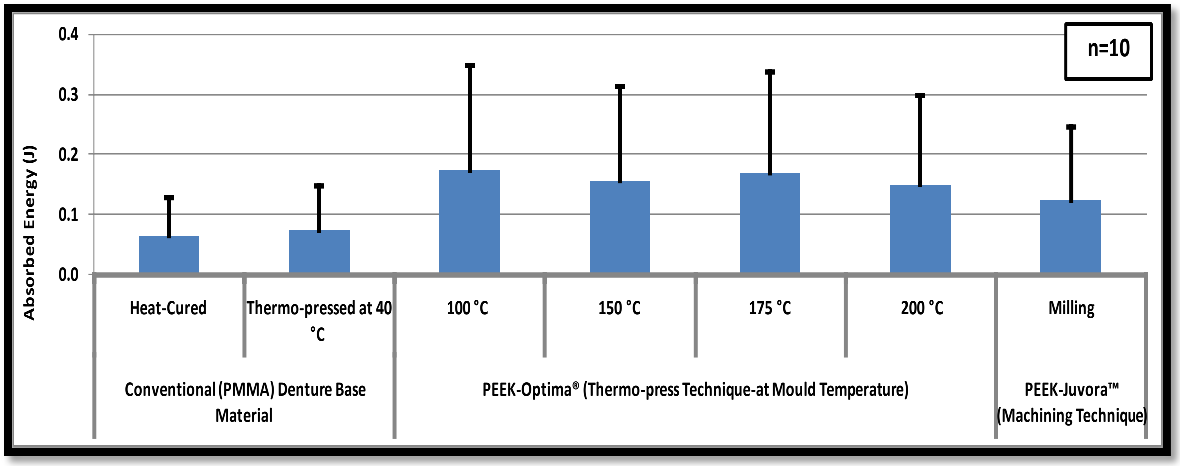


Figure (7-7): Measurement of notched Izod impact energy absorption by the tested material

Table (7-3): Multi comparison for impact strength (KJ/m^2) test among studied groups

Materials Group (A)	Processing method	Materials Group (B)	Processing method	P-Value	Sig.
PMMA	**Heat-cured**	PMMA	Thermo-pressed at 40 °C	P>0.05	Non
		PEEK- Optima®	Thermo-pressed at 100 °C	P<0.001	Sig
		PEEK-Optima®	Thermo-pressed at 150 °C	P<0.001	Sig
		PEEK-Optima®	Thermo-pressed at 175 °C	P<0.001	Sig
		PEEK-Optima®	Thermo-pressed at 200 °C	P<0.001	Sig
		PEEK-Juvora™	CAM	P<0.05	Sig
PMMA	**Thermo-pressed at 40 °C**	PEEK- Optima®	Thermo-pressed at 100 °C	P<0.001	Sig
		PEEK-Optima®	Thermo-pressed at 150 °C	P<0.001	Sig
		PEEK-Optima®	Thermo-pressed at 175 °C	P<0.001	Sig
		PEEK-Optima®	Thermo-pressed at 200 °C	P<0.001	Sig
		PEEK-Juvora™	CAM	P<0.05	Sig
PEEK-Optima®	**Thermo-pressed at 100 °C**	PEEK-Optima®	Thermo-pressed at 150 °C	P<0.05	Sig
		PEEK-Optima®	Thermo-pressed at 175 °C	P>0.05	Non
		PEEK-Optima®	Thermo-pressed at 200 °C	P<0.05	Sig
		PEEK-Juvora™	CAM	P<0.05	Sig
PEEK-Optima®	**Thermo-pressed at 150 °C**	PEEK-Optima®	Thermo-pressed at 175 °C	P>0.05	Non
		PEEK-Optima®	Thermo-pressed at 200 °C	P>0.05	Non
		PEEK-Juvora™	CAM	P>0.05	Non
PEEK-Optima®	**Thermo-pressed at 175 °C**	PEEK-Optima®	Thermo-pressed at 200 °C	P>0.05	Non
		PEEK-Juvora™	CAM	P<0.05	Sig
PEEK-Optima®	**Thermo-pressed at 200 °C**	PEEK-Juvora™	CAM	P>0.05	Non

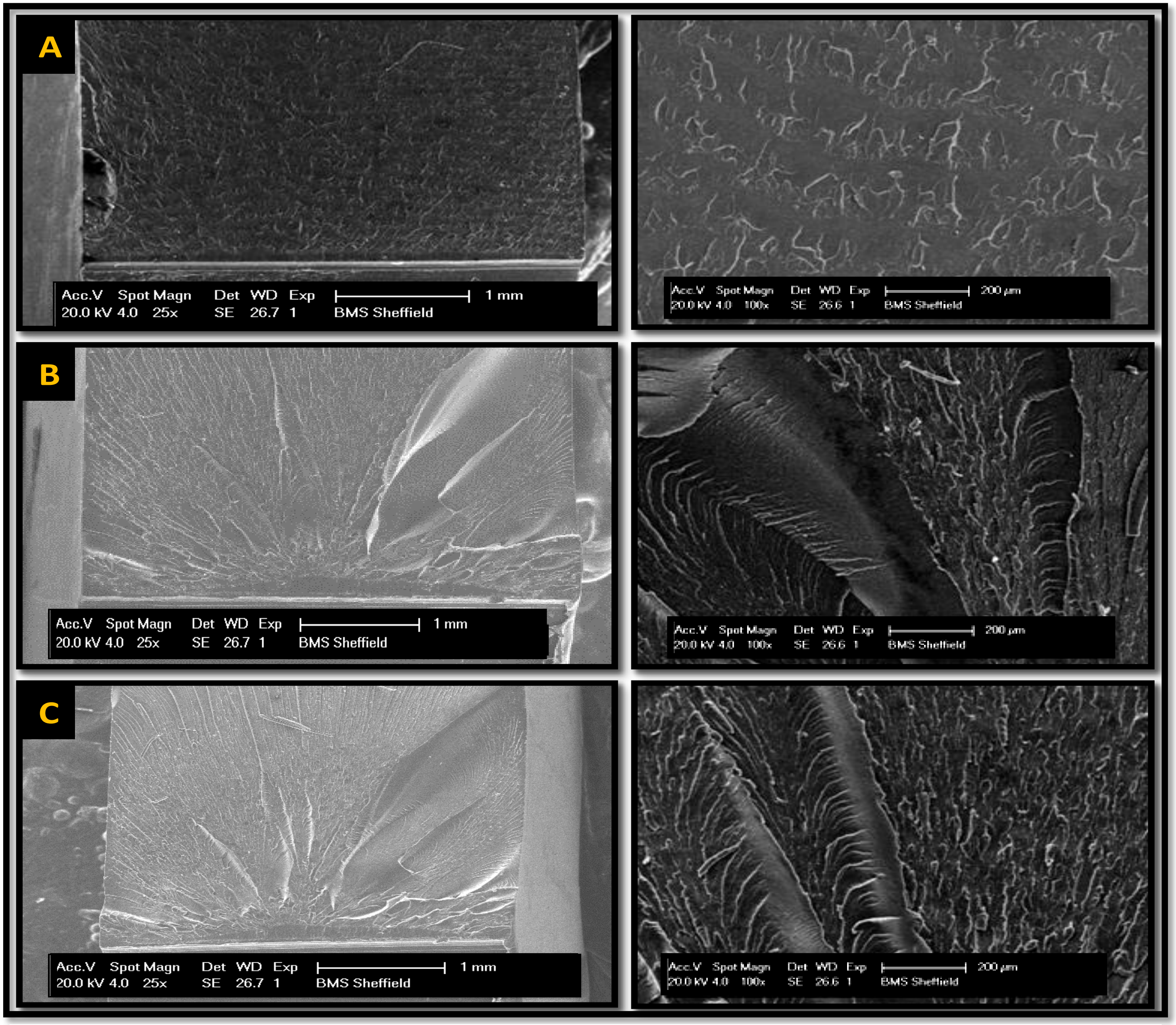


Figure (7-8): SEM of fractured surfaces of the studied material with 0.25 mm radius notch. **A.** thermo-pressed PMMA; PEEK-Optima® thermo-pressed at mould temperature of **B,** 100 °C; and **C.** 150 °C

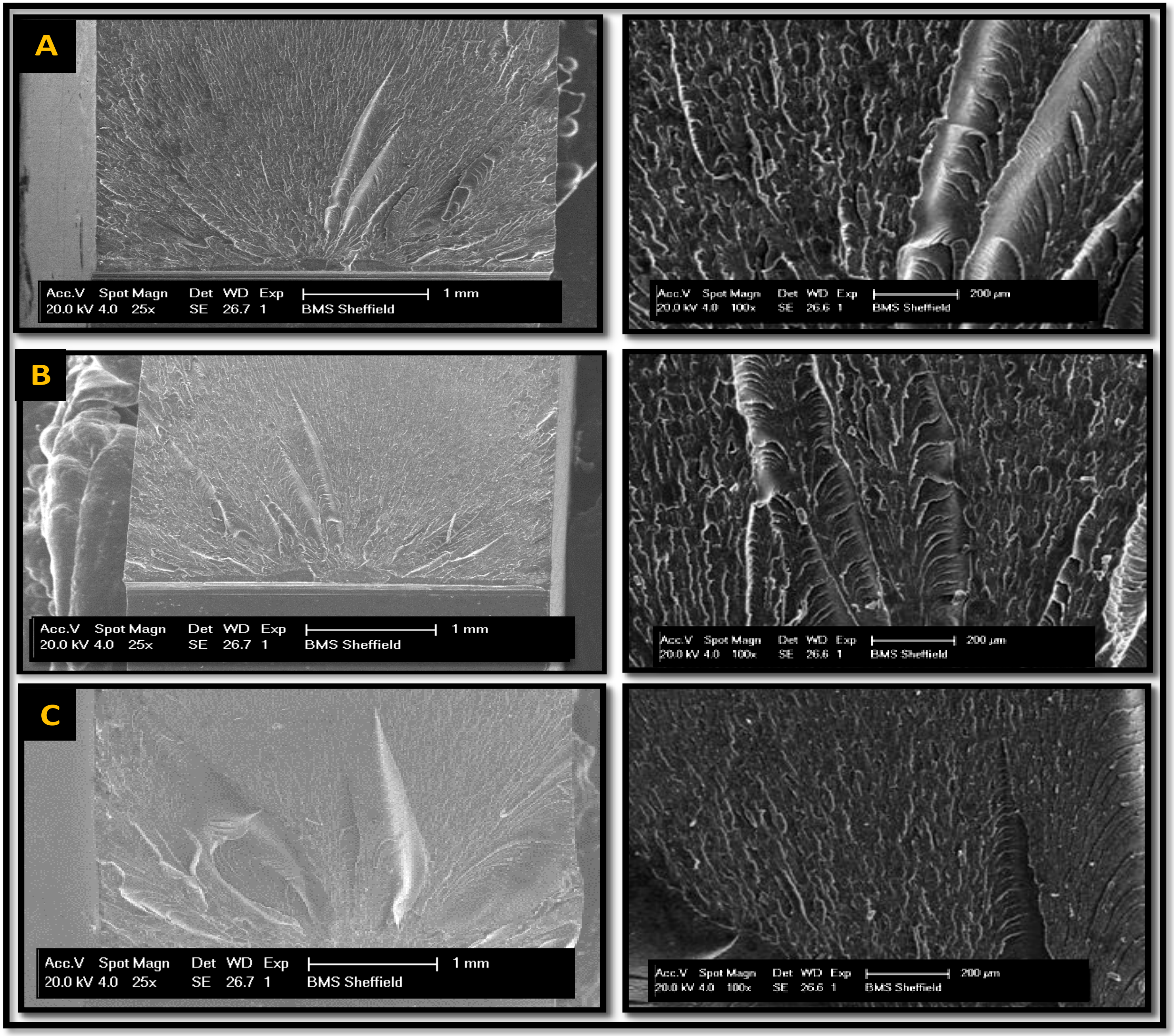


Figure (7-9): SEM of fractured surfaces of the studied material with 0.25 mm radius notch. **A.** PEEK-Optima® thermo-pressed at mould temperature of 175 °C; **B.** 200 °C; and **C.** milled PEEK-Juvora™

Impact strength: Generally, there was no statistically significant difference ($P>0.05$) between the impact strength of the PMMA processed by heat-cured water-bath, with a mean value of 2.3 (±0.2) KJ/m^2, and that of PMMA processed by thermo-press technique, at 2.2 (±0.1) KJ/m^2. However, there was a statistically significant difference in the impact strength of the PMMA, the PEEK-Optima® NI1 processed by denture injection method ($P<0.001$), and the PEEK-Juvora™ processed by CAM production method ($P<0.05$).

Statistically there were a significant differences ($P<0.05$) in the impact strength of the PEEK-Optima®NI1 polymer processed at different mould temperatures. There was a statistically significant difference in impact strength between the PEEK thermo-pressed at mould temperature of 100 °C below the PEEK T*g*, with mean value of 5.7 (±0.4) KJ/m^2, ($P<0.05$), and the PEEK thermo-pressed at mould temperatures above the PEEK T*g* (150 and 200 °C), with mean values of 5 (±0.4) and 4.8 (±0.4) KJ/m^2 respectively. However, there was no statistically significant difference ($P>0.05$) compared to that thermo-pressed at 175 °C mould temperature, at 5.3(±0.5) KJ/m^2 mean value. Among the PEEK-Optima® polymer samples thermo-pressed at mould temperature above the PEEK T*g* at 150, 175, and 200 °C no statistically significant differences ($P>0.05$) were identified.

However, statistically significant differences ($P<0.05$) was identified between PEEK-Juvora™ processed by CAM production method with an impact strength mean value of 4 (±1) KJ/m^2, and PEEK-Optima® thermo-pressed at 100 and 175 °C mould temperature, and also the PMMA that processed by different techniques. Yet, no significant difference (P>0.05) was identified between PEEK-Juvora™ and PEEK-Optima® thermo-pressed at 150 and 200 °C mould temperatures.

Absorbed energy: Generally, statistically significant differences (P≤0.001) were identified between the absorbed energy of the PMMA sample processed by heat-cured water-bath, with a mean value of 0.063 (±0.004) Joules and that of thermo-pressed PMMA of 0.074 (±0.004) Joules. Also, there was a statistically significant difference between the absorbed energy of the PMMA processed by both techniques and that of the PEEK-Juvora™ (P<0.05) processed by CAM production method, of 0.123 (±0.029) Joules. In addition, the absorbed energy of PMMA was significant (P≤0.001) compared to that of the PEEK-Optima® NI1 processed by denture injection method, at 100, 150, 175, and 200 °C of 0.174 (±0.012), 0.156 (±0.013), 0.169 (±0.017), and 0.150 (±0.012) Joules respectively.

In addition, no statistically significant differences (P>0.05) were identified in the absorbed energy of the PEEK-Optima® polymer samples processed at different mould temperatures except (P<0.05) in the case of that thermo-pressed at 100 °C mould temperature of 0.174 (±0.012) Joules, and that at 200 °C mould temperatures of 0.150 (±0.012) Joules. Yet, PEEK-Juvora™ showed significant difference (P<0.05) from all the tested materials except (P>0.05) in the case of the PEEK-Optima® thermo-pressed at 150 and 200 °C mould temperature.

Visual inspection revealed that most of the PMMA resin fractures were brittle, and under scanning electron microscopy (SEM), these brittle fractures exhibited well-defined, flat, compact, and organised surface fractures, whereas on the PEEK-

Optima®NI1 and PEEK-Juvora™ there were semi-brittle and intermediate fractures that presented disorganized and jagged surfaces. However, both types of PEEK presented irregular surface patterns when compared to PMMA, with a high number of grooves in the brittle fractures and presence of crazing in the intermediate fractures; figures (7-8) and (7-9).

7.1.3. Discussion

Continuous efforts have been made to decrease the risk of denture fractures by increasing dental material's strength. This has been done by adding filling materials to reinforce the denture material (Doğan *et al*., 2008; Foo *et al*., 2001); or by changing the chemistry of the polymers by co-polymerization and cross-linking (Misch, 2014); or by incorporation of new techniques to the dental field and manufacture of novel materials with increased resistance to fractures (Miyazaki *et al*., 2009). One technique that has been recommended to improve the physical properties of dentures is injection moulding (Foo *et al*., 2001).

In this study, the sensitivity of PEEK-Optima®NI1 and PEEK-Juvora™ as a denture base in the presence of notches under impact conditions was reported using the Izod impact test. This was compared to the sensitivity of conventional PMMA processed by both heat-cured and thermo-pressed methods.

Comparisons of impact strength values among the studied groups showed that the PMMA presented lower impact values compared to the PEEK polymer. This result may be attributable to incomplete polymerization within the chemical composition of PMMA, even after processing (Johnson *et al*., 1993). Meanwhile, PEEK has a strong chemical structure in comparison with the PMMA resins, and this may have impacted the results (Tung and Dynes, 1987; Kurtz, 2011a). Another hypothesis to explain the higher impact strength value presented by PEEK polymer relates to the type of cross-linking agent within its chemical composition (Talbott *et al*., 1987). Nevertheless, the impact strength of the thermo-pressed PEEK decreased progressively with increases of moulding temperature above the PEEK T*g* (Cebe *et al*., 1987).

In the current study, the PEEK-Optima® exhibited reduction in impact strength as the mould temperature increased. The results on impact strength testing showed an increase for injection moulded specimens with decrease of mould temperature below the PEEK T*g* at 100 °C (PEEK T*g* = 143 °C). This is not too surprising, since the PEEK T*g* cover a range that is frequency amorphous, which leads to more elastic behaviour. However, when the mould temperature was increased, above the PEEK T*g* a tendency for impact strength to decrease was observed in the 150, 175, 200 °C test groups. It may be seen that at all elevated temperatures the PEEK material appears to have less resistance to fracture (Rae *et al*., 2007). The samples exhibited no obvious strength deriving from the notch effect, unlike in specimens at lower mould temperature. This reduction could be due to the injected PEEK exhibited more crystalline behaviour at elevated mould temperatures which provide the necessary time for the crystals to align in symmetrical rather than amorphous pattern.

The injection moulded PEEK specimens were found to have higher impact strength values than the thermo-pressed and compression moulded PMMA specimens, and this might be due to the molecular orientation of novel PEEK backbone chains caused by the injection moulding process (Kurtz, 2011b). Hamanaka *et al*. may support these findings since they found that all the injection moulded thermoplastic resins in their study had significantly higher impact strength compared to the conventional PMMA (Hamanaka *et al*., 2011).

It seems that unfilled PEEK material, whether injected or machined, may influence the product's mechanical properties. Most of such material products are made by injection moulding which uses pellets or granules of thermoplastic polymers. Due to the insignificant difference in crystallinity of the polymer when prepared at different moulding temperatures, the strength of PEEK material may mainly rely on crystalline orientation.

The impact strength of PEEK-Juvora™ with a notch weakening effect and machined by CAM was found to be lower than that of injected PEEK-Optima®NI1. This could be related to the highly crystallinity of Juvora material due to the annealing process carried out for CAM purposes (Kurtz, 2011b). This is done to provide a stable material, and to release stress that could be generated during the CAM process and which would affect the product's dimensional accuracy. The results of this testing may support our original hypotheses as the higher moulding temperatures may affect the strength of the PEEK as a denture base material. The lowering of the impact strength may result from the increase in crystallinity of this material which generally may result either from the use of high moulding temperature for the thermo-pressed PEEK type (Chivers and Moore, 1994), or the annealing technique for machining the PEEK. Factors such as different material composition and the time and type of polymerization used in the experiments must also be considered, as they are directly responsible for inter-chain force and polymer chain arrangements (Memon *et al*., 2001; Kurtz, 2011b).

The absorbed energy at the maximum impact strength of the thermo-pressed PMMA samples was superior to that of the heat-cured water-bath PMMA. This may be related to the different processing methods and the composition of these materials (Van Noort, 2013). The PEEK-Optima® NI1, when processed by denture injection method at different mould temperatures above the PEEK T*g* retained the same energy absorbance. In this respect the PEEK-Optima®NI1 was superior to the PMMA processed by the two different techniques. This may be due to the PEEK's backbone morphology (Kurtz, 2011c) compared to the chemical structure of the (Anusavice *et al*., 2013; Van Noort, 2013). The PEEK-Juvora™ specimens absorbed less energy than the PEEK-Optima® samples thermo-pressed at 100 and 175 °C, while they revealed the same ability for energy absorbance as those thermo-pressed at 150 and 200 °C mould temperatures.

Fracture surface morphologies were examined with a scanning electron microscope (SEM). After fracturing, the specimens were dissected, mounted, and sputtered with gold to promote electrical conductivity to reduce charging, and then micrographs were taken. Regarding fracture morphology, the number of semi-brittle fractures occurring in the PEEK specimens as the mould temperature increased was higher than the number of such fractures at 100 °C below the PEEK T*g*. Polymers with matrixes that have amorphous components of low glass transition temperatures become tougher with the presence of Izod impact energy (Brillhart and Botsis, 1994). It is important to note that PEEK at 100 °C exhibited a high number of intermediate fractures, perhaps because it suffers huge plastic deformation, and probably absorbs more energy during an impact strength test. According to Pawlak and Galeski, elastic cavitation may occur in semicrystalline polymers with crystals of higher resistance to the onset of plastic behaviour, while plastic deformation occurs in crystals of lower plastic resistance

(Pawlak and Galeski, 2005). This explanation is supported by the fracture surface appearance of the notched geometries, which showed that propagation of cracks through crazed regions left behind patchwork morphology. However, a number of semi-brittle fractures were found in the PEEK-Juvora™. These exhibited a notch weakening deformation mechanism with cracking growth behaviour that led to final fracture (Sobieraj and Rimnac, 2011), and a semi-brittle behaviour with very little plastic deformation impact energy. This may be related to the annealing process for the PEEK-Juvora™ for CAM machining production method, and this could increase PEEK's crystalline percentage which in turn would lead to a more brittle product (Invibio, 2004a). On the other hand, PMMA showed a number of brittle fractures and this may reflect the polymer's fracture surface characteristics and parameters, as the polymer resins can primarily demonstrate brittle fractures (Reinhart, 1987; Merrett *et al*., 2002; Callister and Rethwisch, 2007).

7.1.4. Conclusion

The following conclusions are drawn from this study:

1. The machined PEEK-Juvora™ and thermo-pressed PEEK-Optima®NI1 had higher Izod impact strength than that of PMMA processed by two techniques.

2. There were no differences in terms of Izod impact strength between the PEEK-Optima® samples thermo-pressed at different mould temperatures above the PEEK T*g* of 150, 175, and 200 °C.

3. The PEEK-Juvora™ and PEEK-Optima® had superior levels of absorbed Izod impact fracture energy than that of PMMA processed by two techniques.

4. Under SEM, a number of semi-brittle fractures were found in the PEEK-Juvora™ sample, and in the thermo-pressed PEEK-Optima® specimens the number of semi-brittle fractures increased as the mould temperature increased above the PEEK T*g*. Meanwhile, a high number of intermediate fractures was noticed in the PEEK-Optima® thermo-pressed at 100 °C mould temperature below the PEEK T*g*.

To sum up, although the PEEK-Optima®NI1 could be considered as a notch weakening material as it is processed at mould temperatures above the PEEK T*g*, the impact strength of PEEK-Optima®NI1 and machined PEEK-Juvora™ as a denture material was superior to that of the conventional PMMA.

7.2. Flexural Properties (4-Point Bending)

Aim

This study aims to determine the flexural properties of PEEK as a denture base material using 4-point bending test compared to conventional PMMA and Co-Cr denture material.

Objectives

The objectives of this present study are to evaluate the flexural behaviour of:

a. PEEK-Optima®NI1 thermo-pressed by denture injection method with different mould temperatures.
b. PEEK-Juvora™ machined by CAM.
c. PEEK materials and to compare with that of conventional PMMA and Co-Cr denture material.

7.2.1. Materials and Methods

Mould and Sample Preparation for 4-Point Test

Four-point test samples were prepared according to ISO 1567 (n=10). Rectangular wax blocks of 12.00 mm X 4.00 mm X 66 mm width, depth, and length respectively were used to create uniform silicone mould spaces for the wax samples for conventional processing, injection moulding, and casting of materials. Specimens were moulded for thermo-pressing materials, and invested for Co-Cr alloy. The preparation, flasking, and mould injection of wax specimens were implemented as described for the impact test. Co-Cr dental alloy was an additional conventional denture material used for comparison in the 4-point bending test. Ten rectangular wax blocks of 10.00 mm X 2.50 mm X 65 mm width, depth, and length respectively were used to create uniform silicone mould spaces for metal casting samples. The wax replicated samples were coated with surface tension liquid and invested using phosphate bonded investment material, and left to set for one hour initially. After the initial set, the casting ring was placed in an oven set at 900 ˚C for 2 h to burnout the wax.

Processing Procedure

All the processing methods for the tested materials followed the Impact test procedures. For the injection moulding technique, the specimens were flasked according to the manufacturer’s instructions using PEEK-Optima® granules and brecrystal PMMA materials. The Thermopress 400 injection system was used, in addition to water-bath heat-curing of PMMA. Co-Cr alloy was used to fabricate the metal samples (as previously mentioned in general materials and methods in chapter three). After casting, the casting ring was allowed to cool on the bench overnight.

The specifications for the denture base polymers followed ISO recommendations (1567-2001), table (7-4). However, the test was static and carried out in dry conditions, whilst the length of 65 (±0.2) mm was used as a variation of the final dimensions.

Table (7-4): Specifications for denture base resins (Chitchumnong *et al.*, 1989)

Specimen Size	64.00 x 10.00 (±0.3) x 2.50 (±0.03) mm
Storage	In water at 37 (±1) ˚C for 50 (±2) hours
Crosshead Speed	5 (± 1) mm/min
Span length	50.0 (±0.1) mm
Water bath Temperature	37 (±1) ˚C

CAD/CAM Milling Technique

The designed file for the 4-point bending testing specimen created using the SketchUp 3D modeling program was exported to the milling machine to be manufactured into PEEK specimens as described for the impact test, and figure (7-2).

Finishing and Polishing

Co-Cr samples were sandblasted to remove the adherent investment material and the green oxide layer coating the surface after the casting procedure. Then, all the test samples of PMMA, PEEK, and Co-Cr were machine-polished using 600 and 1200 grit metallographic grinding papers to standardise the study sample dimensions, figure (7-10). The Co-Cr specimens were finally polished electronically, and the dimensions were measured using digital calipers of 0.02mm accuracy. All the specimens were stored in distilled water for 50 (±2h) at 37 (±1 °C) before implementing the flexural strength test, figure (7-11) and (7-12).

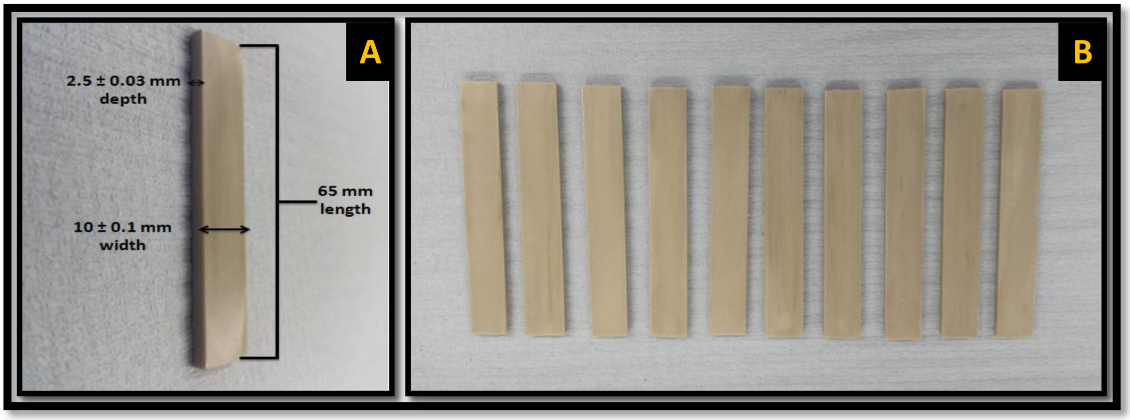


Figure (7-10): A. 4-point bend test sample dimensions; **B.** specimens prepared for testing procedure

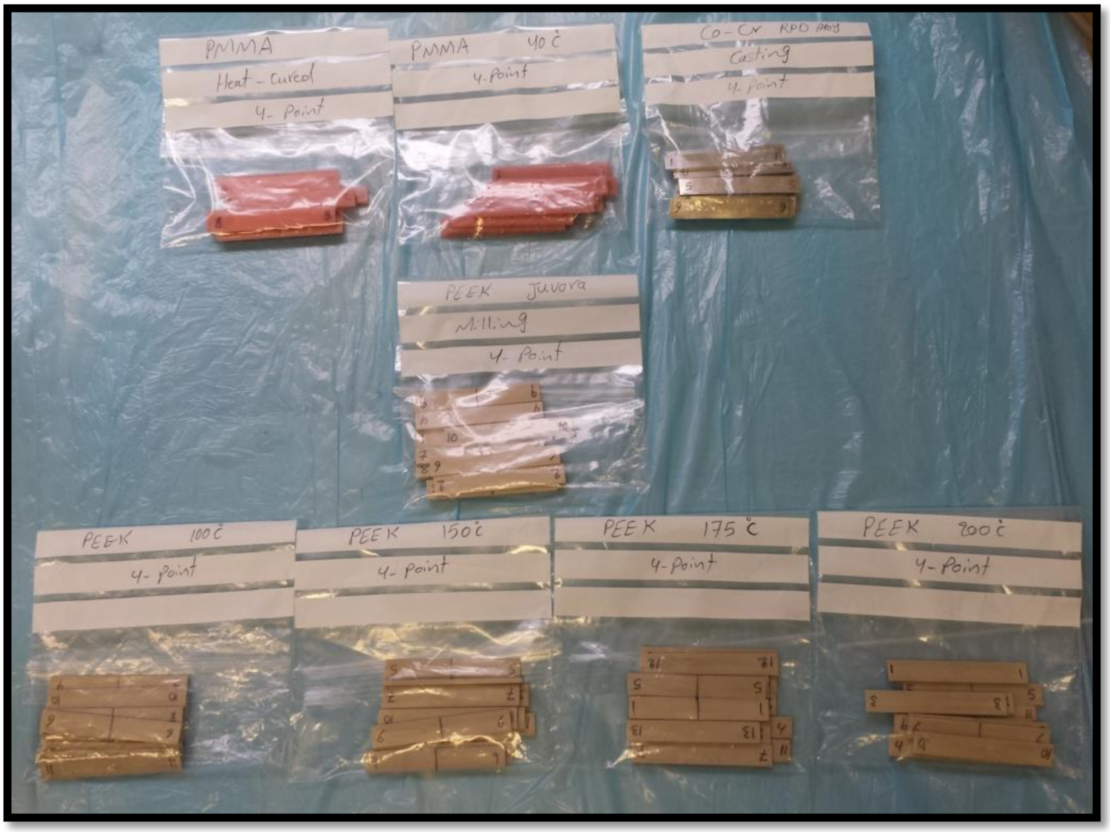


Figure (7-11): 4-point bending sample prepared for water storage

Figure (7-12): Storage of the sample in water for 50 (±2h) at 37 (±1 °C) before the testing procedure

Testing Procedure

Figure (7-13) shows the steps and procedures for implementing the 4-point bend test. Mechanical testing of the sample was carried out using a Lloyds universal machine of 2.5 KN loading capacity. A flexural test jig with two loading plungers and two polished cylindrical supports of 3.2 mm in radii was used. The supports were parallel to within 0.1 mm and at right angles to the longitudinal centreline, and distance between the support centres of 50 (±0.1) mm prior to force application the specimen was aligned with simultaneous contact of the plungers to the loading bars. This was accomplished by using pressure spot indicator paste to provide symmetrical load distribution and avoid any torsion which might have increased the stress levels in the beam. The force on the loading plungers was increased uniformly from 5 N using a constant crosshead speed of 5 (±1) mm /min until the load on the specimen reached 100 N.

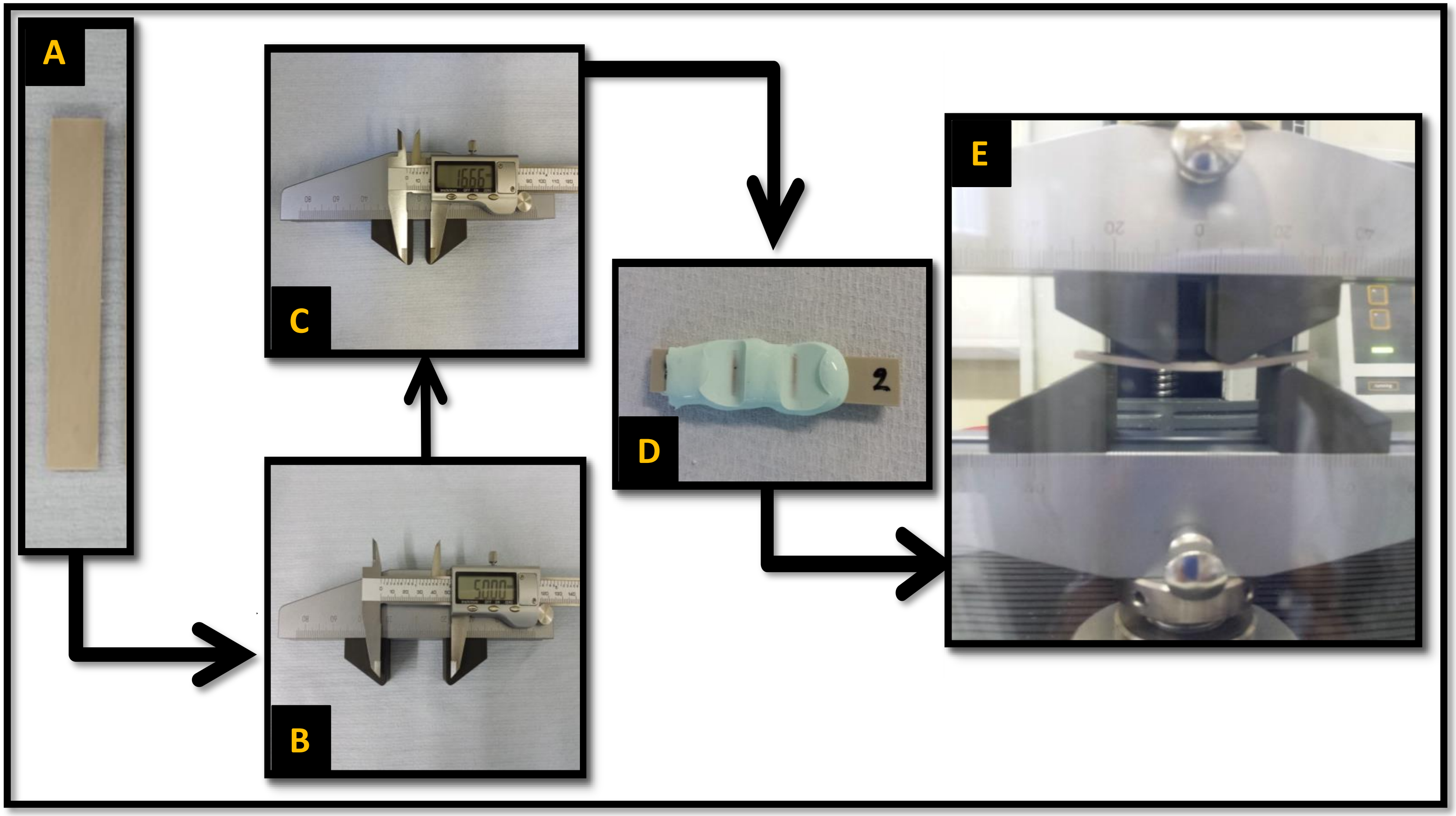


Figure (7-13): A. 4-point bend test specimen; **B.** distance between centres of the lower supports; **C.** distance between centres of the upper plungers; **D.** pressure spot indicator; **E.** PEEK specimen under 4-point loading noses showing the deflection of the specimen

7.2.2. Results

The statistical methods used to analyse the results included analysis of variation (ANOVA), and the test performed at a confidence level of 95 % and significant P-value of ($P \leq 0.05$).

Exploratory analysis was conducted in a series of steps, and the flexural properties of the PEEK-Optima® injected at 100, 150, 175 and 200 °C mould temperatures, machined PEEK-Juvora™, and the conventional Co-Cr and PMMA base materials were compared via analysis of variance (ANOVA), see appendix part (F).

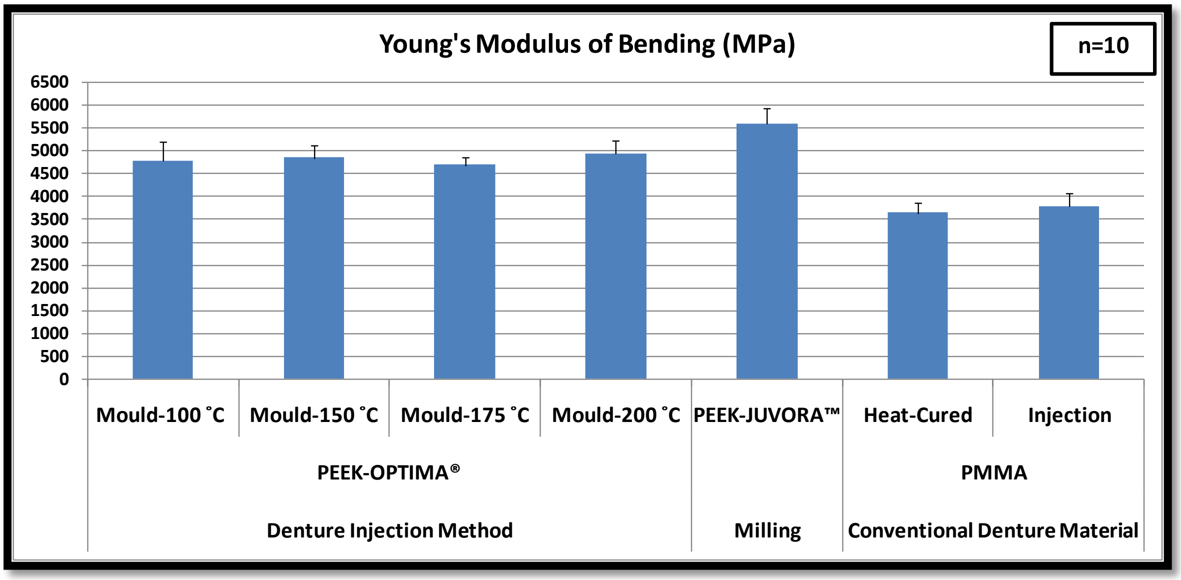


Figure (7-14): The mean distribution of the elastic modulus of the tested polymer materials

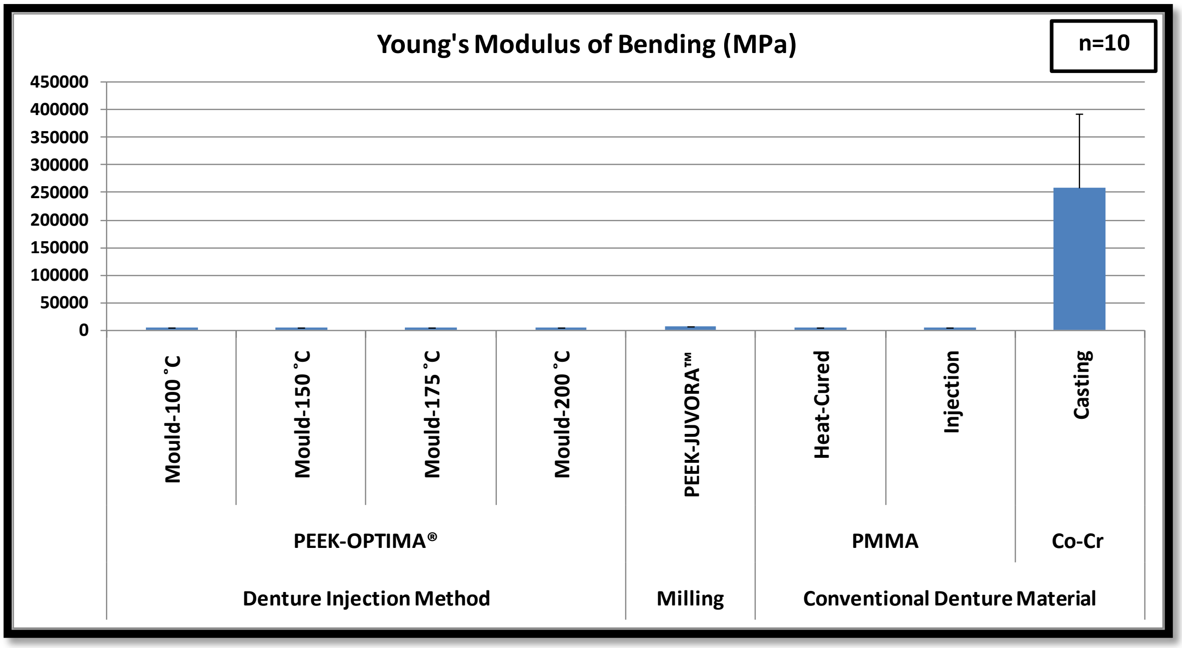


Figure (7-15): The mean distribution of the elastic modulus of the tested polymer materials compared to the Co-Cr base alloy

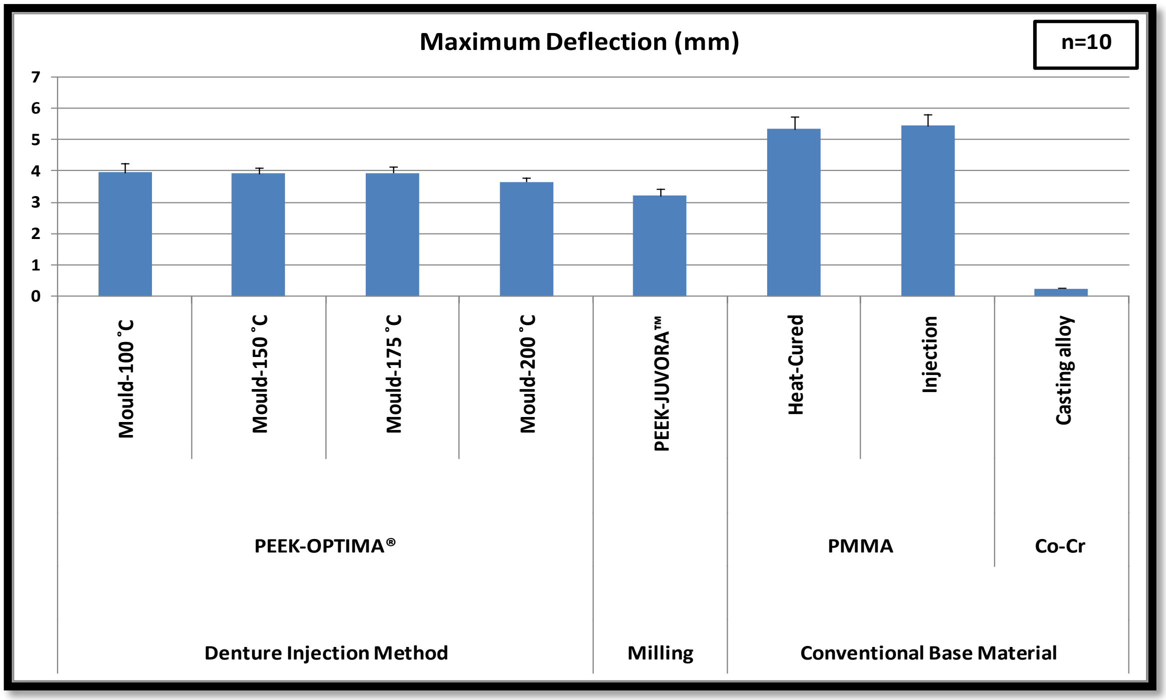


Figure (7- 16): The mean distribution of the maximum deflection of the tested polymer materials compared to the Co-Cr base alloy

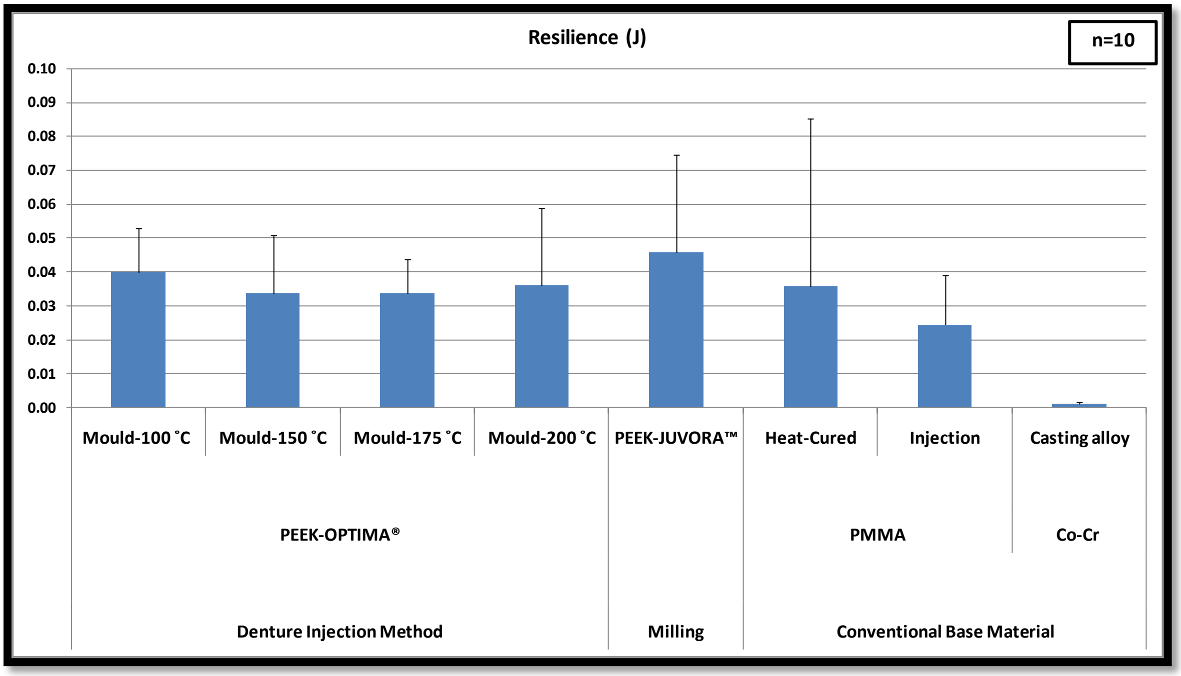


Figure (7-17): The mean distribution of the maximum deflection of the tested polymer materials compared to the Co-Cr base alloy

Generally, the flexural properties were identified among the tested materials under maximum load of 100 N.

Young's modulus: there was a statistically significant difference ($P<0.05$) between the modulus of elasticity of the Co-Cr of 259044 (±134694) MPa compared to that of the PEEK and PMMA tested material, figure (7-14). However, there was no statistically significant difference ($P>0.05$) between the modulus of elasticity of the PMMA processed by heat-curing, with mean value of 3632 (±228) MPa, and that of thermo-pressed PMMA, at 3784 (±290) MPa. There was a statistically significant difference ($P<0.001$) between the modulus of elasticity of the PMMA and that of the PEEK-Optima® processed by denture injection method at different mould temperatures, and that of the PEEK-Juvora™ processed by CAM production method, of 5591 (±329) MPa, figure (7-15). On the other hand, statistically there were no significant differences ($P>0.05$) between the modulus of elasticity of the PEEK-Optima® polymer that processed at different mould temperatures of 100, 150, 175, and 200 °C, at 4773 (±420) MPa, 4840 (±275) MPa, 4686 (±163) MPa, and 4936 (±278) MPa respectively. Statistically significant differences ($P<0.05$) found in the modulus of elasticity of the PEEK-Juvora™ processed by CAM production method and that of PEEK-Optima® thermo-pressed at different mould temperatures.

Flexural deflection: there was a statistically significant difference in the flexural deflection of the Co-Cr of 0.26 (±0.02) mm compared to that of PEEK and PMMA tested material ($P<0.001$), figure (7-16). However, there was no statistically significant difference ($P>0.05$) in flexural deflection between the PMMA processed by heat-cured water-bath, at mean value 5.4 (±0.4) mm, and that thermo-pressed at 40 °C, at 5.5 (±0.4) mm. Meanwhile, there were statistically significant differences ($P<0.001$) in flexural deflection between the PMMA and the PEEK-Optima® processed by denture injection method at different mould temperatures, and also compared to the PEEK-Juvora™ processed by CAM production method, of 3.2 (±0.2) mm. Statistically there was no significant difference ($P>0.05$) in flexural deflection between the PEEK-Optima® polymer processed at different mould temperatures except($P<0.05$) between the PEEK-Optima thermo-pressed at 200 °C of 3.7 (±0.1) mm, 150 °C, at 3.9 (±0.4) mm, and 175 °C, at 4 (±0.2) mm. The PEEK-Juvora™ processed by CAM production method showed a statistically significant difference ($P<0.001$) in flexural deflection compared to PEEK-Optima® thermo-pressed at different mould temperatures.

Resilience: statistically there was a significant difference (P<0.05) in the resilience of the Co-Cr of 0.001 (±0.0007) Joules compared to the PEEK material and the PMMA thermo-pressed at 40 °C. There was no statistically significant difference (P>0.05) in resilience between the PMMA processed by heat-cured water-bath, at 0.36 (±0.05) Joules and thermo-pressed PMMA, at 0.25 (±0.02) Joules mean value. Also, there was a statistically non-significant difference (P>0.05) in the resilience between the PMMA and the PEEK-Optima® processed by denture injection method at different mould temperatures, and also in comparison to the PEEK-Juvora™ processed by CAM production method, of 0.46 (±0.03) Joules. In addition, there was no significant difference (P>0.05) in the resilience between the PEEK-Optima® polymer processed at different mould temperatures, of 100, 150, 175, and 200 °C, at 0.40 (±0.01), 0.34 (±0.02), 0.34 (±0.01), and 0.36 (±0.02) Joules respectively. Furthermore, there was statistically non-significant difference (P>0.05) in resilience between the PEEK-Juvora™ processed by CAM production method and PEEK-Optima thermo-pressed at different mould temperatures, figure (7-17).

7.2.3. Discussion

Polymethylmethacrylate (PMMA) resins are the most commonly used materials for denture construction (Ali *et al*., 2008), although different materials have been introduced (Kanie *et al*., 2004). Nevertheless, PMMA resin has low fracture strength (Ali *et al*., 2008).Generally denture wearers are older with potentially less muscle control (Misch, 2014), which can lead to accidental denture fractures (Kanie *et al*., 2004; Doğan *et al*., 2008).

Despite the fact that many methods have been established to test the flexural strength of denture base polymers, it seems that none of these methods has demonstrated very accurate values (Chitchumnong *et al*., 1989). According to pilot study under biaxial fractural strength (BFS), the PEEK polymer exhibited no tendency to fracture in fatigue testing; however, plastic deformation was observed and further investigation of PEEK's flexural behaviour is required.

Four-point flexural testing followed international standards for polymer materials, including ISO 1567:2001 dentistry denture base polymers. This is the most common technique for measuring flexural properties of denture bases (Reis *et al*., 2006).

In this study, a loading force was applied to specimens at a crosshead speed of 5 mm/min based on studies by Chitchumnong *et al*. (Chitchumnong *et al*., 1989) and Barbosa *et al*. (Barbosa *et al*., 2007). In this study the maximum load of 100 N was applied to the specimens and the flexural behaviour of the tested sample was evaluated with no tendency to fracture.

The results demonstrated that the minimal flexural strength was not achieved since the sample did not fracture under the maximum load of 100 N. However, flexural properties such as Young's modulus (flexural modulus, modulus elasticity), deflection at the maximum load, and resilience were evaluated.

The maximum bend under 100 N for all the tested material demonstrated a higher mean value than that required by ISO 1565 at fracture. This could be considered as indicating that the tested materials are suitable for clinical use. However, it is essential to examine other flexural properties before making final decision.

The Young's modulus or modulus of elasticity is the resistance of an object to being deformed permanently when a force is applied to it. No difference in the modulus of elasticity of PMMA was noticed in samples processed by the two techniques. However, the Young's modulus of the PEEK-Optima® thermo-pressed at different mould temperatures was higher than that of the PMMA. Meanwhile, the elastic modulus of the machined PEEK-Juvora™ was higher than that of the injected PEEK-Optima®. However, no differences in the flexural modulus were found among the PEEK-Optima® thermo-pressed at different mould temperatures. According to ISO standardisation, the modulus of elasticity of the denture base material should be 2000 MPa (Takabayashi, 2010). Therefore, all the tested materials correlated with the standard values. However, the PEEK polymer had higher modulus of elasticity than the tested PMMA.

Under a load of 100 N and across the tested groups, the maximum deflection was noticed with the PMMA samples, while the Co-Cr sample exhibited the lowest deflection. The PEEK-Juvora™ samples exhibited inferior deflection compared to PEEK-

Optima® thermo-pressed at different mould temperatures. Nevertheless, the PEEK-Optima® thermo-pressed at 200 °C mould temperature had the lowest deflection compared to that thermo-pressed at 150 and 175 °C mould temperatures.

Resilience is the ability of a material to return to its original shape after the removal of a stress. There was no difference in resilience between the PEEK-Optima® and the CAM PEEK-Juvora™. Also, there was no difference in resilience between the PEEK polymer and the PMMA resin material. This is leading to the fact that these polymers release the stress exerted on them as soon as the load is removed. Meanwhile, the Co-Cr casting alloy had the lowest resilience. This may relate to the stress that is retained in the sample and which is expressed clearly by the tested sample keeping the bent shape after load removal. This may in turn affect the underlying tissues when a denture base made of Co-Cr is under load.

7.2.4. Conclusion

Under the maximum load of 100 N, the following conclusions are drawn from this study:

1. The Co-Cr had higher Young's modulus than the other tested materials.
2. The machined PEEK-Juvora™ had higher Young's modulus than the injected PEEK-Optima®NI1.
3. The PMMA sample exhibited the maximum bend deflection, while the Co-Cr exhibited the lowest bend deflection.
4. The maximum bend deflection of the PEEK-Juvora™ was lower than that of the PEEK-Optima®NI1 thermo-pressed at different mould temperatures.
5. The PEEK-Optima® NI1 sample injected at 200 °C mould temperature was lower than that injected at 150 and 175 °C mould temperatures above the PEEK T*g*.
6. The Co-Cr had inferior resilience ability than the machined PEEK-Juvora™, thermo-pressed PEEK-Optima®NI1 and PMMA processed by the two techniques.

7.3. Tensile Strength

Aim

This study aims to determine the tensile strength characteristics of PEEK as a denture base compared to conventional PMMA denture material.

Objectives

The objectives of this present study are to evaluate the tensile strength of:

a. PEEK-Optima®NI1 thermo-pressed by denture injection method at different mould temperatures.
b. PEEK-Juvora™ machined by CAM.
c. PEEK materials in comparison with that of conventional PMMA

7.3.1. Materials and Methods

Mould and Sample Preparation for Tensile Strength Test

Tensile test samples were prepared according to ISO 527-1 and 2: 2012, (n=10). Flat dumbbell-shaped specimens were prepared of 16 (±1) mm lengths; 3 (±0.2) mm widths; and 2 (±0.2) mm thicknesses at the parallel segment. Figure (7-18) shows the dimensions used to create uniform silicone mould spaces for the thermoplastic test materials. Thermoplastic specimens were prepared by moulding and injection, PEEK-Juvora™ by milling. Wax specimen preparation, flasking, mould injection, and polishing were implemented as described for the impact and 4-point tests.

Processing Procedure

All the processing methods followed the Impact and 4-point test procedures. The injection of PEEK and thermo-press PMMA materials was carried out using the Thermopress 400 injection system and the water-bath for heat-cured PMMA. The specifications for denture base polymers followed ISO recommendations (527-1 and 2: 2012).

CAD/CAM Milling Technique

PEEK-JUVORA^{TM} blanks were milled using the Roland milling machine as described in previous sections, and the dimensions of the specimens were designed using 3D SketchUp software designer program, figure (7-19).

Tensile Testing Procedure

The measurements were taken using a universal testing machine with 50 mm grip-to-grip distance and 2.5 KN load cell at 25 °C. The ISO standards do not include guidelines for measurement of tensile strength under wet conditions. In the present study, therefore, tensile specimens, figure (7-20), were stored in water at 37 (±1) °C for 50 (±2) hours and testing was performed under dry conditions.

The ISO standards include a wide range of tensile strength testing speeds. Since the purpose of this test was to measure the tensile stress, and because the area of the parallel segment in the fabricated specimen was two-thirds of the standard specification (50 mm/min), the testing speed was set at 30 mm/min as a proportional reduction (Takabayashi, 2010). Based on the stress-strain curve, the tensile strength was determined by measuring the strength at the maximum stress; figure (7-21).

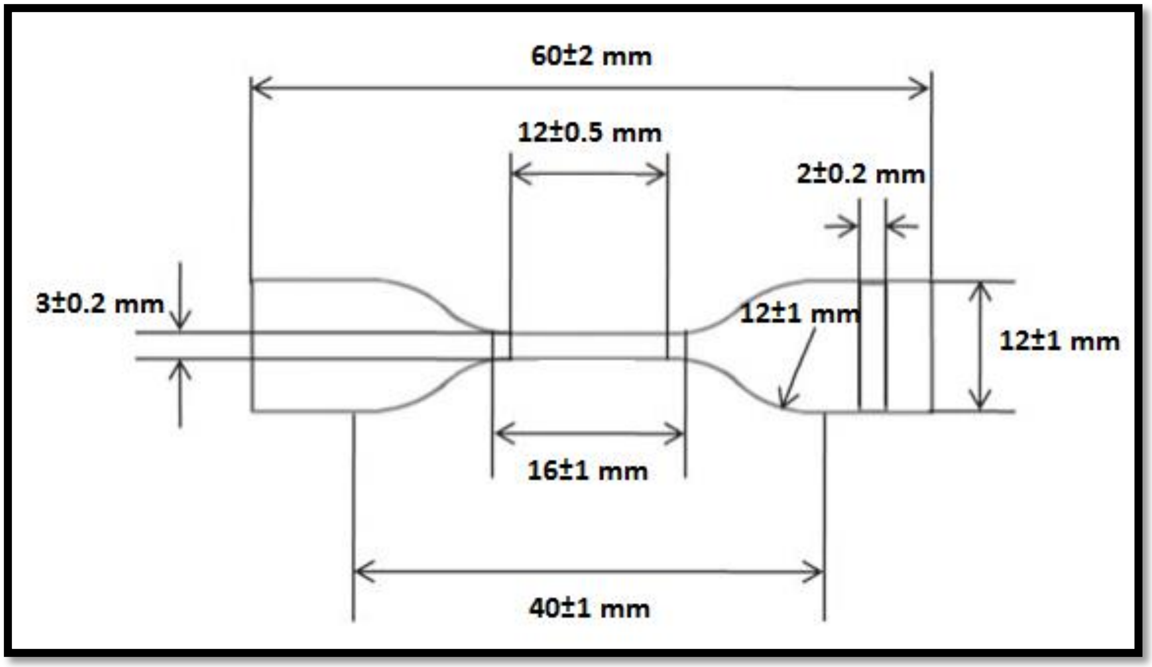


Figure (7-18): The specimen dimensions for the tensile test, overall length: 60±2 mm; gauge length: 12±0.5 mm; initial distance between grips: 40±1 mm; length of narrow parallel-sided portion: 16±1 mm; width of narrow parallel-sided portion: 3±0.2 mm; width at ends: 12±1 mm; thickness: 2±0.2 mm; and large radius: 12±1 mm

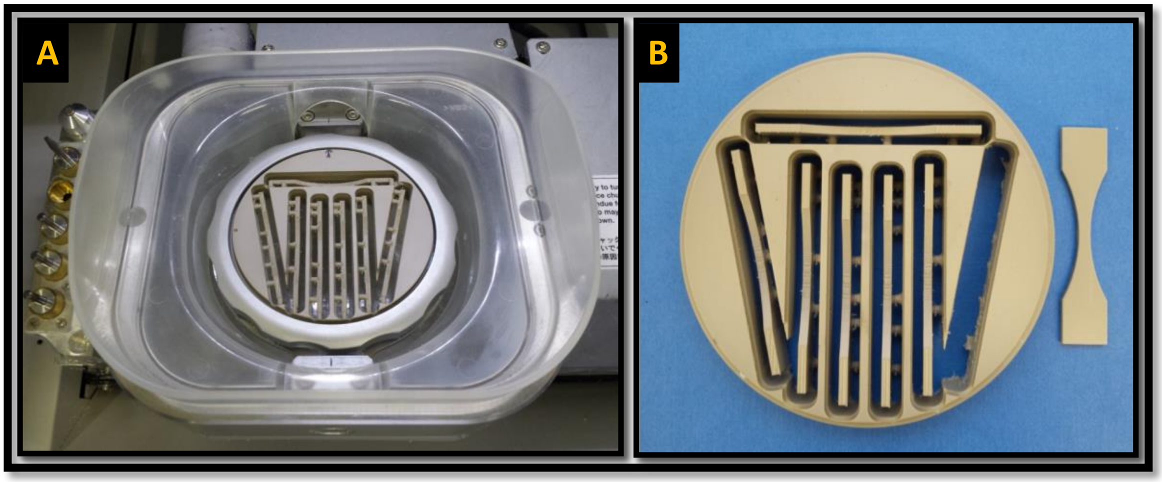


Figure (7-19): A. samples for tensile test fabricated using milling machine; **B.** tensile specimens made of PEEK-Juvora™

Figure (7-20): Tensile sample ready for testing. **A.** Conventional PMMA processed by heat-cured and thermo-pressing techniques; **B.** PEEK experimental samples fabricated using thermo-pressing technique and CAM production method

Figure (7-21): PEEK specimen undergoing tensile testing procedure

7.3.2. Results

Suitable statistical methods used to analyse and assess the results included analysis of variation (ANOVA), and the test performed at a confidence level of 95 % and significant P-value of ($P \leq 0.05$).

Exploratory analysis was conducted in a series of steps; the tensile strength, deflection and the load at break data of the PEEK-Optima® thermo-pressed at 100, 150, 175 and 200 °C mould temperatures, machined PEEK-Juvora™, and the conventional PMMA were compared via analysis of variance (ANOVA), see appendix part (G).

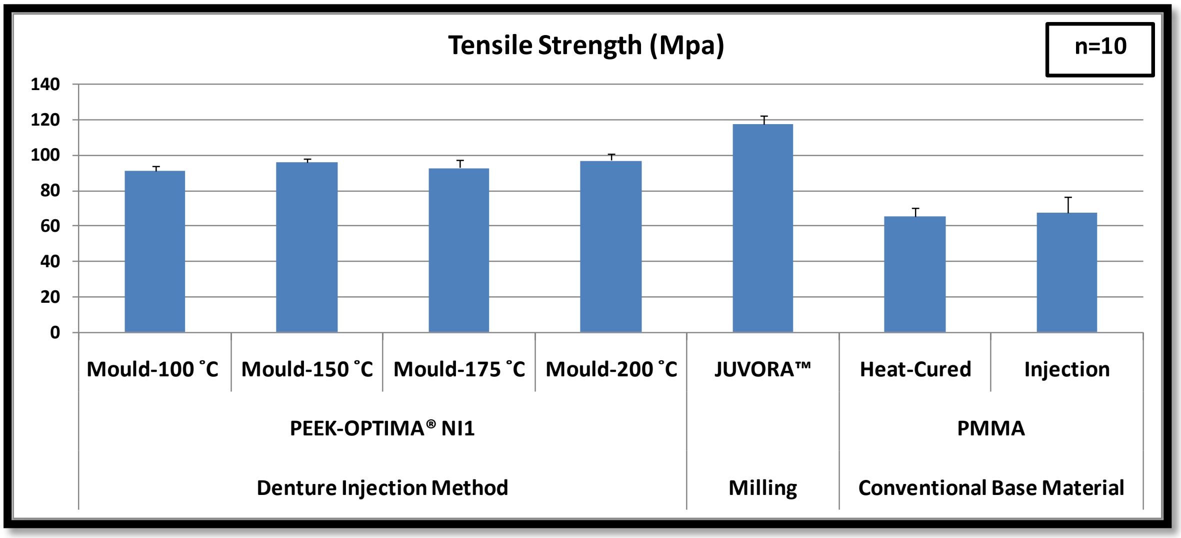


Figure (7-22): The mean distribution of the tensile strength of the tested materials

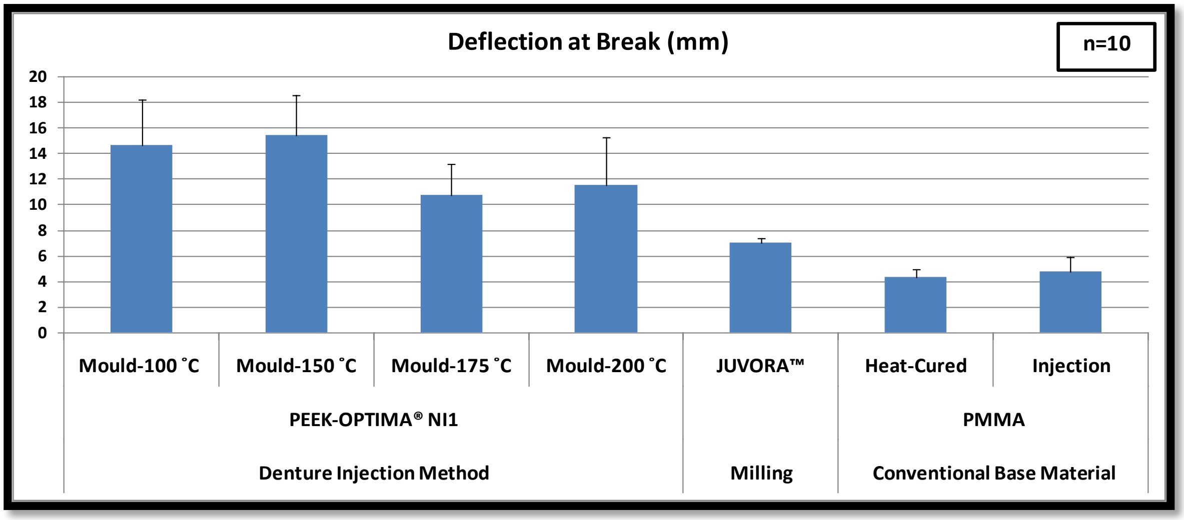


Figure (7-23): The mean distribution of the sample deflection of the tested materials at break

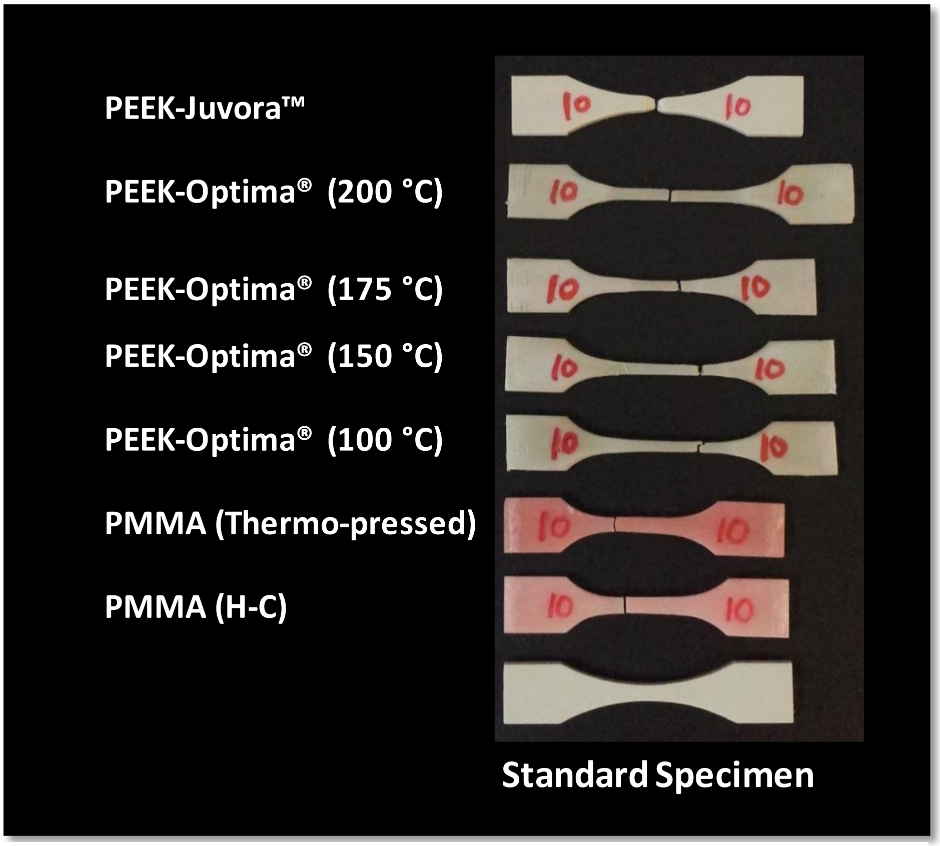


Figure (7-24): Specimens after tensile strength testing of non-metal denture base materials

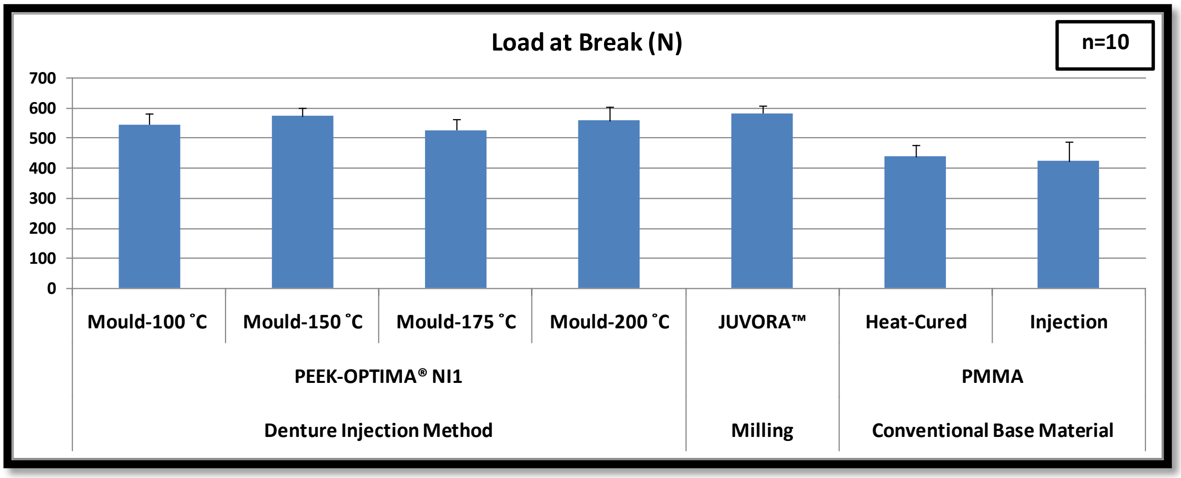


Figure (7-25): The mean distribution of the load needed for the tested materials to break under tensile testing

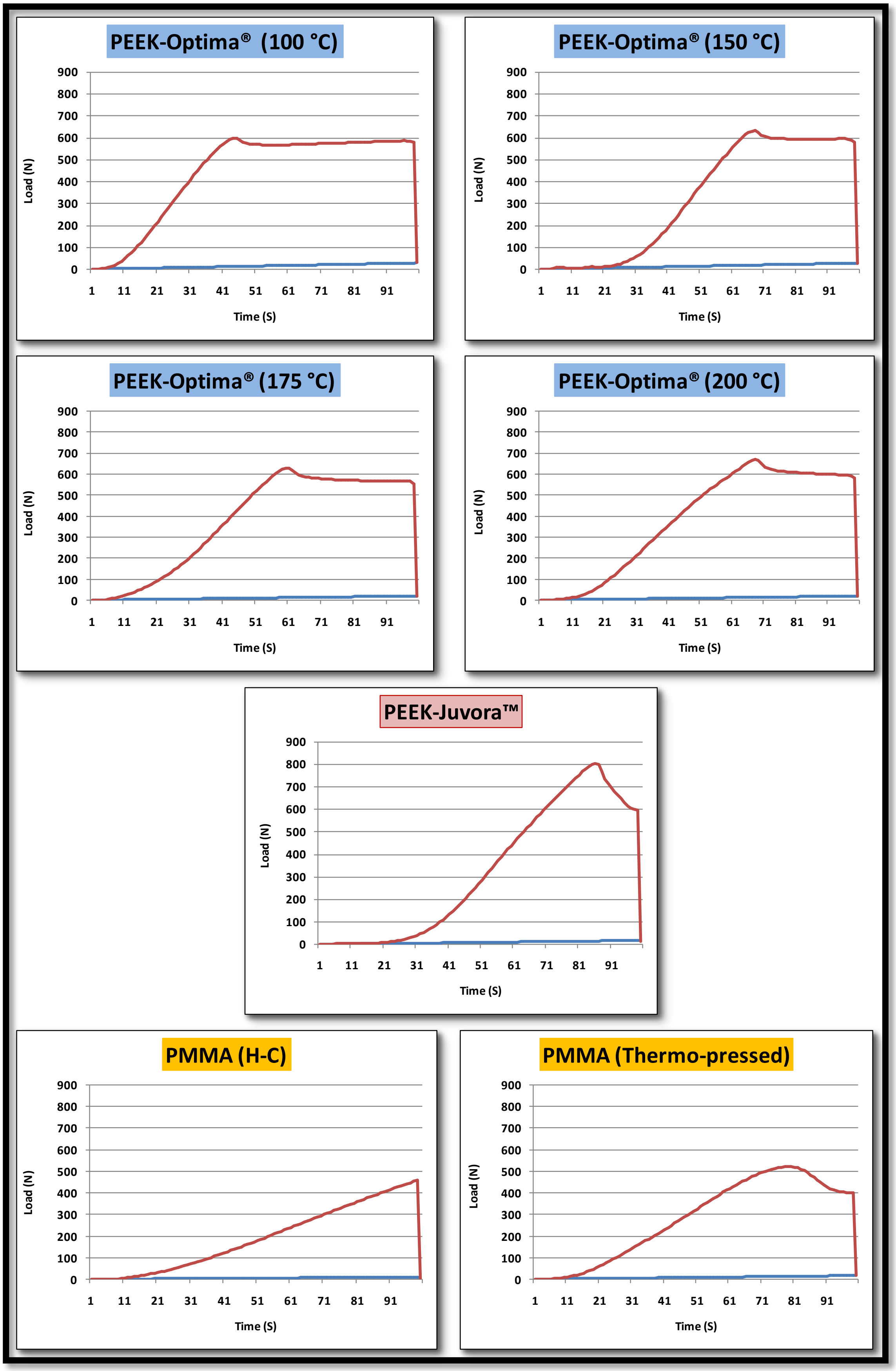


Figure (7-26): Diagram showing elastic deformation of the tested materials under tensile testing at the load of break

Tensile Strength: Figure (7-22) shows that there was a statistically significant difference (P<0.05) in the tensile strength value of PEEK polymer when compared with the conventional heat-cured and thermo-pressed Polymethylmethacrylate (PMMA).

Generally, there was no statistically significant difference (P>0.05) between the tensile strength of the PMMA processed by heat-curing and water-bath, at mean value of 65 (±5) MPa, and that processed by thermo-press technique, at 68 (±9) MPa. However, there were statistically significant differences in tensile strength between the PMMA and the PEEK-Optima® processed by denture injection method (P<0.001), and the PEEK-Juvora™ processed by CAM production method (P<0.001).

Statistically there were significant differences (P<0.05) in the tensile strength of the PEEK-Optima® polymer samples processed at different mould temperatures. There was a statistically significant difference (P<0.05) between PEEK that was thermo-pressed at mould temperature of 100 °C below the PEEK T*g*, with a tensile mean value of 91(±3) MPa, and the PEEK injected at mould temperatures above the PEEK T*g* (150 and 200 °C), with mean values of 96 (±2) and 97 (±4) MPa respectively. However, there was no statistically significant difference (P>0.05) compared to that injected at 175 °C mould temperature of 93 (±5) MPa mean value. There were no significant statistical differences (P>0.05) among the PEEK-Optima® polymer samples injected at mould temperatures above the PEEK T*g* (150, 175, and 200 °C).

PEEK-Juvora™ processed by CAM production method with a tensile strength mean value of 118 (±5) MPa exhibited statistically significant differences (P<0.001) in comparisons to

PEEK-Optima® thermo-pressed at different mould temperatures, and also in comparisons to the PMMA processed by the two different techniques.

Deflection at Break: Figure (7-23), there was no statistically significant difference (P>0.05) in deflection between the PMMA samples processed by heat-curing and water-bath, at a mean value of 4 (±1) mm, and those processed by thermo-pressing technique, at 5 (±1) mm. However, there was a statistically significant difference in deflection between the PMMA samples and the PEEK-Optima® processed by denture injection method and the PEEK-Juvora™ samples that processed by CAM production method (P<0.05).

The PEEK-Optima® samples thermo-pressed at mould temperature of 100 °C below the PEEK T*g*, with a deflection mean value of 15 (±4) mm, exhibited a statistically non-significant difference (P>0.05) from PEEK thermo-pressed at mould temperatures above the PEEK T*g* (150, 175 and 200 °C), with mean values of 15 (±3), 11 (±2) and 12 (±4) mm respectively. However, there was a statistically non-significant difference (P>0.05) deflection between the PEEK-Optima® samples thermo-pressed at different mould temperature above the PEEK T*g* except in the cases of samples thermo-pressed at mould temperatures of 150 °C, of 15 (±3)mm, and at 175 °C, of 11 (±2) mm deflection mean value (P<0.05).

PEEK-Juvora™ samples processed by CAM production method, with a deflection mean value of 7 (±0.4) mm, showed statistically significant differences (P<0.05) compared to PMMA processed by the two different techniques and the PEEK-Optima® samples thermo-pressed at different mould temperatures.

All the materials tested fractured during the tensile strength test; figure (7-24).

Load at Break: As shown by figures (7-25) and (7-26), there was no statistically significant difference ($P>0.05$) between the load needed to break the PMMA samples processed by both heat-curing and water-bath, with a mean value of 439 (±38) N, and those processed by thermo-pressed technique, at 424 (±63) N. However, there was a statistically significant difference ($P<0.001$) between the load needed to break the PMMA samples produced by the two processing techniques and that needed to break the PEEK-Optima® processed by denture injection method, and also that needed to break the PEEK-Juvora™ samples processed by CAM production method.

There was a statistically non-significant differences ($P>0.05$) between PEEK-Optima® samples thermo-pressed at mould temperature of 100 °C below the PEEK T*g*, with a break load mean value of 547 (±34) N, and the PEEK injected at different mould temperatures above the PEEK T*g* (150, 175 and 200 °C), with load at break mean value of 577 (±26), 528 (±37), and 562 (±43) N respectively. Also, there was statistically non-significant differences ($P>0.05$) in the load needed to break the PEEK-Optima® samples thermo-pressed at mould temperatures above the PEEK T*g*.

PEEK-Juvora™ samples processed by CAM production method, with a break load mean value of 585 (±22) N, exhibited statistically significant differences ($P<0.05$) compared to the PMMA processed by the two different techniques, and the PEEK-Optima® samples thermo-pressed at 175 °C, of 528 (±37) N, while the difference was statistically non-significant ($P>0.05$) in relation to samples thermo-pressed at 100, 150, and 200 °C mould temperatures.

7.3.3. Discussion

Denture material may elongate under tension load and return to its original shape and size when unloaded. However, beyond the elastic region there may be a plastic deformation whereby the original form may not be completely regained after unloading. Thermoplastic materials have recently become a treatment option for patients who have potential reactions or are allergic to PMMA and certain metals (Kuwahara *et al*., 2004; Yunus *et al*., 2005). In addition, these thermoplastic denture materials are characterised by flexibility and a highly elastic nature which act as advantages in terms of reducing the stress on abutment teeth (Meijer and Wolgen, 2007; Kaplan, 2008).

Among the wide range of polymer materials that have been widely promoted for dental applications, PEEK has been highlighted as having potential for such purposes (Fujihara *et al*., 2004; Santing *et al*., 2012; Stawarczyk *et al*., 2013). Many researchers have studied the tensile properties of PEEK and its composites as thin films prepared with different thermal histories for orthopedic purposes (Cebe *et al*., 1987; Bakar *et al*., 2003b; Converse *et al*., 2007). Unfortunately, no information about the tensile strength of the PEEK as a denture base material is available up to now. The application of PEEK as a denture material using dental lab equipment and facilities may change PEEK's tensile strength and thereby affect the final dental prosthesis. Therefore, the tensile test for PEEK polymer was carried out using a universal testing machine with a crosshead speed of 30 mm/min at room temperature, and according to ISO standardisation for thermoplastic denture material. The ultimate tensile strength and the deflection to break were determined.

Generally, among the tested samples the lowest tensile strength, deflection and load at break was identified the PMMA, both in that processed by conventional heat-curing and that processed by denture injection methods, and no differences in mechanical properties were observed between the PMMA samples processed by the two different methods. This could support the finding of many researchers that PMMA is a polymer that exhibits inferior mechanical properties (Doğan *et al*., 1995; John *et al*., 2001; Alhareb and Ahmad, 2011; Ucar *et al*., 2012), and this may highlight the need for investigation of new polymers with improved mechanical properties.

From the testing of the materials it can be seen that the tensile strength of PEEK-Optima®NI1 was dependent on the mould temperature. However, increasing the mould temperature produced no difference in tensile strength between PEEK-Optima® samples thermo-pressed at 100 and 175 °C mould temperatures. This may be related to the unstable crystalline-amorphous parts within the mould at temperature of 175 °C and at 100 °C below the PEEK T*g* (Blundell and Osborn, 1983; Cebe *et al*., 1987; Hamdan and Swallowe, 1996). The PEEK-Juvora™ samples exhibited superior tensile strength compared to that of the thermo-pressed PEEK-Optima®. This may derive from the inherent characteristics of stable crystalline-amorphous phases of the PEEK-Juvora™ which are managed and controlled during the preparation process for machining purposes (Invibio, 2004b).

All the tested materials fractured during the tensile strength test. Necking was noticed over the entire parallel segment of the dumbbell-shape specimens as a result of the reduction in the cross-sectional area of the specimen under tensile loading (Kaplan, 2008; Takabayashi, 2010). It was evident from the typical load-displacement curve for the PEEK-Optima®, PEEK-Juvora™ and the PMMA tested material that the PEEK-Optima® thermo-pressed material exhibited both ductile and brittle behaviour, depending on the mould temperature. As shown in figure (7-24), the milled PEEK-Juvora™ and PEEK-Optima® samples that thermo-pressed at 200 °C mould temperature showed that the fracture tendency were at the middle area of the parallel segment of the specimen. This may reflect the suitability of these materials as a denture base material as this could improve the uniform distribution of the stress within the denture base under load.

It could also be seen that increasing the mould temperature may resulted in the PEEK-Optima® losing its ductility, as shown by the failure occurring in the elastic region illustrated in figure (7-26). Also, the PEEK-Juvora™ may exhibit ductile failure and brittle behaviour. This may be related to the annealing process which may have affected the PEEK-Juvora™ discs and improved the crystalline percentage of the material, leading to a less ductile product (Invibio, 2004b).

Superior load to break the sample was observed in the PEEK-Juvora™ processed by CAM production method, of 585 (±22) N, compared to, 577 (±26) N and 562 (±43) N for the PEEK-Optima® thermo-pressed at 150 and 200 °C respectively. This indicates that as the mould temperature increased above the PEEK T*g* the PEEK-Optima® mechanical properties may have improved and the resistance to break was enhanced.

7.3.4. Conclusion

The following conclusions are drawn from this study:

1. PEEK-Juvora™ and PEEK-optima®NI1 had higher tensile strength, deflection and load at break than PMMA processed by both heat-cured water-bath and thermo-pressed technique.
2. There was no difference in the tensile strength of the PEEK-Optima® thermo-pressed at different mould temperatures above the PEEK T*g*, of 150, 175, and 200 °C.
3. The PEEK-Optima® NI1 thermo-pressed at different mould temperature had the same deflection; while that at 175 °C mould temperature had lower deflection compared to that thermo-pressed at 150 °C.
4. The PEEK-Juvora™ had higher load at break compared to PMMA and PEEK-Optima® thermo-pressed at 175 °C.
5. The PEEK-Optima® NI1 thermo-pressed at different mould temperature had the same same load at break under tensile test.

To sum up, PEEK flexibility and highly elastic nature could decrease the stress transmited to the unerlying supporting tissues. The machined PEEK-Juvora™ and thermo-pressed PEEK-Optima®NI1 at 200 °C mould temperature illustrate fracture tendency at the middle area of the parallel segment of the specimen which could improve the uniform distribution of the stress within the denture base under load.

Chapter Eight

Effects of a Novel PEEK Clasp Design on the Retentive Force at Different Tooth Undercuts

Chapter Eight: Clasp Design and Retentive Force

Introduction

Since the flexibility is an essential feature of the clasps in RPDs, a material with high flexibility may not be the material of choice for use as major connectors. Therefore, both high flexural modulus and strength are more important than a high level of deflection (Ucar *et al*., 2012).

Despite the fact that the material characteristics of thermoplastic resin have been studies *in vitro*, detailed designs non-metal clasp dentures are still to be produced. Clinical problems including the failure of resin clasps have been frequently encountered in the practical use of non-metal clasp dentures. The material characteristics of many thermoplastic materials, including PEEK, have been evaluated *in vitro* to investigate their mechanical and physical properties. However, all the manufacturers of thermoplastic materials and laboratories making non-metal clasp dentures still recommend the original denture design. Moreover, these experiments were executed on rectangle test specimens that were not in clasp form, and design details for thermoplastic clasps in RPDs, such as thickness, width, and amount of undercut, to achieve appropriate retention and avoid clasp failure have not been fully established.

PEEK as a new thermoplastic material was evaluated previously in this study and compared to the PMMA. It shows mostly superior mechanical and physical properties as a denture base material for non-metal clasp dentures, to assist in determining the clinical suitability of thermoplastic polymer. Due to the lack of studies, there is insufficient scientific evidence regarding the properties of PEEK as a thermoplastic denture material. Even though the indications and contraindications for the use of PEEK as a denture material have never been clearly defined, some practitioners have already begun using them based on their preferences and clinical experience (Costa-Palau *et al*., 2014; Zoidis *et al*., 2015). Hence, the clinicians have to be provided with appropriate guidelines for using and designing the PEEK as a denture material, especially since the displacement of soft tissue would be made greater by denture flexibility. One of the questions relating to the use of PEEK material for RPD clasps was whether these flexible materials could maintain sufficient retention. PEEK's flexibility and highly elastic nature through its mechanical properties could decrease the stress on abutment teeth, whilst, in addition, the clasp dimensions could affect the retention. However, no studies have reported on comparison between the traditional Cobalt-Chromium and PEEK-Optima®NI1, and PEEK-Juvora™.

From an independent point of view it appears that more scientific investigation on this topic is required. Therefore, in this study a full clasp for PEEK polymer will be designed and tested.

Due to lack of clarity over number of thermal cycles that would be suitable for testing clinical use, assumptions were made that insertion/removal of the clasp would be performed three times in a day and the durability of PEEK thermoplastic polymer would be about 3 years. Therefore, 6600 thermal deflection were set up in this insertion/removal test.

Aim

This study aims to investigate the retentive force of a novel clasp design for PEEK thermoplastic material at 3 different undercut depths. Clasp fatigue cycling was equated to 3 years period of use for the purpose of comparisons to the conventional Co-Cr RPDs clasp.

Objectives

The objectives of the present study are as follow:

1. To thermo-cycle the clasps design under repeated loads up to 6600 thermal deflection to represent 3 years of insertion/removal use.
2. Investigation of the PEEK clasp design as a non-metal clasp's denture by measuring the clasp retentive force at different tooth undercuts.

8.1. Materials and Methods

8.1.1. Preparing the Study Case Model

A study model was constructed to represent an ideal RPD situation with a standardised undercut. A case study model of class III mod.1 Kennedy classification was prepared. After making impressions of the working cast and molar die, the stone sample was fabricated using hardened Type IV diestone moulding material which is suitable for scanning purposes. The same cast was used in all production procedures, the only exception being production of the abutment's molar tooth. The molar tooth was assessed and duplicated and then trimmed and surveyed manually to achieve the different desirable undercuts of 0.25, 0.50, and 0.75 mm. The undercuts were measured using traditional manual surveying tools, figure (8-1).

8.1.2. Cast Study Scan

The stone study cast was scanned using a 3D DWOS-RPDs software designer program (3D Dental Wings Operating System of Removable Partial Dentures). The undercut amount was measured again digitally using the system depth scale, figure (8-2). After surveying, the cast was exported into (.Stl) file form to be retrieved for use in designing the PEEK and Co-Cr clasps.

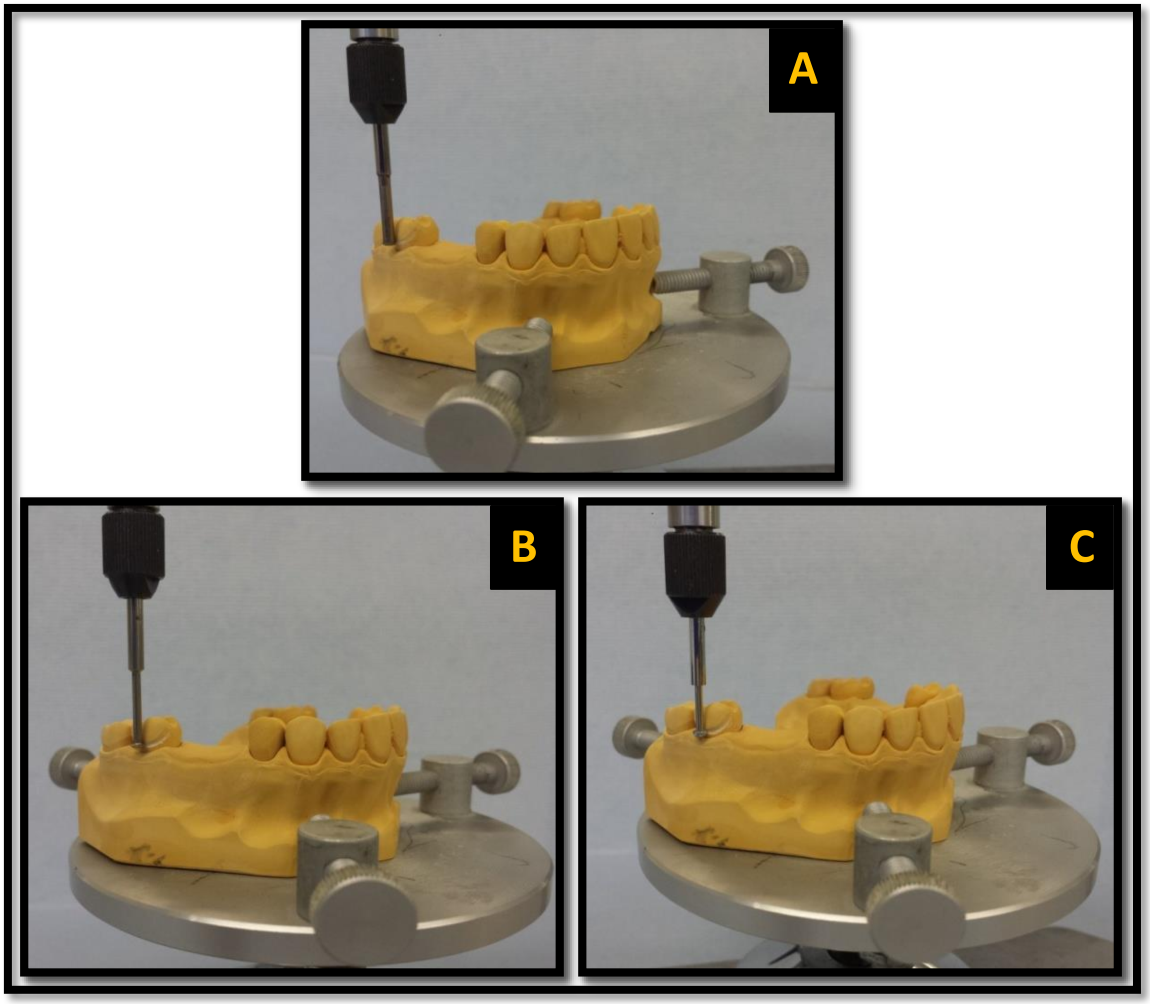
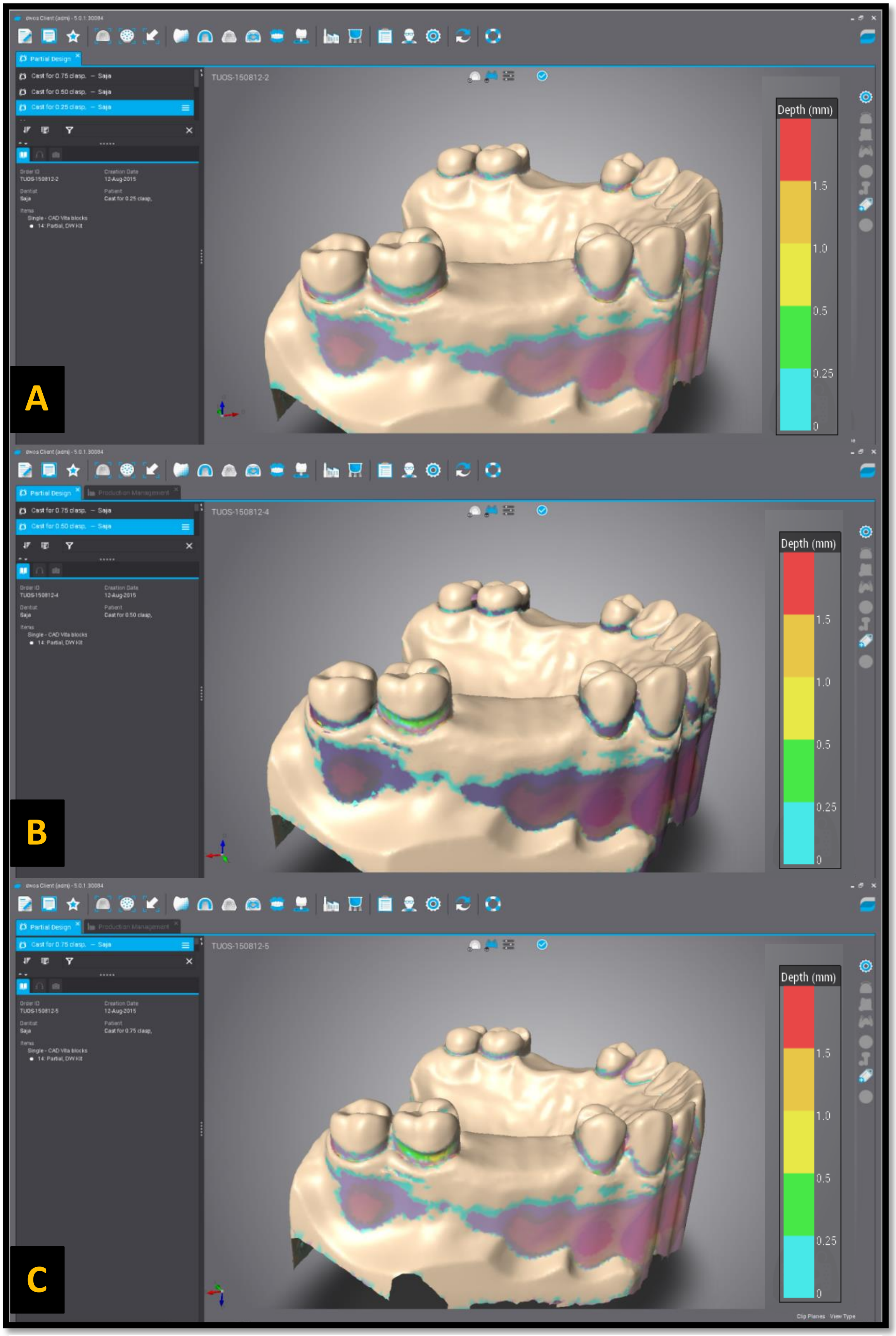


Figure (8-1): Cast study of different tooth undercuts, **A.** 0.25 mm; **B.** 0.50 mm; and **C.** 0.75 mm



Cast for 0.75 clasp. – Saja
Cast for 0.50 clasp. – Saja
Cast for 0.25 clasp. – Saja

Order ID: TUOS-150812-2
Creation Date: 12-Aug-2015
Dentist: Saja
Patient: Cast for 0.25 clasp,
Items: Single - CAD Vita blocks
- 14: Partial, DW Kit

Order ID: TUOS-150812-4
Creation Date: 12-Aug-2015
Dentist: Saja
Patient: Cast for 0.50 clasp,
Items: Single - CAD Vita blocks
- 14: Partial, DW Kit

Order ID: TUOS-150812-5
Creation Date: 12-Aug-2015
Dentist: Saja
Patient: Cast for 0.75 clasp,
Items: Single - CAD Vita blocks
- 14: Partial, DW Kit

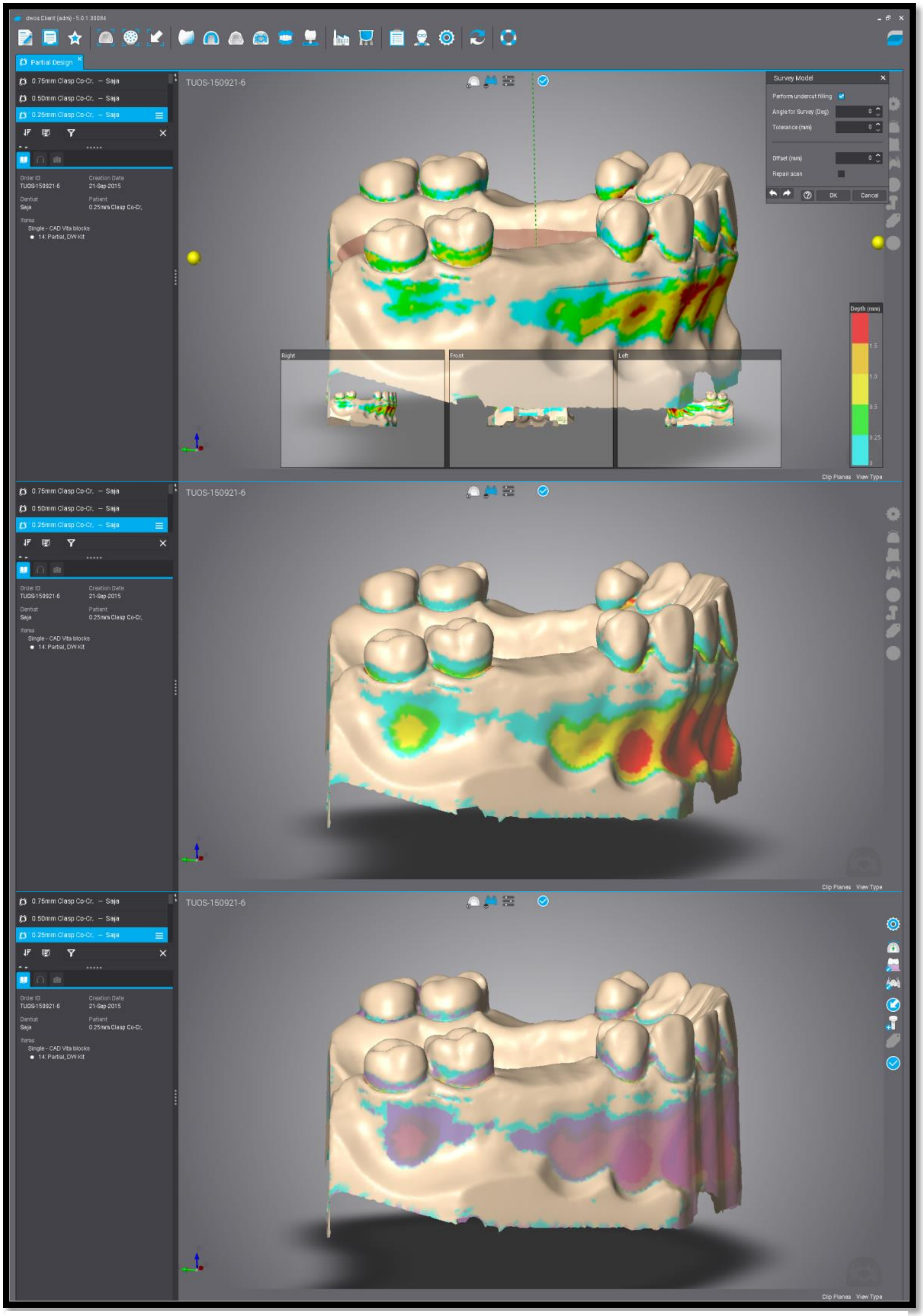
Figure (8-2): Case study with molar tooth undercut gauge for PEEK clasp design at: **A.** 0.25 mm; **B.** 0.50 mm, and **C.** 0.75 mm

8.1.3. Clasp Design

The Co-Cr clasp was designed according to the most common conventional design pattern, and the PEEK clasp was designed according to the novel dimensions devised by this study and supported by the tensile strength results for this material. However, the occlusal rest dimensions were the same as those used for the Co-Cr clasp. This was a spoon shaped design, of 1 mm thickness, 3 mm width, and at right angles to the minor connector on the proximal surface. A pin cylinder holder was added to all the clasp designs to serve as an attachment for fixation to the sample jig holders of the testing machines.

Conventional Co-Cr Clasp Design

Figures (8-3) to (8-11) show the steps for designing the Co-Cr clasp. The exported (.Stl) file for the study cast model was retrieved into the RPD (3D-DWOS) platform for design of the clasps. The cast was digitally surveyed at Zero position and the undesirable undercut was blocked. The dimensions for the traditional Co-Cr clasp were designed using the molar tooth. The clasp arm pattern originated from a proximal plate and curved 120 degrees around the tooth surface in a single plane. Average clasp width and thickness of the designed arm was 1 mm; however, at 30 degrees they were 0.92 mm and 0.97 mm, respectively, while at 120 degrees they were 0.73 mm and 0.79 mm, respectively (Mahmoud *et al*., 2005). The clasp was designed and fabricated to 1 mm thickness, and then was finished and polished to the recommended dimensions using a digital micrometer device. The tip of the retentive clasp arm engaged with the tooth undercuts at specific points of 0.25 mm, 0.50 mm, and 0.75 mm, the desirable undercuts, while the width and thickness of the designed reciprocal (Bracing) arm was 2 mm and this was located passively on the palatal surface of the selected tooth.



dwos Client (adm) - 5.0.1.30084

Partial Design

0.75mm Clasp Co-Cr. – Saja
0.50mm Clasp Co-Cr. – Saja
0.25mm Clasp Co-Cr. – Saja

Order ID: TUOS-150921-6
Creation Date: 21-Sep-2015
Dentist: Saja
Patient: 0.25mm Clasp Co-Cr.
Items: Single - CAD Vita blocks
- 14: Partial, DW Kit

TUOS-150921-6

Survey Model
Perform undercut filling ☑
Angle for Survey (Deg): 0
Tolerance (mm): 0
Offset (mm): 0
Repair scan ☐

Figure (8-3): The cast was surveyed digitally at Zero position with blocking of the undesirable undercuts using DWOS

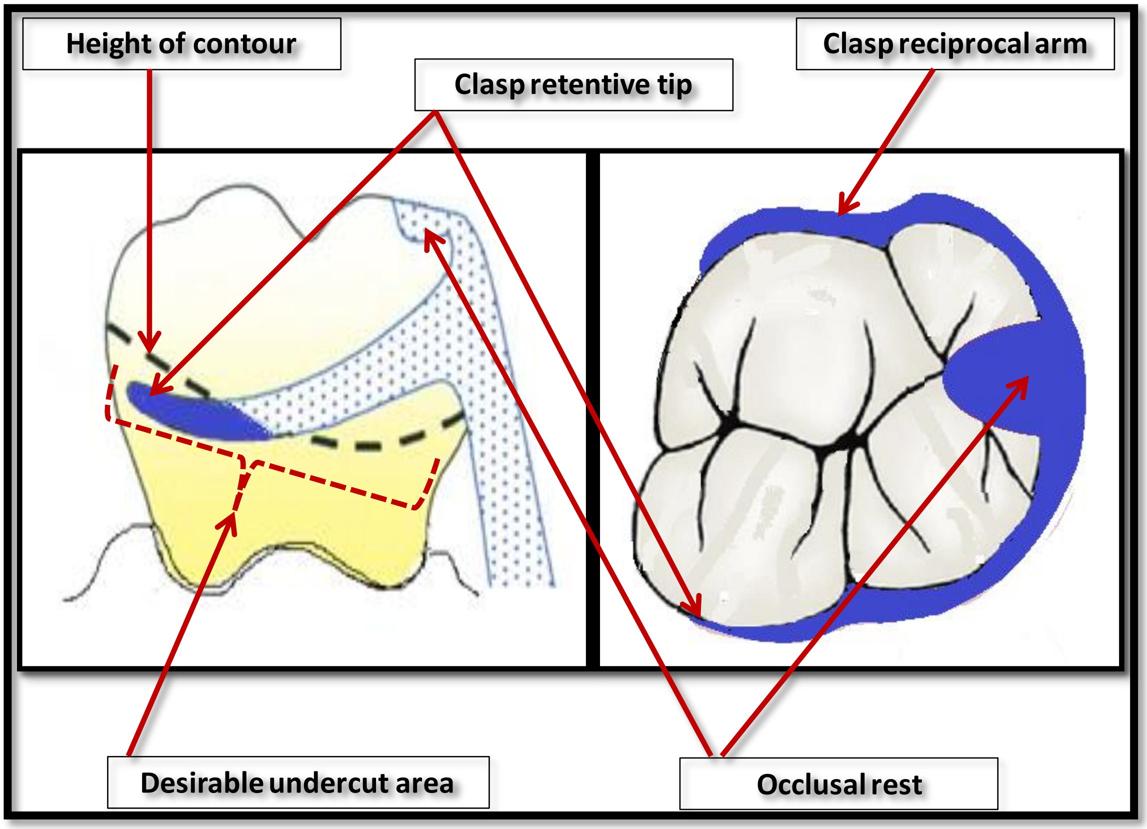
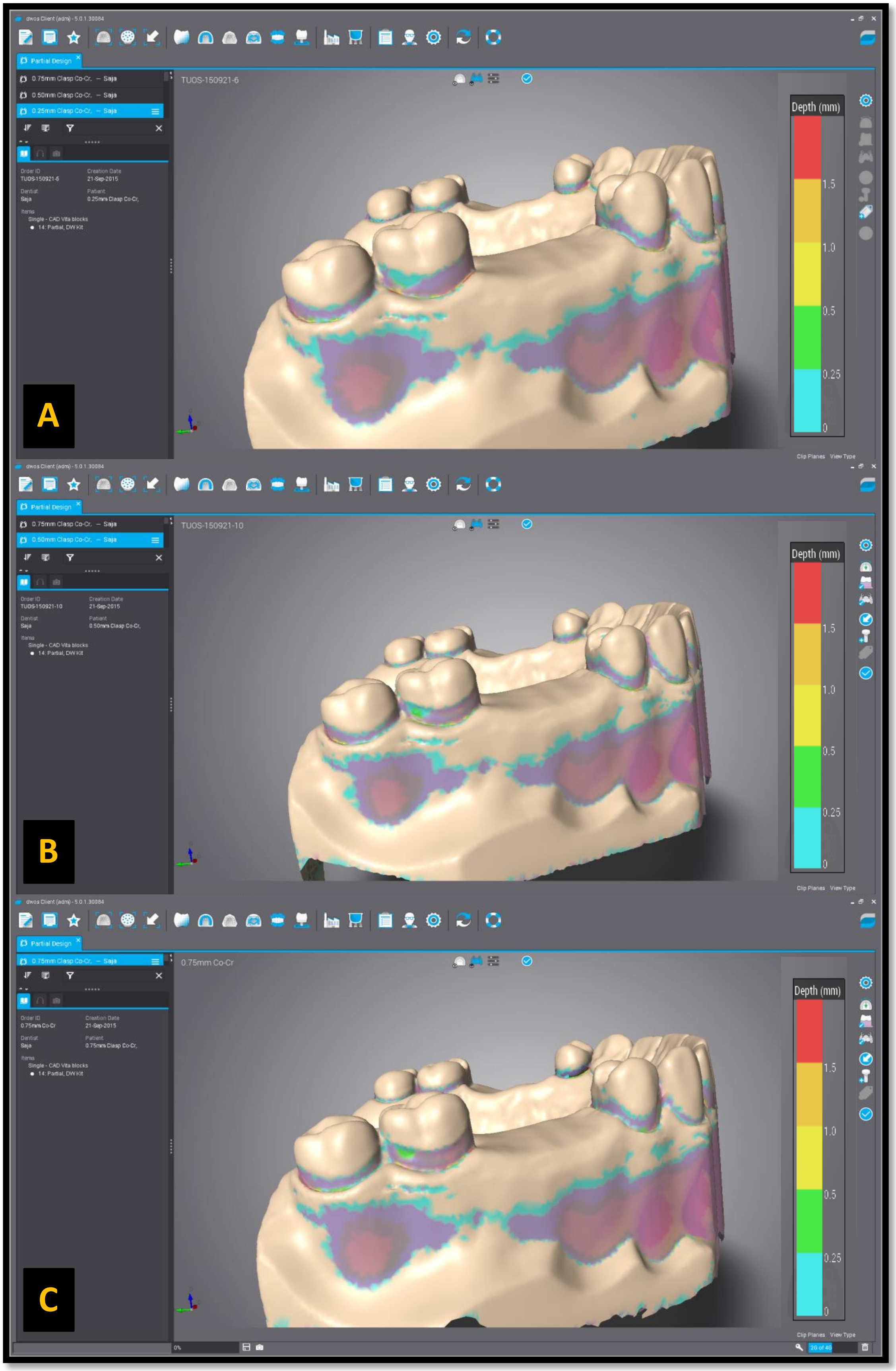


Figure (8-4): Conventional Co-Cr clasp design



A

0.75mm Clasp Co-Cr, – Saja
0.50mm Clasp Co-Cr, – Saja
0.25mm Clasp Co-Cr, – Saja

TUOS-150921-6

Order ID: TUOS-150921-6
Creation Date: 21-Sep-2015
Dentist: Saja
Patient: 0.25mm Clasp Co-Cr,
Items: Single - CAD Vita blocks
- 14: Partial, DW Kit

B

0.75mm Clasp Co-Cr, – Saja
0.50mm Clasp Co-Cr, – Saja

TUOS-150921-10

Order ID: TUOS-150921-10
Creation Date: 21-Sep-2015
Dentist: Saja
Patient: 0.50mm Clasp Co-Cr,
Items: Single - CAD Vita blocks
- 14: Partial, DW Kit

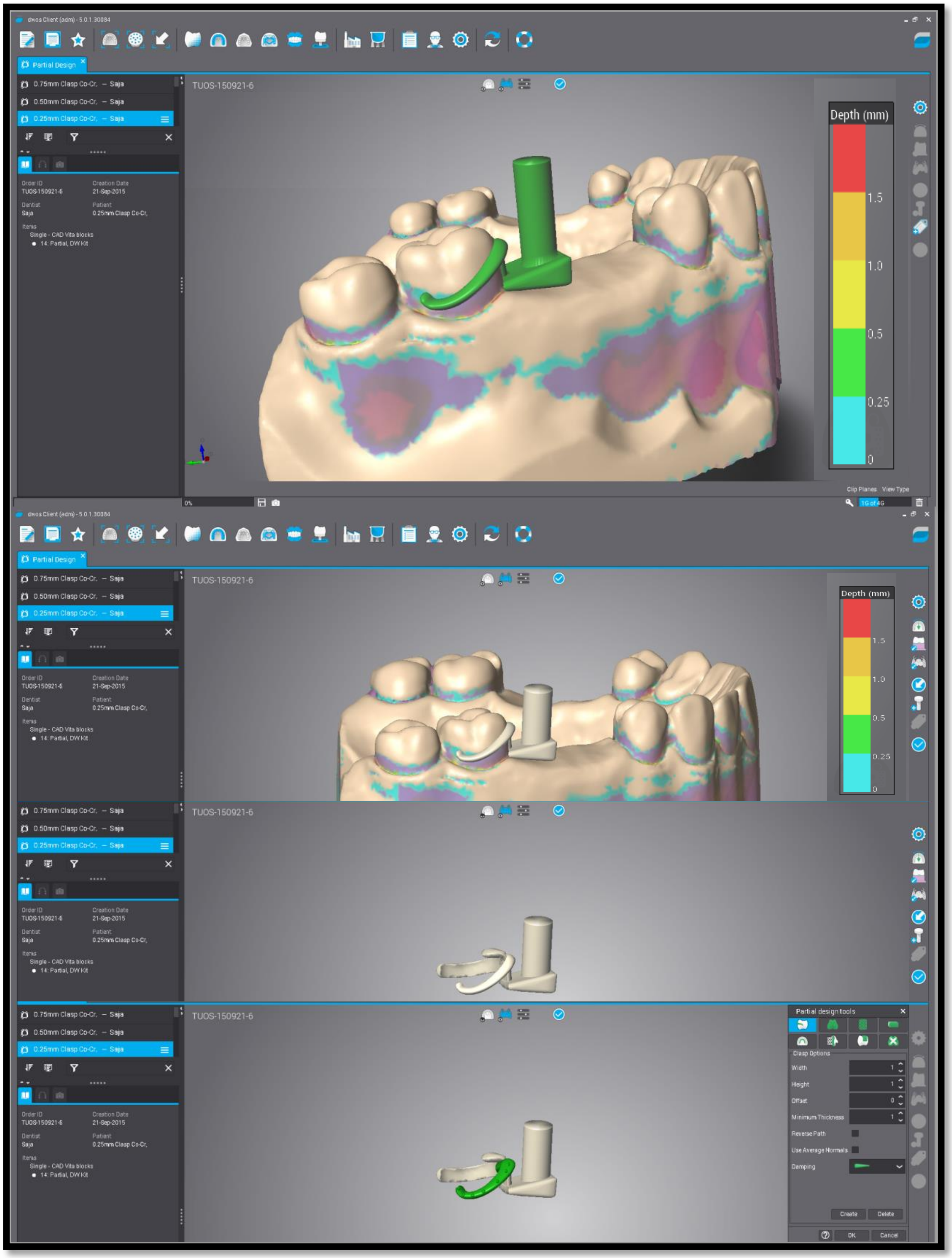
C

0.75mm Clasp Co-Cr, – Saja

0.75mm Co-Cr

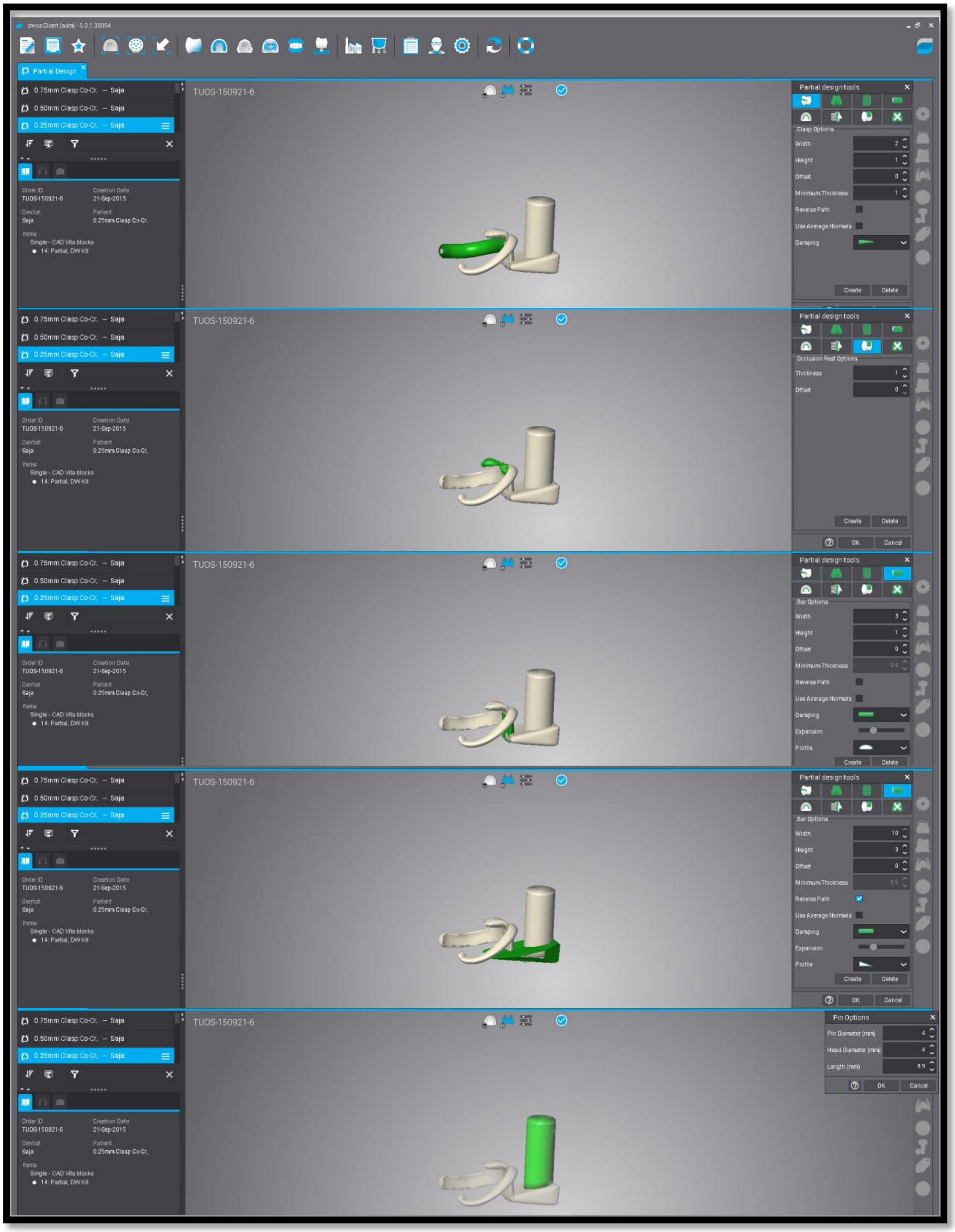
Order ID: 0.75mm Co-Cr
Creation Date: 21-Sep-2015
Dentist: Saja
Patient: 0.75mm Clasp Co-Cr,
Items: Single - CAD Vita blocks
- 14: Partial, DW Kit

Figure (8-5): Case study with molar tooth undercut gauge for Co-Cr clasp design at, **A.** 0.25 mm; **B.** 0.50 mm, and **C.** 0.75 mm



Clasp Options
Width 1
Height 1
Offset 0
Minimum Thickness 1
Reverse Path ☐
Use Average Normals ☐
Damping

Figure (8-6): Co-Cr clasp design with a retentive tip located at 0.25 mm on the tooth undercut gauge



dwos Client (adm) - 5.0.1.30084

Partial Design

0.75mm Clasp Co-Cr. – Saja
0.50mm Clasp Co-Cr. – Saja
0.25mm Clasp Co-Cr. – Saja

Order ID: TUOS-150921-6
Creation Date: 21-Sep-2015
Dentist: Saja
Patient: 0.25mm Clasp Co-Cr.
Items: Single - CAD Vita blocks
- 14: Partial, DW Kit

TUOS-150921-6

Partial design tools – Clasp Options
Width: 2
Height: 1
Offset: 0
Minimum Thickness: 1
Reverse Path: ☐
Use Average Normals: ☐

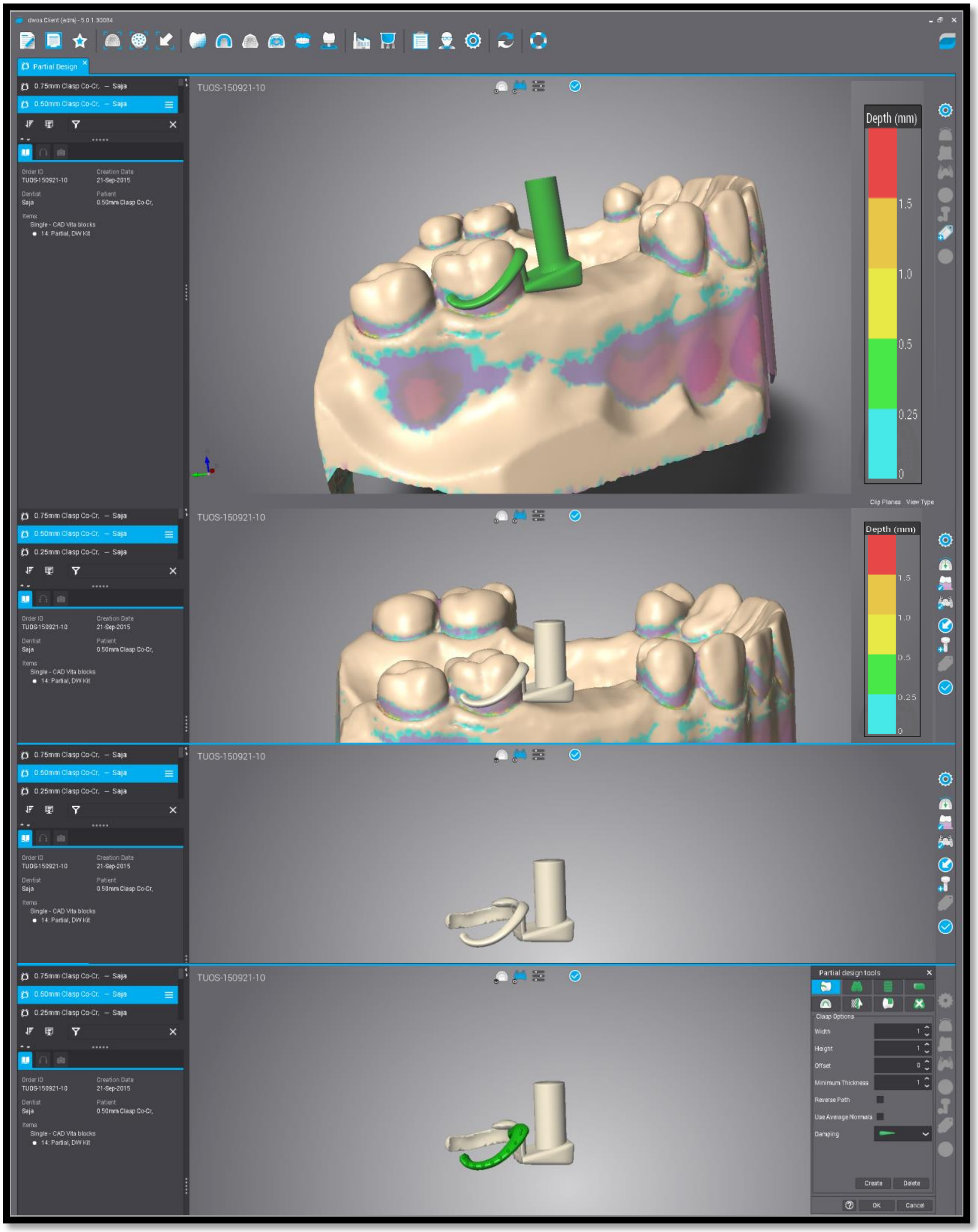
Partial design tools – Occlusion Rest Options
Thickness: 1
Offset: 0

Partial design tools – Bar Options
Width: 3
Height: 1
Offset: 0
Minimum Thickness: 0.5
Reverse Path: ☐
Use Average Normals: ☐

Partial design tools – Bar Options
Width: 10
Height: 3
Offset: 0
Minimum Thickness: 0.5
Reverse Path: ☑
Use Average Normals: ☐

Pin Options
Pin Diameter (mm): 4
Head Diameter (mm): 4
Length (mm): 8.5

Figure (8-7): Co-Cr clasp design at 0.25 mm undercut with a 2 mm thickness reciprocal arm, occlusal rest, and pin holder for test purposes

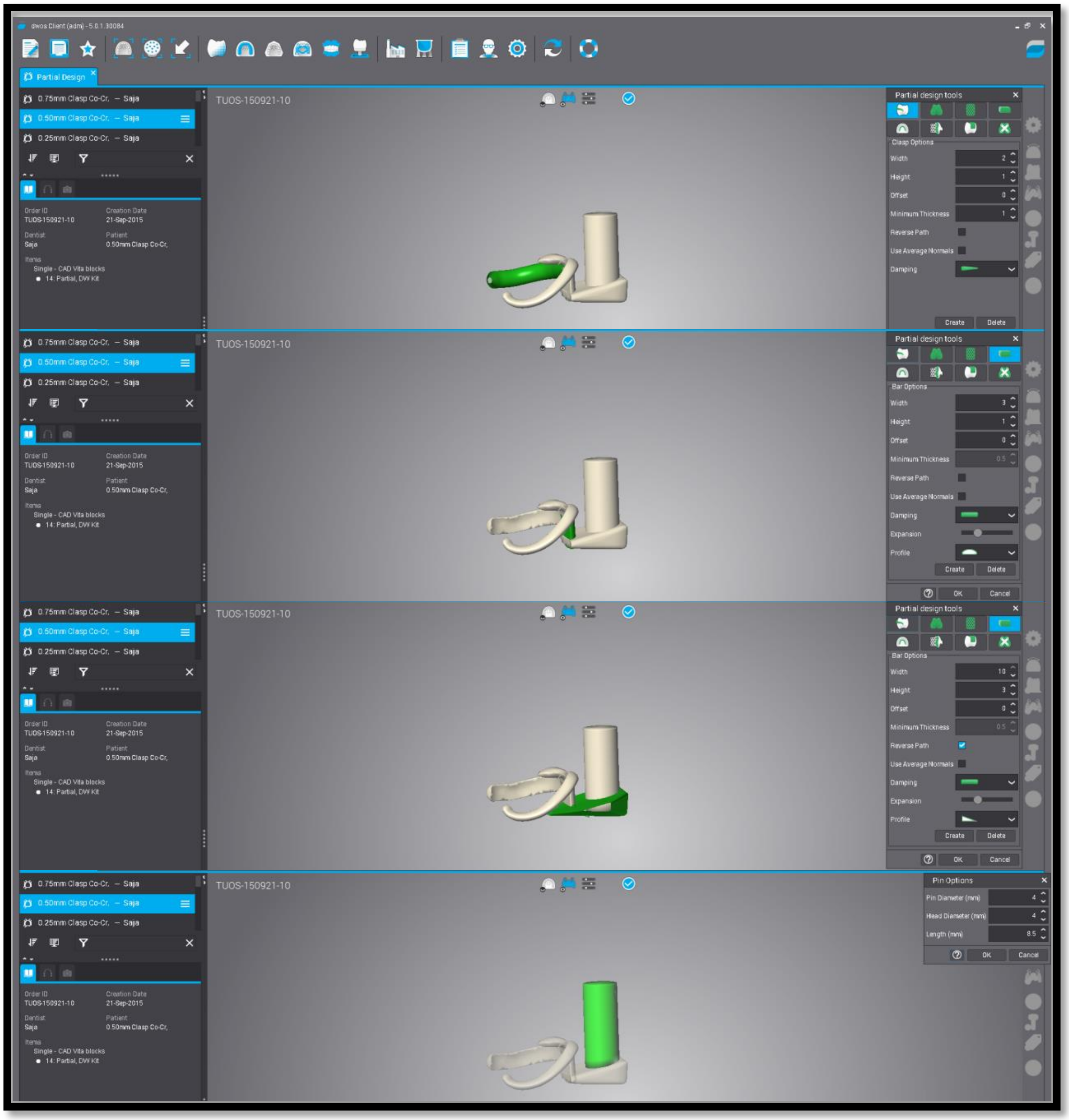


0.75mm Clasp Co-Cr. — Saja
0.50mm Clasp Co-Cr. — Saja
0.25mm Clasp Co-Cr. — Saja

Order ID: TUOS-150921-10
Creation Date: 21-Sep-2015
Dentist: Saja
Patient: 0.50mm Clasp Co-Cr.
Items: Single - CAD Vita blocks
- 14: Partial, DW Kit

Clasp Options
Width: 1
Height: 1
Offset: 0
Minimum Thickness: 1
Reverse Path: ☐
Use Average Normals: ☐

Figure (8-8): Co-Cr clasp design with a retentive tip located at 0.50 mm on the tooth undercut gauge


dwos Client (adm) - 5.0.1.30084

Partial Design

0.75mm Clasp Co-Cr. — Saja
0.50mm Clasp Co-Cr. — Saja
0.25mm Clasp Co-Cr. — Saja

Order ID: TUOS-150921-10
Creation Date: 21-Sep-2015
Dentist: Saja
Patient: 0.50mm Clasp Co-Cr,
Items:
Single - CAD Vita blocks
- 14: Partial, DW Kit

TUOS-150921-10

Partial design tools – Clasp Options
Width: 2
Height: 1
Offset: 0
Minimum Thickness: 1
Reverse Path: ☐
Use Average Normals: ☐

TUOS-150921-10

Partial design tools – Bar Options
Width: 3
Height: 1
Offset: 0
Minimum Thickness: 0.5
Reverse Path: ☐
Use Average Normals: ☐

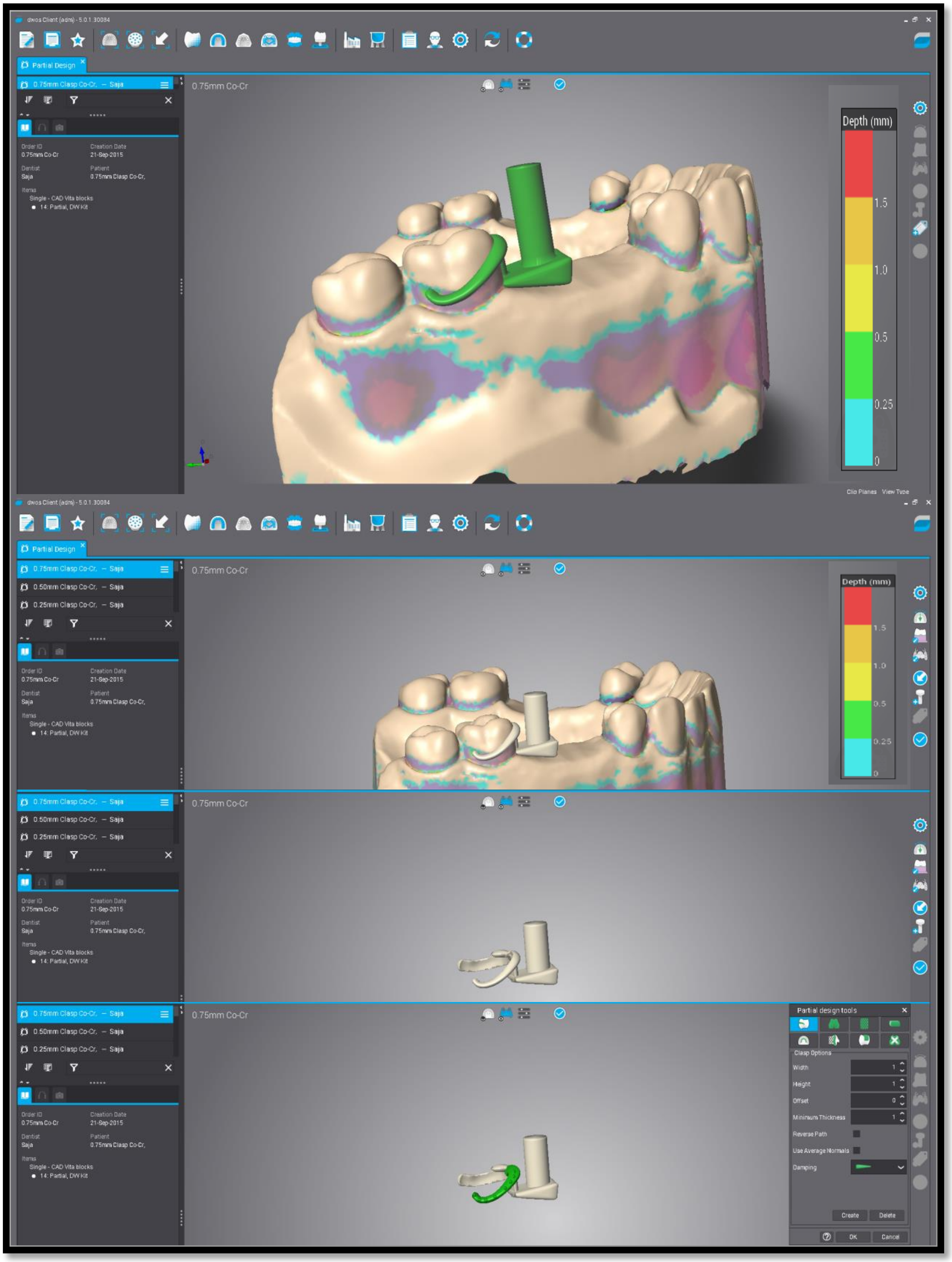
TUOS-150921-10

Partial design tools – Bar Options
Width: 10
Height: 3
Offset: 0
Minimum Thickness: 0.5
Reverse Path: ☑
Use Average Normals: ☐

TUOS-150921-10

Pin Options
Pin Diameter (mm): 4
Head Diameter (mm): 4
Length (mm): 8.5

Figure (8-9): Co-Cr clasp design at 0.50 mm undercut with a 2 mm thickness reciprocal arm, occlusal rest, and pin holder for test purposes

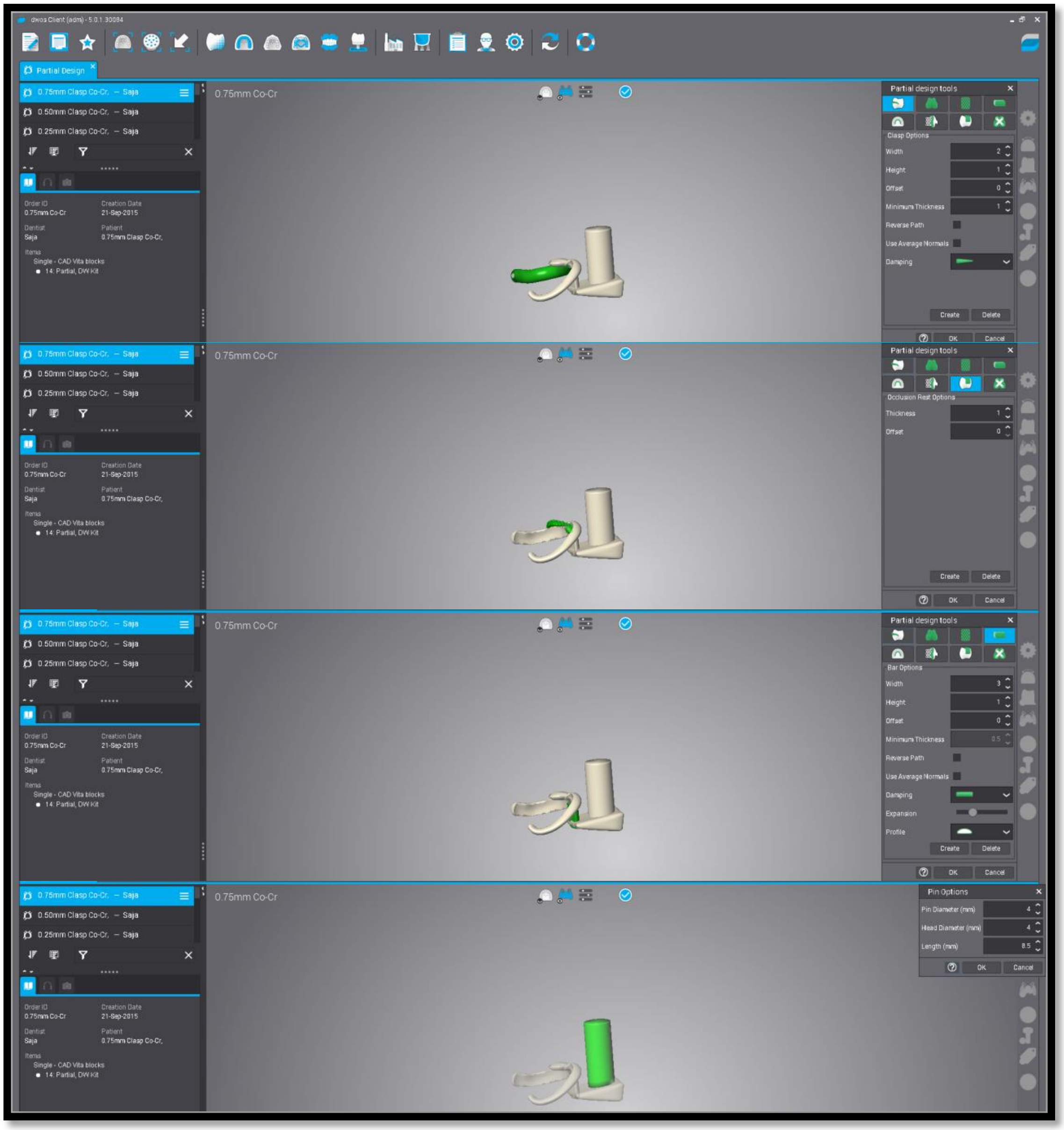


0.75mm Clasp Co-Cr, — Saja
0.50mm Clasp Co-Cr, — Saja
0.25mm Clasp Co-Cr, — Saja

Order ID: 0.75mm Co-Cr
Creation Date: 21-Sep-2015
Dentist: Saja
Patient: 0.75mm Clasp Co-Cr,
Items: Single - CAD Vita blocks
- 14: Partial, DW Kit

Clasp Options
Width: 1
Height: 1
Offset: 0
Minimum Thickness: 1
Reverse Path: ☐
Use Average Normals: ☐
Damping

Figure (8-10): Co-Cr clasp design with a retentive tip located at 0.75 mm on the tooth undercut gauge



Order ID
0.75mm Co-Cr

Creation Date
21-Sep-2015

Dentist
Saja

Patient
0.75mm Clasp Co-Cr,

Items
Single - CAD Vita blocks
- 14: Partial, DW Kit

Clasp Options
Width 2
Height 1
Offset 0
Minimum Thickness 1
Reverse Path ☐
Use Average Normals ☐

Occlusion Rest Options
Thickness 1
Offset 0

Bar Options
Width 3
Height 1
Offset 0
Minimum Thickness 0.5
Reverse Path ☐
Use Average Normals ☐

Pin Options
Pin Diameter (mm) 4
Head Diameter (mm) 4
Length (mm) 8.5

Figure (8-11): Co-Cr clasp design at 0.75 mm undercut with a 2 mm thickness reciprocal arm, occlusal rest, and pin holder for test purposes

PEEK Clasp Design

The same study cast model used to design a novel clasp pattern for PEEK material. The PEEK clasp was designed on the same molar tooth used for the Co-Cr clasp, with a design of dove-wing appearance. The clasp was designed with a novel strap arm pattern that originated from a proximal plate and curved around the buccal tooth surface with a dove-wing arm. The retentive clasp flange (lower part) engaged the tooth undercuts at the 0.25 mm, 0.50 mm, and 0.75 mm desirable undercut areas. The clasp was designed with short arm for aesthetic purposes, to end buccally at the buccal groove of the molar tooth. Meanwhile, the reciprocal arm curved around the palatal tooth surface with a passive action to end disto-platally. The average thickness of the designed retentive and reciprocal arm was 1.5 mm. The dimensions and shape of the clasp are demonstrated clearly in figure (8-12) to (8-18).

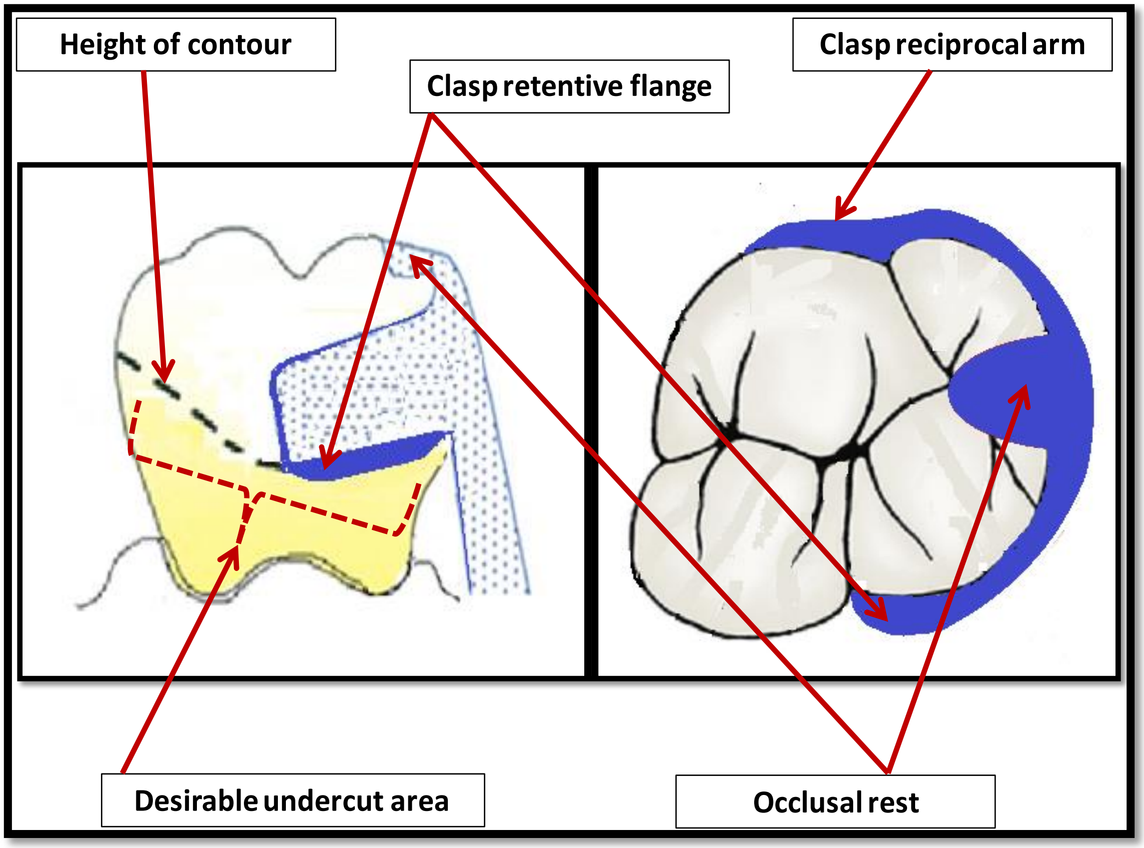
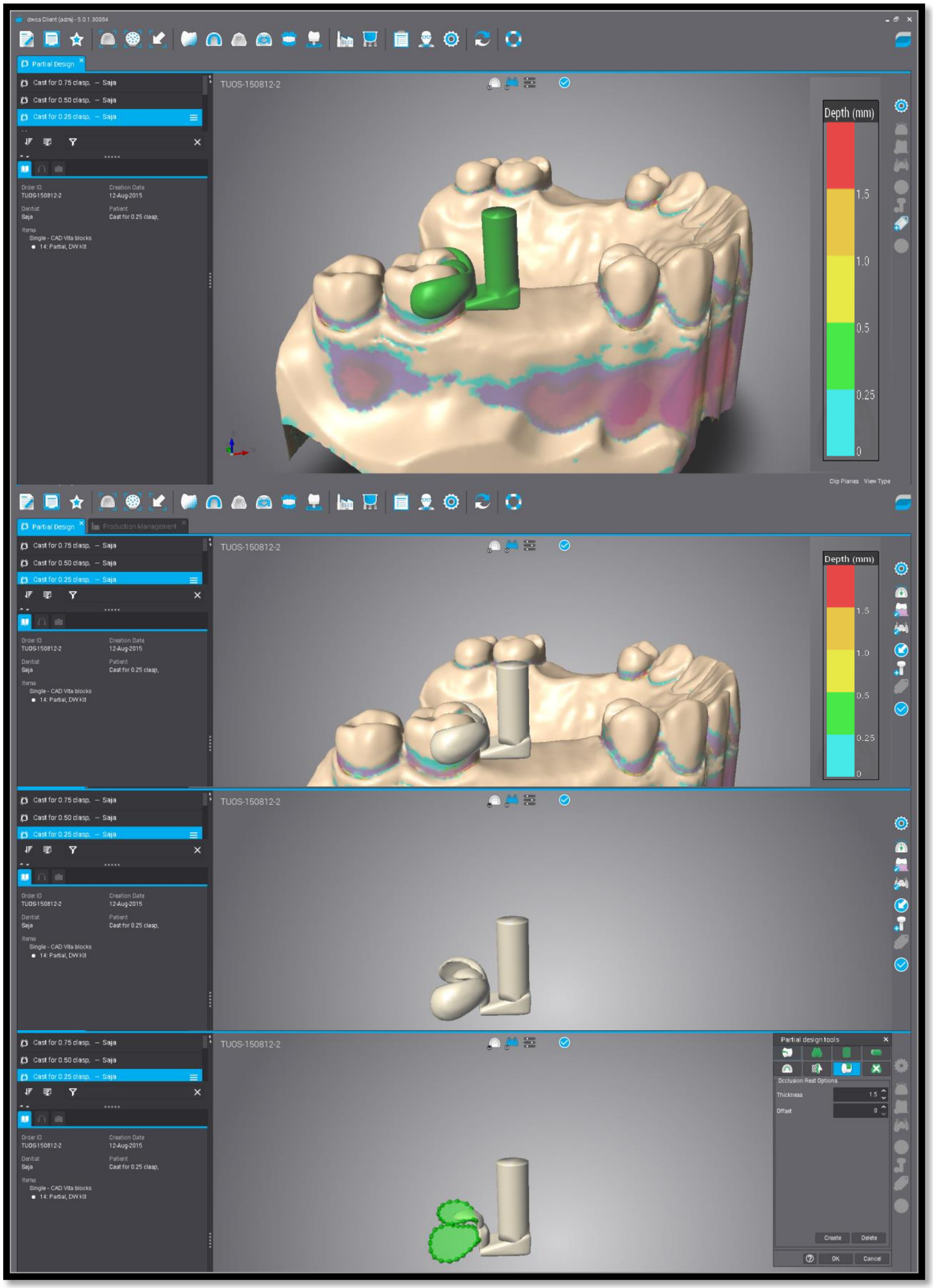


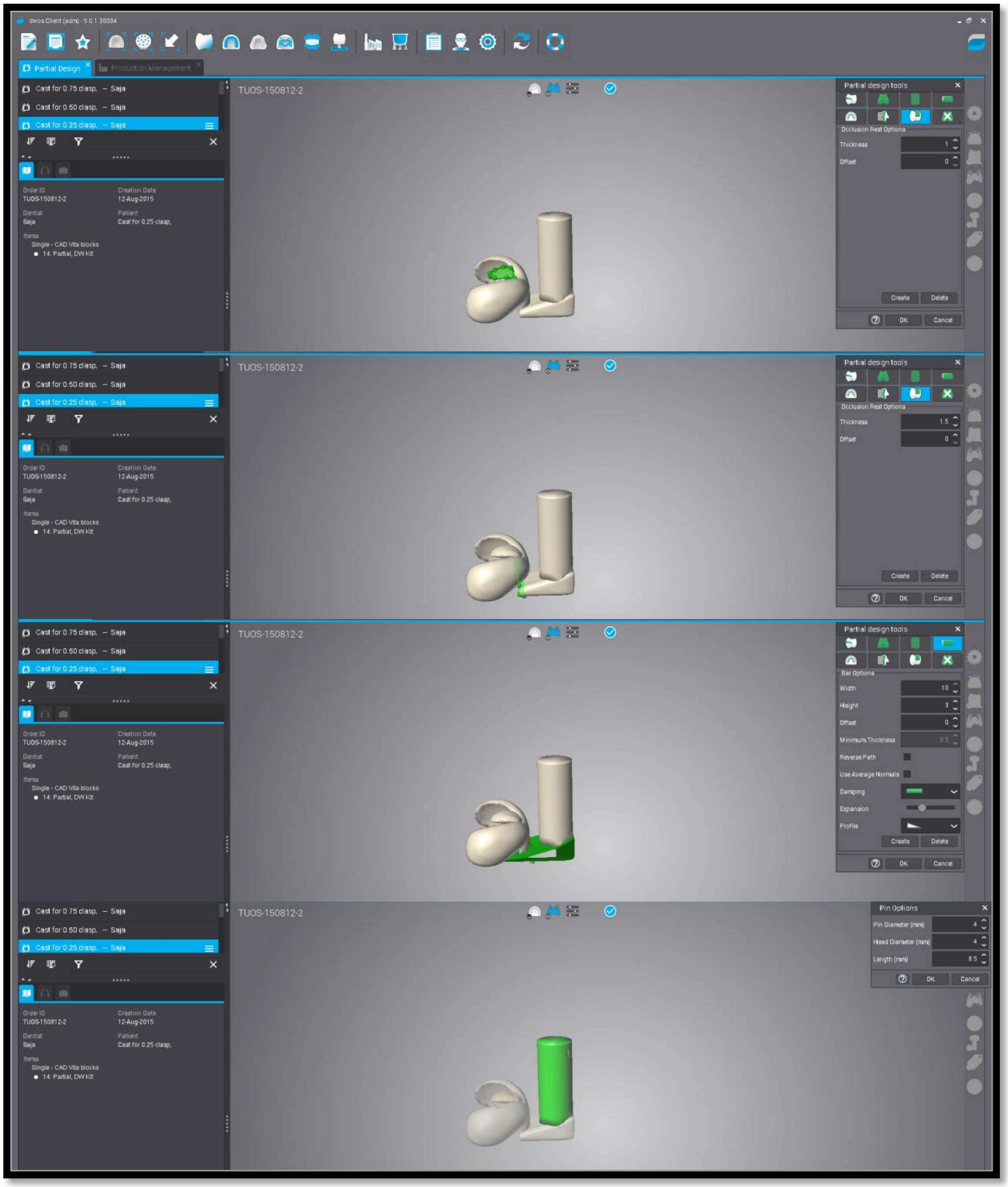
Figure (8-12): Novel clasp design for PEEK material



Order ID: TUOS-150812-2
Creation Date: 12-Aug-2015
Dentist: Saja
Patient: Cast for 0.25 clasp,
Items: Single - CAD Vita blocks
- 14: Partial, DW Kit

Occlusion Rest Options
Thickness: 1.5
Offset: 0

Figure (8-13): PEEK clasp design with a retentive flange of 1.5 mm thickness seated on the 0.25 mm tooth undercut area



dwos Client (adm) - 5.0.1.30084

Cast for 0.75 clasp. – Saja
Cast for 0.50 clasp. – Saja
Cast for 0.25 clasp. – Saja

Order ID: TUOS-150812-2
Creation Date: 12-Aug-2015
Dentist: Saja
Patient: Cast for 0.25 clasp,
Items: Single - CAD Vita blocks
- 14: Partial, DW Kit

TUOS-150812-2

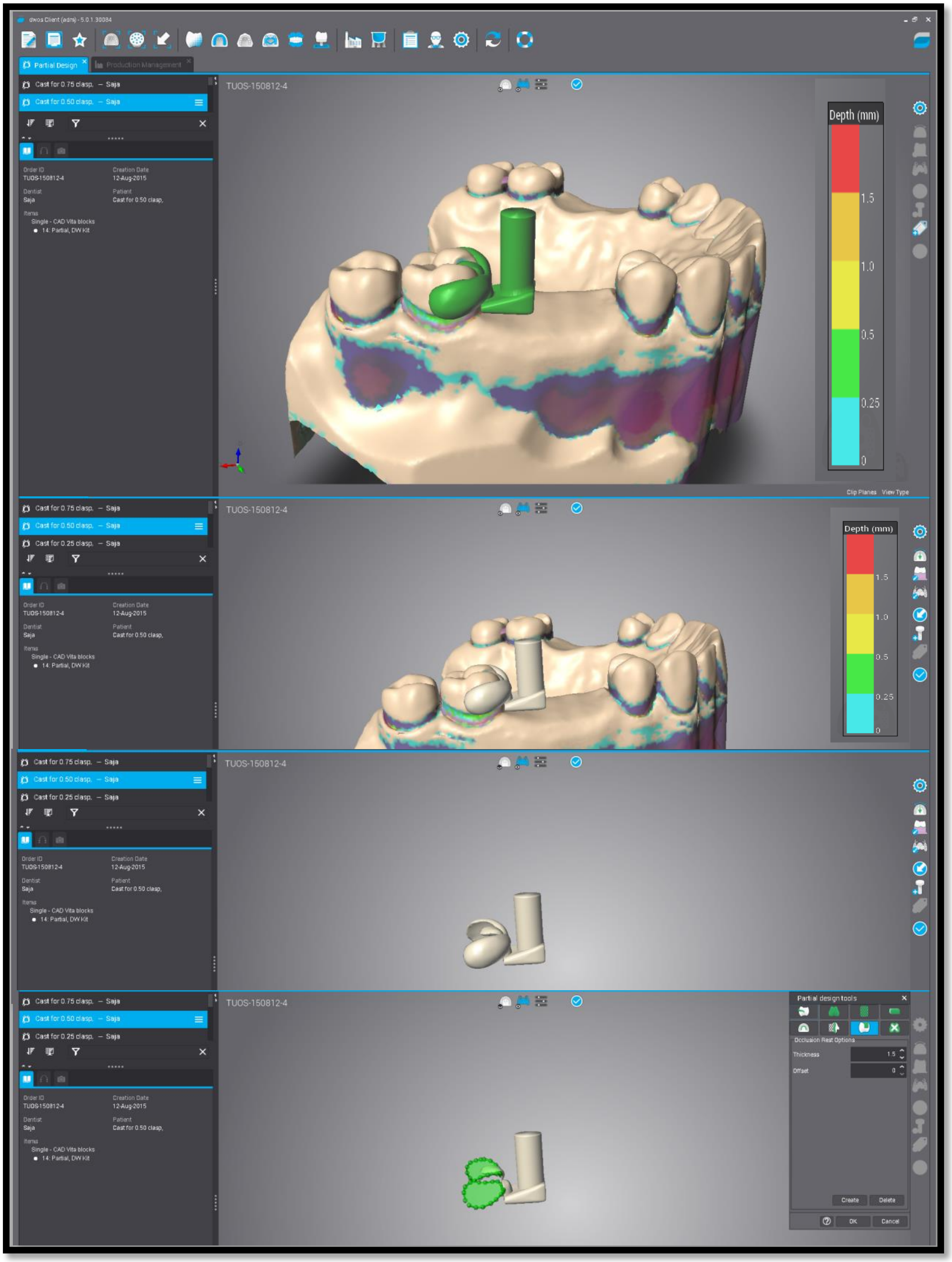
Partial design tools – Occlusion Rest Options
Thickness: 1
Offset: 0

Partial design tools – Occlusion Rest Options
Thickness: 1.5
Offset: 0

Partial design tools – Bar Options
Width: 10
Height: 3
Offset: 0
Minimum Thickness: 0.5
Reverse Path ☐
Use Average Normals ☐
Damping
Expansion
Profile

Pin Options
Pin Diameter (mm): 4
Head Diameter (mm): 4
Length (mm): 8.5

Figure (8-14): PEEK clasp design at 0.25 mm undercut with occlusal rest, and a pin holder for test purposes

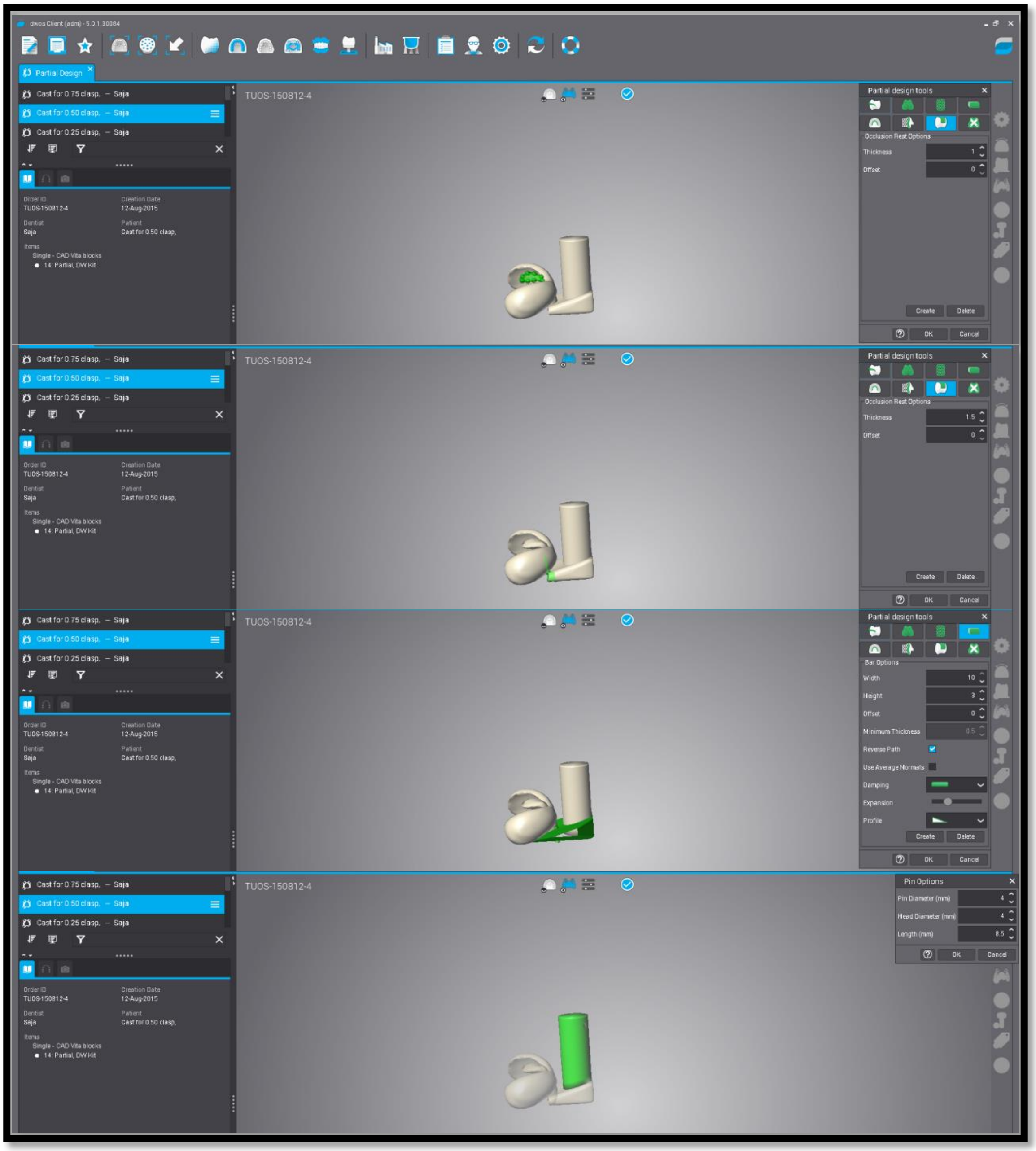


Cast for 0.75 clasp. – Saja
Cast for 0.50 clasp. – Saja
Cast for 0.25 clasp. – Saja

Order ID: TUOS-150812-4
Creation Date: 12-Aug-2015
Dentist: Saja
Patient: Cast for 0.50 clasp,
Items: Single - CAD Vita blocks
- 14: Partial, DW Kit

Occlusion Rest Options
Thickness: 1.5
Offset: 0

Figure (8-15): PEEK clasp design with a retentive flange of 1.5 mm thickness seated on the 0.50 mm tooth undercut area



Cast for 0.75 clasp. – Saja
Cast for 0.50 clasp. – Saja
Cast for 0.25 clasp. – Saja

Order ID: TUOS-150812-4
Creation Date: 12-Aug-2015
Dentist: Saja
Patient: Cast for 0.50 clasp,
Items: Single - CAD Vita blocks
- 14: Partial, DW Kit

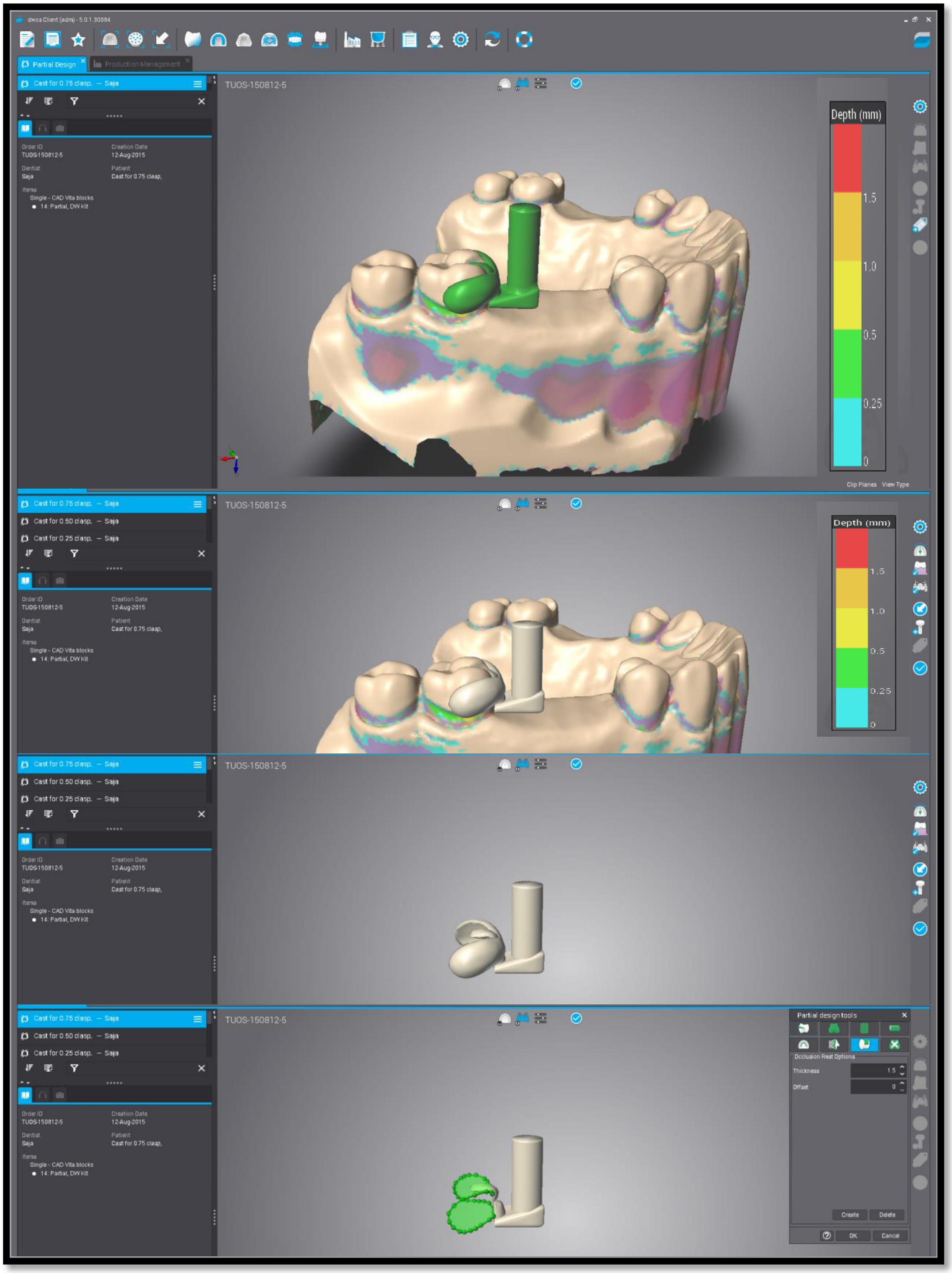
Occlusion Rest Options
Thickness: 1
Offset: 0

Occlusion Rest Options
Thickness: 1.5
Offset: 0

Bar Options
Width: 10
Height: 3
Offset: 0
Minimum Thickness: 0.5
Reverse Path: ☑
Use Average Normals: ☐
Damping
Expansion
Profile

Pin Options
Pin Diameter (mm): 4
Head Diameter (mm): 4
Length (mm): 8.5

Figure (8-16): PEEK clasp design at 0.50 mm undercut with occlusal rest, and a pin holder for test purposes



Order ID: TUOS-150812-5

Creation Date: 12-Aug-2015

Dentist: Saja

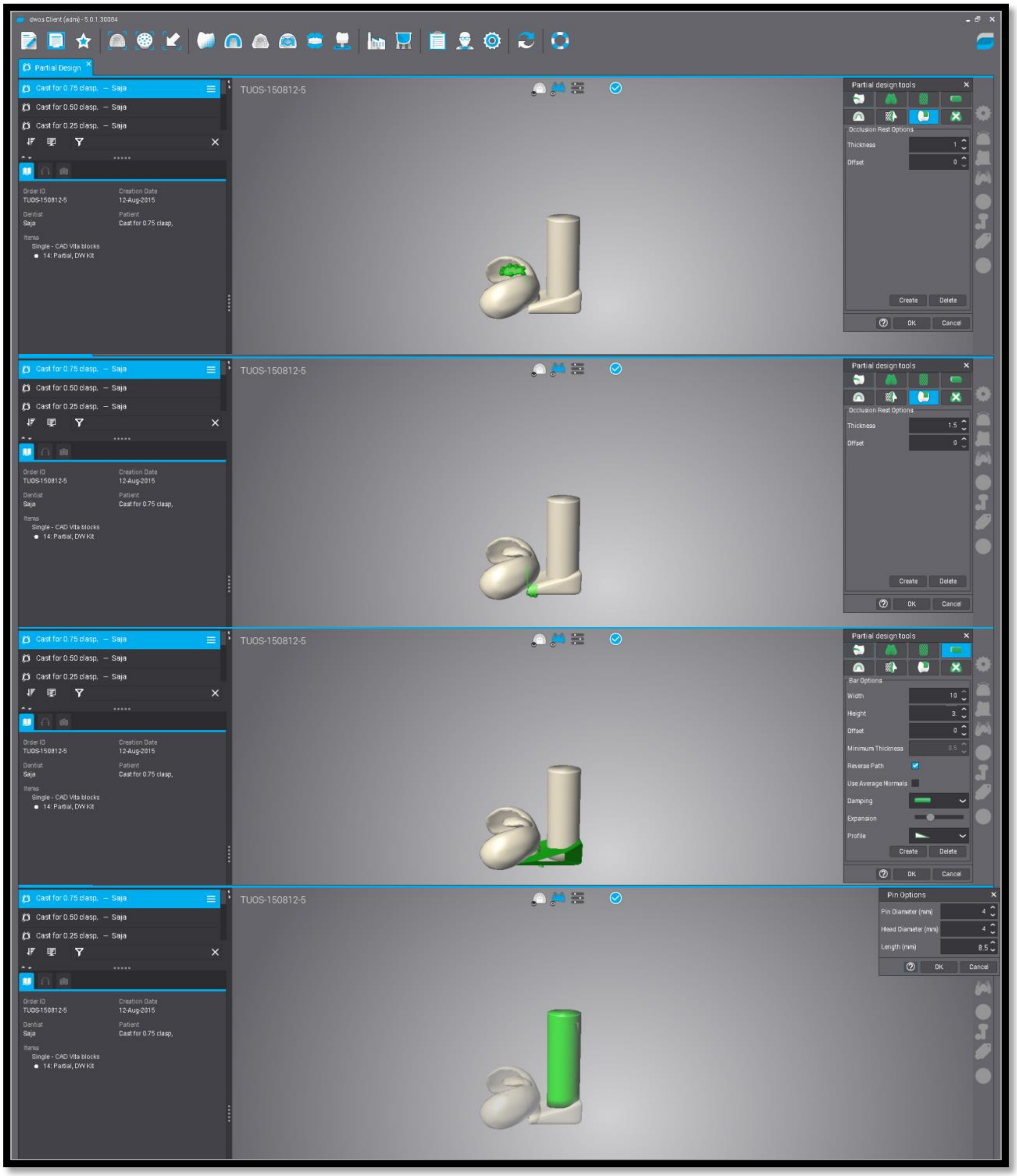
Patient: Cast for 0.75 clasp,

Items:
- Single - CAD Vita blocks
  - 14: Partial, DW Kit

Thickness: 1.5

Offset: 0

Figure (8-17): PEEK clasp design with a retentive flange of 1.5 mm thickness seated on the 0.75 mm tooth undercut area



dwos Client (adm) - 5.0.1.30084

Partial Design

Cast for 0.75 clasp. – Saja
Cast for 0.50 clasp. – Saja
Cast for 0.25 clasp. – Saja

Order ID: TUOS-150812-5
Creation Date: 12-Aug-2015
Dentist: Saja
Patient: Cast for 0.75 clasp,
Items:
Single - CAD Vita blocks
- 14: Partial, DW Kit

TUOS-150812-5

Partial design tools
Occlusion Rest Options
Thickness: 1
Offset: 0

Partial design tools
Occlusion Rest Options
Thickness: 1.5
Offset: 0

Partial design tools
Bar Options
Width: 10
Height: 3
Offset: 0
Minimum Thickness: 0.5
Reverse Path: ☑
Use Average Normals: ☐

Pin Options
Pin Diameter (mm): 4
Head Diameter (mm): 4
Length (mm): 8.5

Figure (8-18): PEEK clasp design at 0.75 mm undercut with occlusal rest, and a pin holder for test purposes

8.1.4. Fabrication of Clasps

The PEEK and Co-Cr digital patterns were converted to (.Stl) file forms to be fabricated into 3D sample; figure (8-19).

Machining Clasps

The PEEK clasps were arranged by software program into the disc space. Then, the machine milled these digital patterns into 3D PEEK clasps using PEEK-Juvora™ blank discs. This was accomplished using the various steps of the machine software processing program, figure (8-20) and (8-21).

Thermo-Pressed Clasps

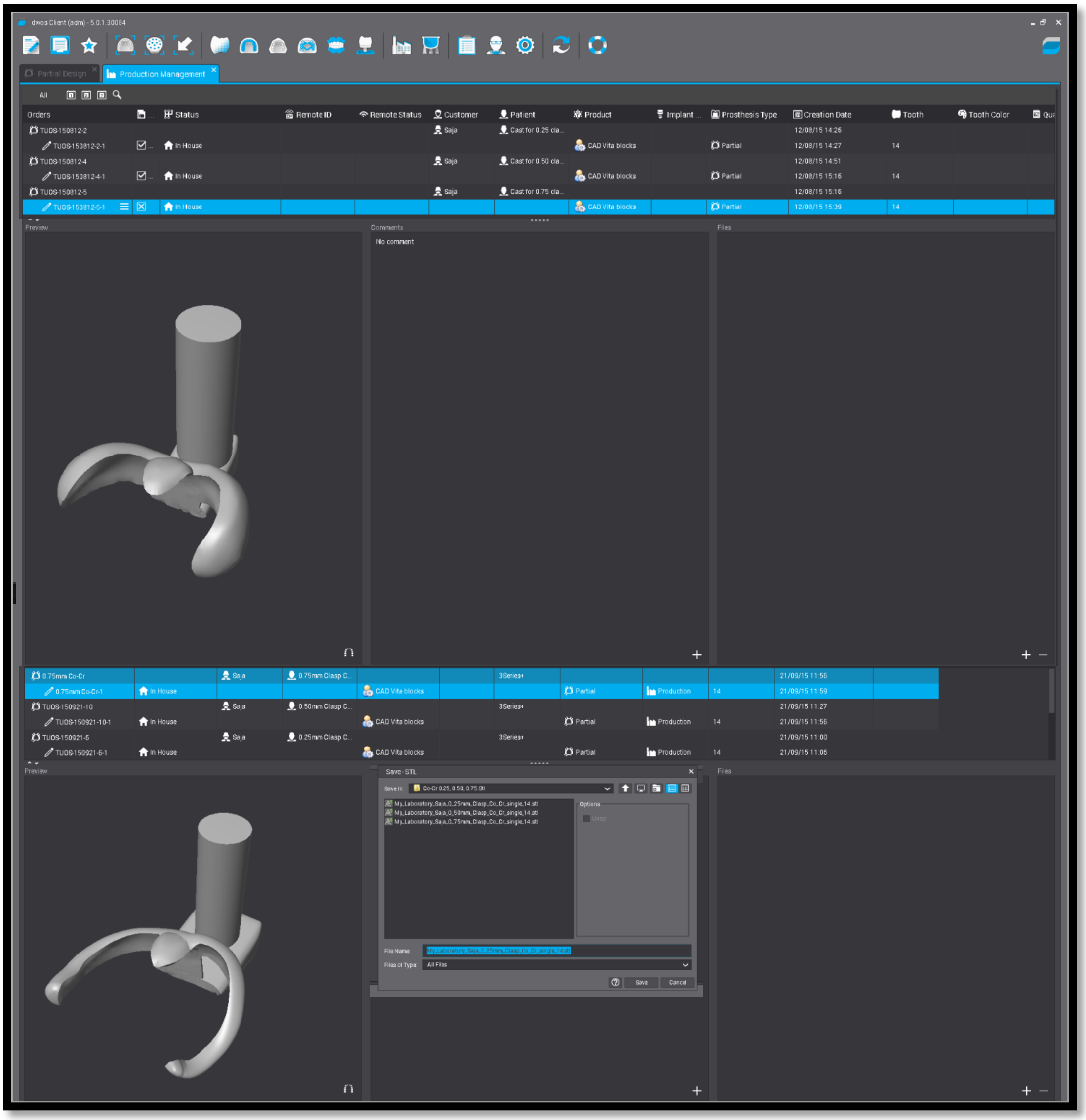
The same digitally designed (.Stl file extension) PEEK clasp was used to prepare the clasps made from thermo-pressed PEEK-Optima® at 200 °C mould temperature. However, after the arrangement of the clasp patterns into the disc space, the machine milled these patterns into 3D wax clasps using wax blanks, figures (8-22) and (8-23). These patterns were used to produce the mould to fabricate the clasps made of PEEK-Optima® granules. The wax patterns were moulded using hard dental diestone moulding material (Type IV), and mixed according to the manufacturer’s instructions (W/P: 20 ml / 100 g). To avoid any undercuts that might affect the final clasp design during the flasking procedure, the wax clasp was invested individually using a cylindrical mass of investment material, figure (8-24A). After flasking and investing of the wax patterns, the wax was eliminated using a wax extraction unit. The mould cavity was then cleaned with hot water and detergent agents. Next the mould left to dry for 30 seconds, and one layer of suitable separating medium for thermo-pressing purposes was added to the mould surface and left to dry overnight, figure (8-24B). Next day, the flasks were assembled tightly by means of screws, ready for preheating in the oven before injection of the PEEK- Optima®NI1 into the mould cavity at 200 °C mould temperature. The PEEK Thermo-pressing procedure was described previously.

Co-Cr Clasps

The Co-Cr clasp pattern (.Stl) files of 0.25, 0.50, and 0.75 mm undercuts were transferred to the milling machine to be milled into wax patterns, figure (8-25) and (8-26). The wax patterns were attached and sprued, figure (8-27A), and then invested and casted using Co-Cr alloy with a phosphate-bonded investment material. The Co-Cr alloy was cast, figure (8-27B), using high-frequency induction melting technology with a centrifugal casting machine. The casting procedures followed the manufacturers' instructions for metals and investments.

8.1.5. Finishing and Polishing

The cast Co-Cr clasps and machined and thermo-pressed PEEK clasp specimens were cut from their connectors and sprues using a diamond dental disc bur of 0.5 mm thickness. PEEK clasps were finished using pink stone burs (medium grit size) and polished using the conventional method. One side was polished with pumice and white polishing compound (USA). This polishing material delivers a high gloss with a slight amount of cut and produces clean, dry results. Meanwhile the Co-Cr clasps were lightly cleaned using a sandblaster with airborne-particle abrasion using 80 µm aluminum oxide particles. Then, white compound was applied for dry polishing and finally the clasps were electrical polished. A digital micrometer was used to optimise the clasp dimensions after the finishing and polishing procedures. After polishing, the samples were named, numbered and retained for the next testing step.



Orders	…	Status	Remote ID	Remote Status	Customer	Patient	Product	Implant …	Prosthesis Type	Creation Date	Tooth	Tooth Color	Qu
TUOS-150812-2					Saja	Cast for 0.25 cla…				12/08/15 14:26			
TUOS-150812-2-1	☑ …	In House					CAD Vita blocks		Partial	12/08/15 14:27	14		
TUOS-150812-4					Saja	Cast for 0.50 cla…				12/08/15 14:51			
TUOS-150812-4-1	☑ …	In House					CAD Vita blocks		Partial	12/08/15 15:16	14		
TUOS-150812-5					Saja	Cast for 0.75 cla…				12/08/15 15:16			
TUOS-150812-5-1	☒	In House					CAD Vita blocks		Partial	12/08/15 15:39	14		

No comment

0.75mm Co-Cr		Saja	0.75mm Clasp C…			3Series+				21/09/15 11:56
0.75mm Co-Cr-1	In House			CAD Vita blocks			Partial	Production	14	21/09/15 11:59
TUOS-150921-10		Saja	0.50mm Clasp C…			3Series+				21/09/15 11:27
TUOS-150921-10-1	In House			CAD Vita blocks			Partial	Production	14	21/09/15 11:56
TUOS-150921-6		Saja	0.25mm Clasp C…			3Series+				21/09/15 11:00
TUOS-150921-6-1	In House			CAD Vita blocks			Partial	Production	14	21/09/15 11:06

Save - STL

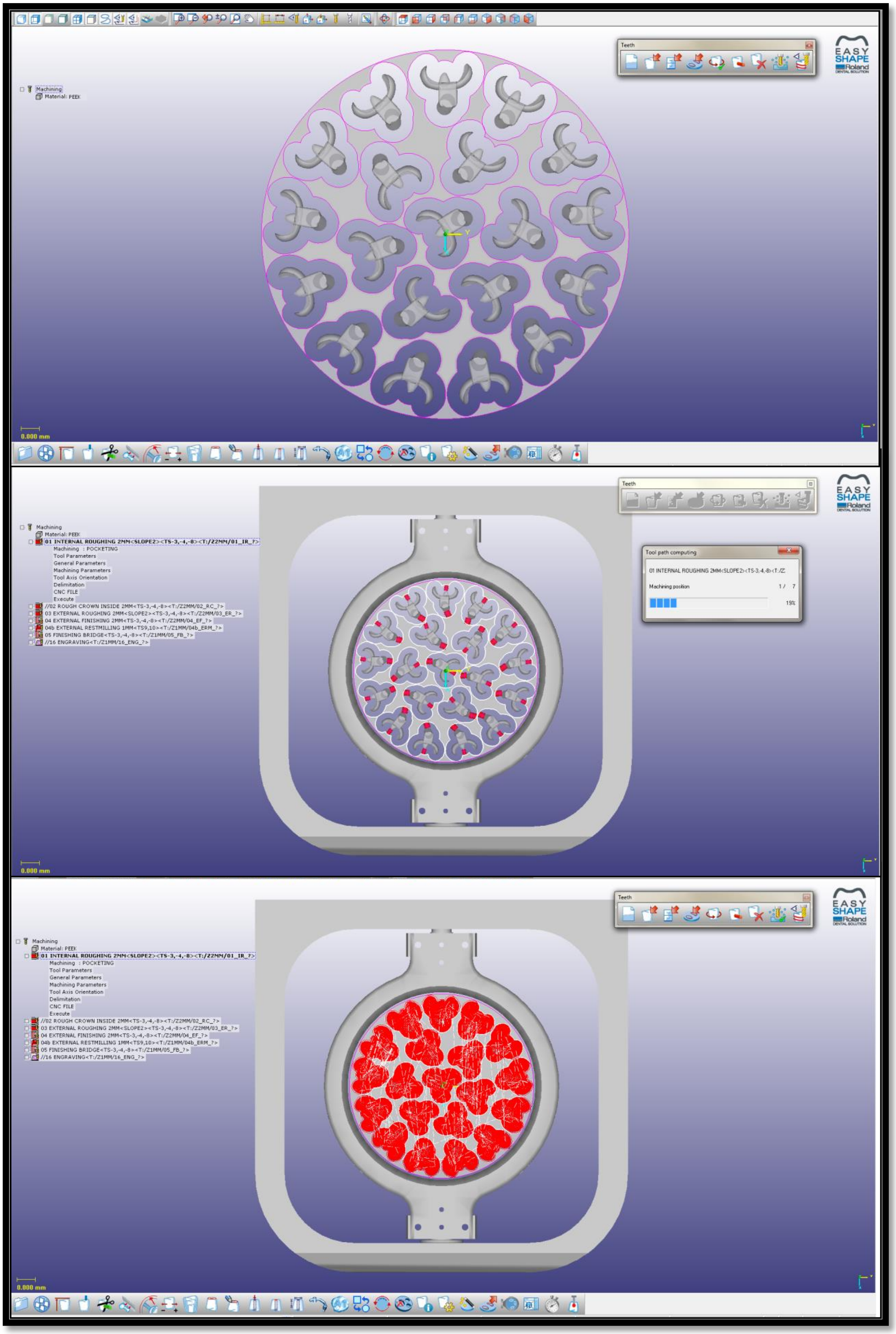
Save In: Co-Cr 0.25, 0.50, 0.75.Stl

My_Laboratory_Saja_0_25mm_Clasp_Co_Cr_single_14.stl
My_Laboratory_Saja_0_50mm_Clasp_Co_Cr_single_14.stl
My_Laboratory_Saja_0_75mm_Clasp_Co_Cr_single_14.stl

☐ Unzip

File Name: My_Laboratory_Saja_0_25mm_Clasp_Co_Cr_single_14.stl
Files of Type: All Files

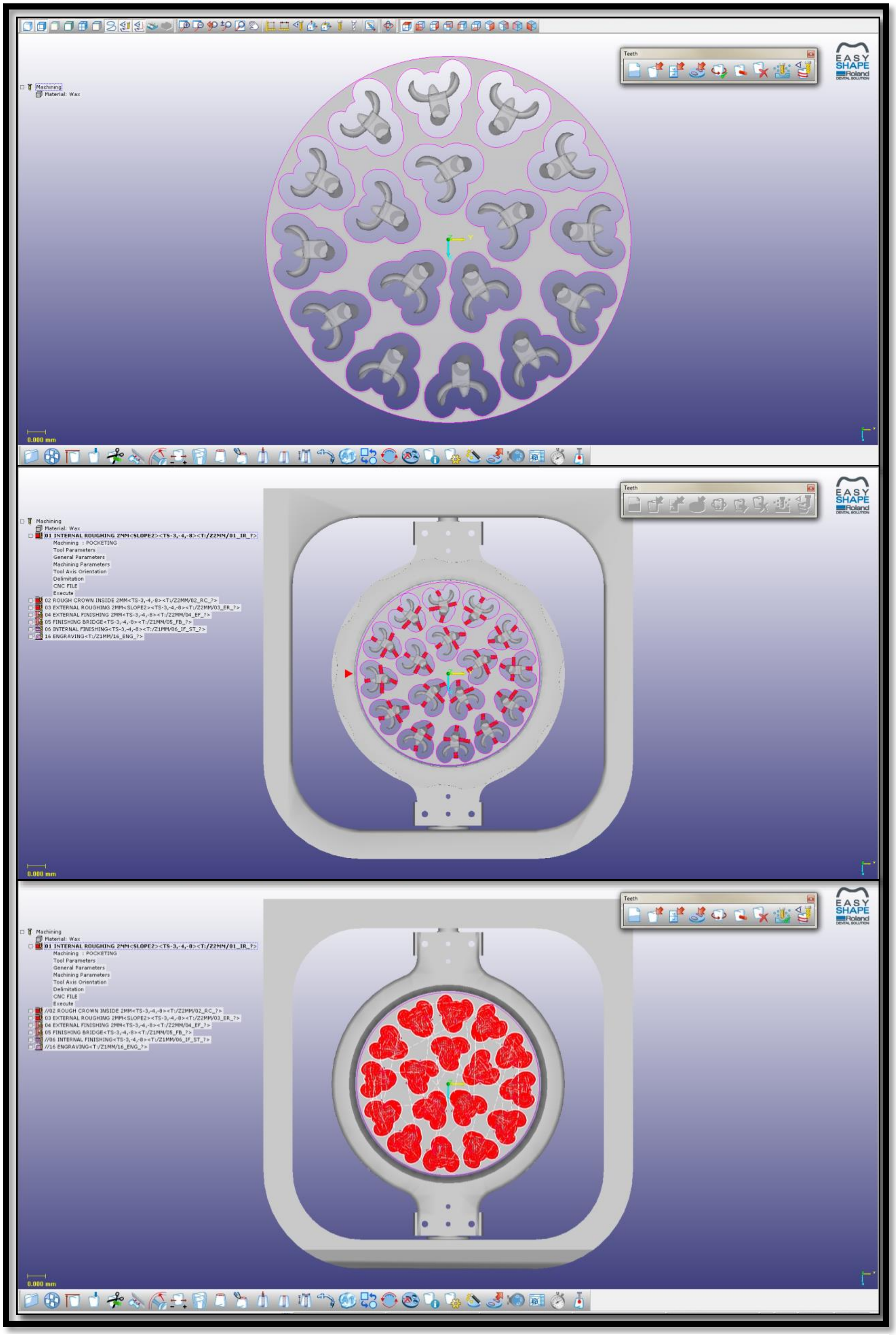
Figure (8-19): PEEK and Co-Cr clasps production route to .Stl file



```
Tool path computing
01 INTERNAL ROUGHING 2MM<SLOPE2><TS-3,-4,-8><T:/Z
Machining position                          1 /   7
                                              19%
```

Figure (8-20): Clasps sample arranged for milling into PEEK using Roland CAD/CAM machine

Figure (8-21): PEEK clasps prepared using PEEK-Juvora™ discs



```
Machining
  Material: Wax
  01 INTERNAL ROUGHING 2MM<SLOPE2><TS-3,-4,-8><T:/Z2MM/01_IR_?>
      Machining  : POCKETING
      Tool Parameters
      General Parameters
      Machining Parameters
      Tool Axis Orientation
      Delimitation
      CNC FILE
      Execute
  02 ROUGH CROWN INSIDE 2MM<TS-3,-4,-8><T:/Z2MM/02_RC_?>
  03 EXTERNAL ROUGHING 2MM<SLOPE2><TS-3,-4,-8><T:/Z2MM/03_ER_?>
  04 EXTERNAL FINISHING 2MM<TS-3,-4,-8><T:/Z2MM/04_EF_?>
  05 FINISHING BRIDGE<TS-3,-4,-8><T:/Z1MM/05_FB_?>
  06 INTERNAL FINISHING<TS-3,-4,-8><T:/Z1MM/06_IF_ST_?>
  16 ENGRAVING<T:/Z1MM/16_ENG_?>
```

```
Machining
  Material: Wax
  01 INTERNAL ROUGHING 2MM<SLOPE2><TS-3,-4,-8><T:/Z2MM/01_IR_?>
      Machining  : POCKETING
      Tool Parameters
      General Parameters
      Machining Parameters
      Tool Axis Orientation
      Delimitation
      CNC FILE
      Execute
  //02 ROUGH CROWN INSIDE 2MM<TS-3,-4,-8><T:/Z2MM/02_RC_?>
  03 EXTERNAL ROUGHING 2MM<SLOPE2><TS-3,-4,-8><T:/Z2MM/03_ER_?>
  04 EXTERNAL FINISHING 2MM<TS-3,-4,-8><T:/Z2MM/04_EF_?>
  05 FINISHING BRIDGE<TS-3,-4,-8><T:/Z1MM/05_FB_?>
  //06 INTERNAL FINISHING<TS-3,-4,-8><T:/Z1MM/06_IF_ST_?>
  //16 ENGRAVING<T:/Z1MM/16_ENG_?>
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Figure (8-22): Clasps sample arranged for milling into wax patterns for PEEK-Optima® thermo-press material

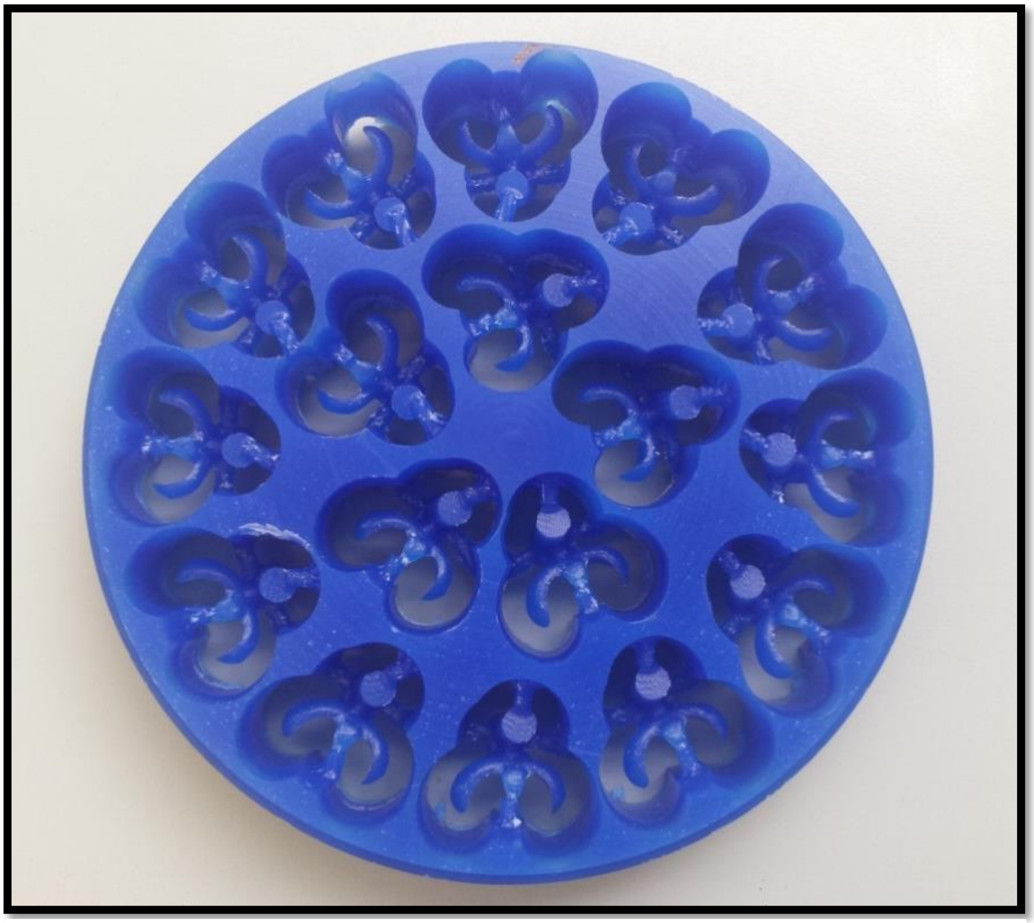

Figure (8-23): Wax clasps prepared using wax discs for thermo-press purposes

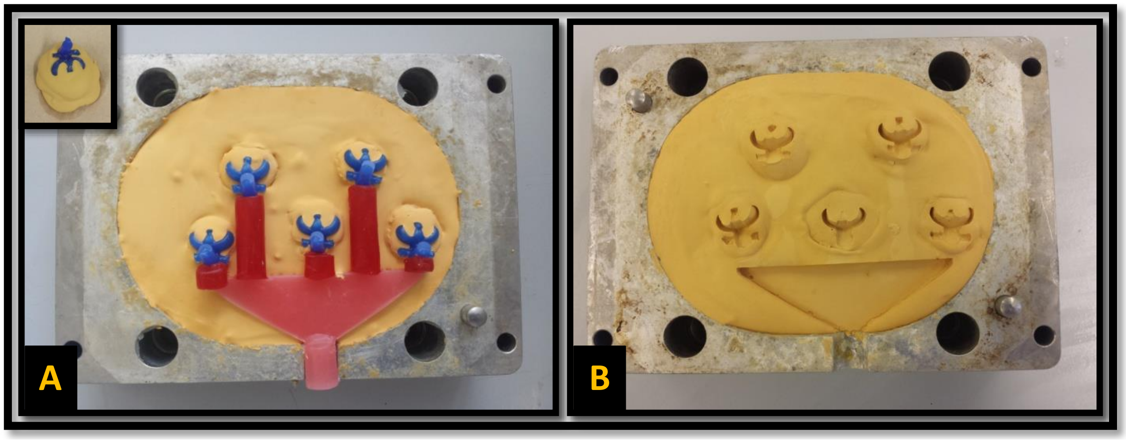

Figure (8-24): A. Wax clasps invested and flasked using type-IV moulding diestone; **B.** mould being left to dry overnight before injecting the PEEK polymer

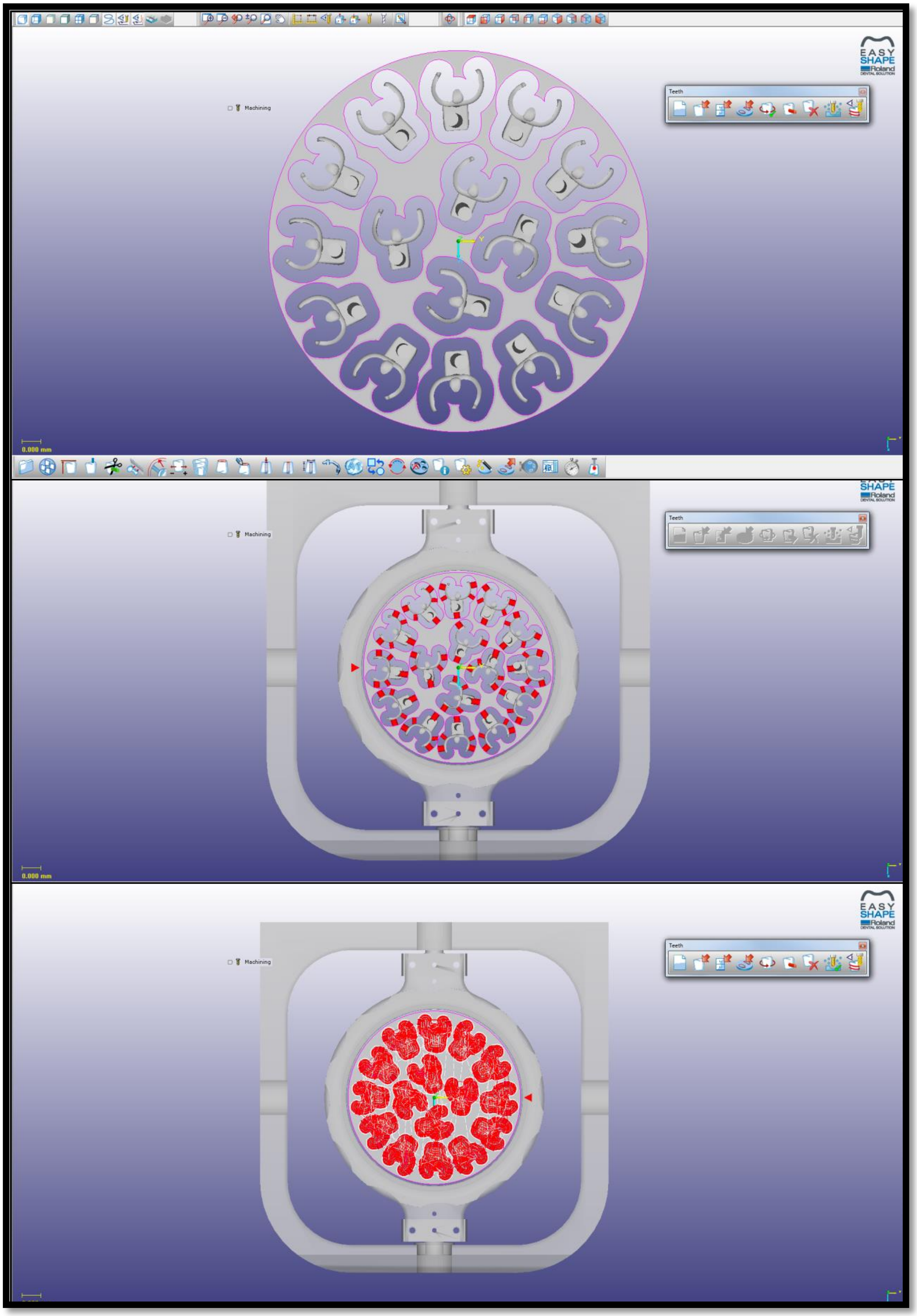

Figure (8-25): Co-Cr clasps sample arranged for milling into wax for Co-Cr specimen using Roland CAM machine

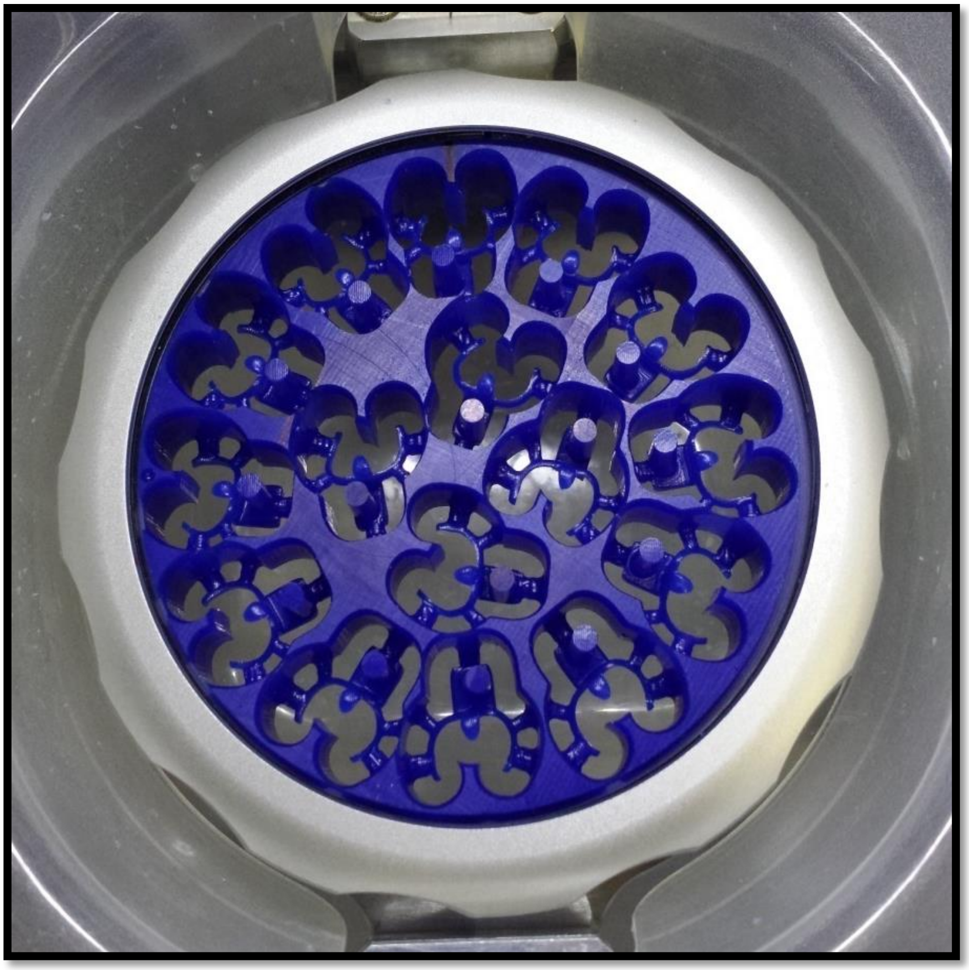

Figure (8-26): Co-Cr wax clasps prepared using milling machine

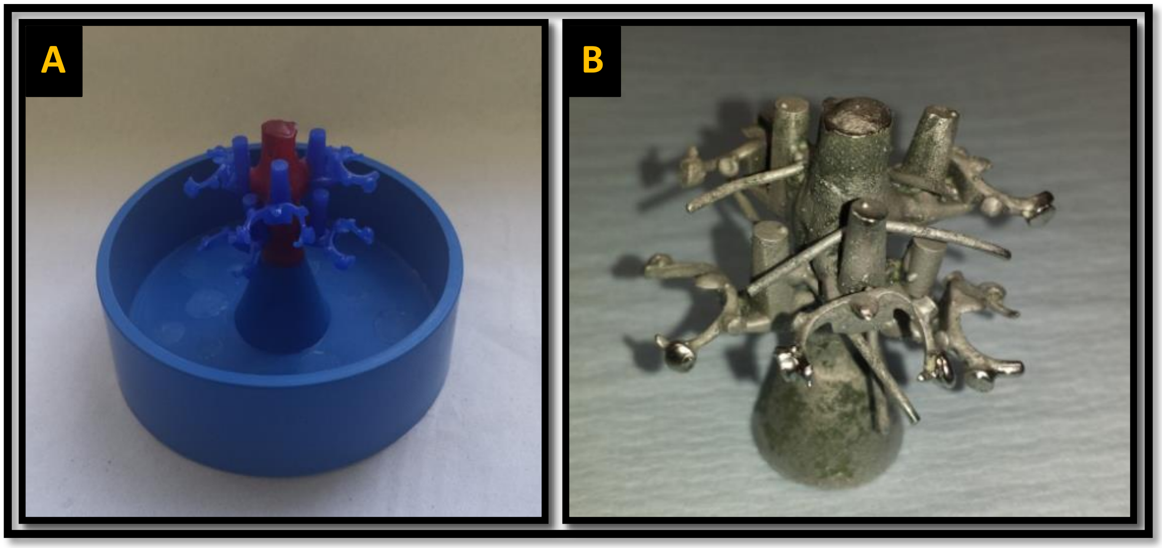

Figure (8-27): A. clasp wax patterns attached and sprued for investing procedure; **B.** Co-Cr clasps after casting

8.1.6. Sample Grouping and Testing Procedures

Ninety specimens were divided into 3 main different experimental groups according to the clasp materials: Co-Cr alloy, thermo-pressed PEEK-Optima®NI1 and machined PEEK-Juvora™. These in turn were sub-divided according to preset clasp deflection of 0.25 mm, 0.50 mm, and 0.75 mm, (n=10), which were specification designed to compare the clasps' functions under different undercuts to the tooth surfaces. Each clasp was tested for retentive force using a Lloyd tensile testing machine and then the cycle was run for suggested cycling period using a fatigue chewing simulator machine. The sample's retentive force was designed to be tested at initial insertion and then after 1st, 2nd and 3rd years. During the cycling test the steps described below were followed.

8.1.7. Clasp Testing Procedure

Clasp Retentive Force

The retentive force of each clasp was measured at a crosshead speed of 30 mm/min of the tensile apparatus. A special clasp holder and jig tools were designed in house for this study. The titanium surveyor arm was attached at one end to the upper part of the tensile jig and tightened using special slots, while at the other end of the arm the clasp was held firmly in place through the cylindrical pin on the designed clasp by a chuck hole of about 4 mm diameter. The teeth, designed with different undercut gauges were duplicated and moulded with a base made of thermoplastic material to be fixed in the lower part of the tensile jig. The distance for release of the clasp from the tooth undercut area during the testing procedure was measured for setting at 3 mm. The initial retentive force was determined for the clasp at the first insertion cycle, and the changes in retentive force at each interval were measured after the cycling period repetition; figure (8-28).

Clasp Fatigue Cycling Test

Fatigue chewing simulator machine was used to carry out this test, figure (8-29). The machine was customised to have 5 stations, each of which had a round ended indenter that was applied to the specimens by a weighted lever arm. Each station had an independent counter which halted automatically once the specimen fractured. The cycling rate could be controlled by setting the machine's control buttons. Sample mounting bases fixed in the water bath allow for a sample to be held in horizontal directions. However, for the present study a special adjustable sample holder was designed in house to fix the sample in the mounting base, to give more adjustability regarding the application of load sample direction, figure (8-30). A thermo-cycling system was circulated the hot water in the sample tank at 37 (±1˚C) and a level of 3 cm above the specimens throughout the experiment; figure (8-31). An indenter of 4.25 mm ball diameter was used in this study, at zero load of (180 N). Due to the limitations of the chewing simulator machine, one insertion/removal cycle represented 2 deflection cycles compared to machines and techniques used in other studies (Takabayashi, 2010; Tannous *et al*., 2012). The clasps were subjected to cycling deflection of preset values of 0.25 mm, 0.50 mm, or 0.75 mm measured using a digital micrometer. The assumption for the cycling was measured according to the following simple calculation, if the patient removed the denture 3 times/day for cleaning, there would be 6 insertion/removal repeated loading cycles, multiplying to 365 days/year equaling (2190 cycles) which would be approximately (2200 deflection/year), (4400 deflection/2years) and (6600 deflection/3 years).

Each specimen was fixed to the testing machine with screws. They were subjected to a cyclic deflection generated by the radial direction force at the tip of each clasp arm at a frequency of 100 deflection/min (2200= 1 year), (4400= 2 Years), and (6600= 3 Years), figure (8-32). This was to represent the removing and insertion of the appliances 3 times a day. The clasps were subjected to cyclic deflection of preset values of 0.25 mm, 0.50 mm, or 0.75 mm undercut gauges.

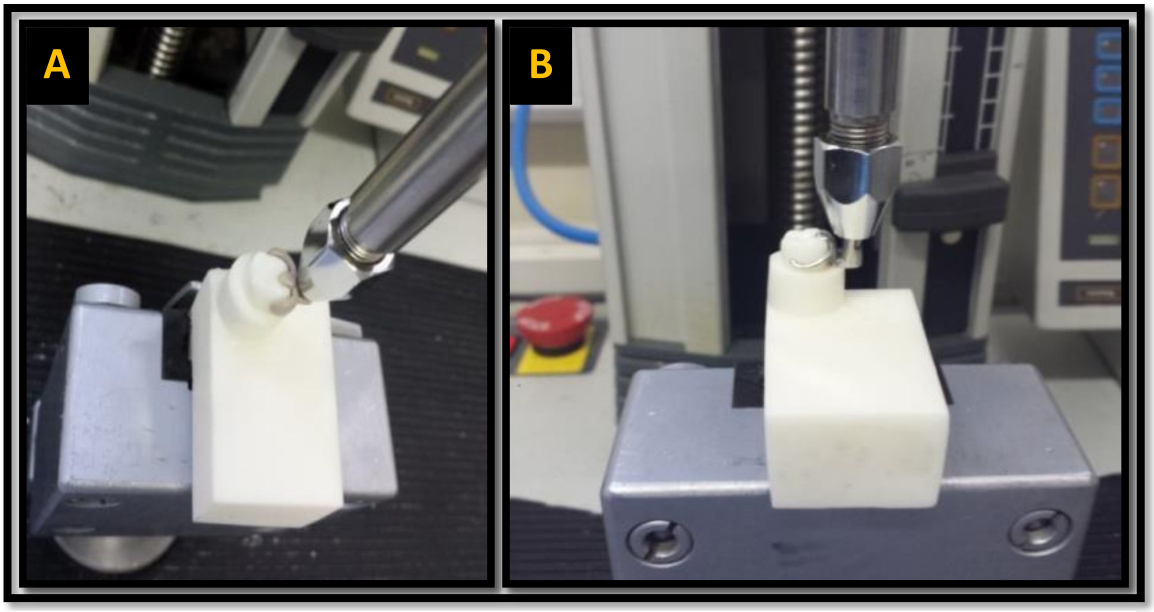

Figure (8-28): Clasps under retentive force test: **A.** PEEK clasp and **B.** Co-Cr clasp

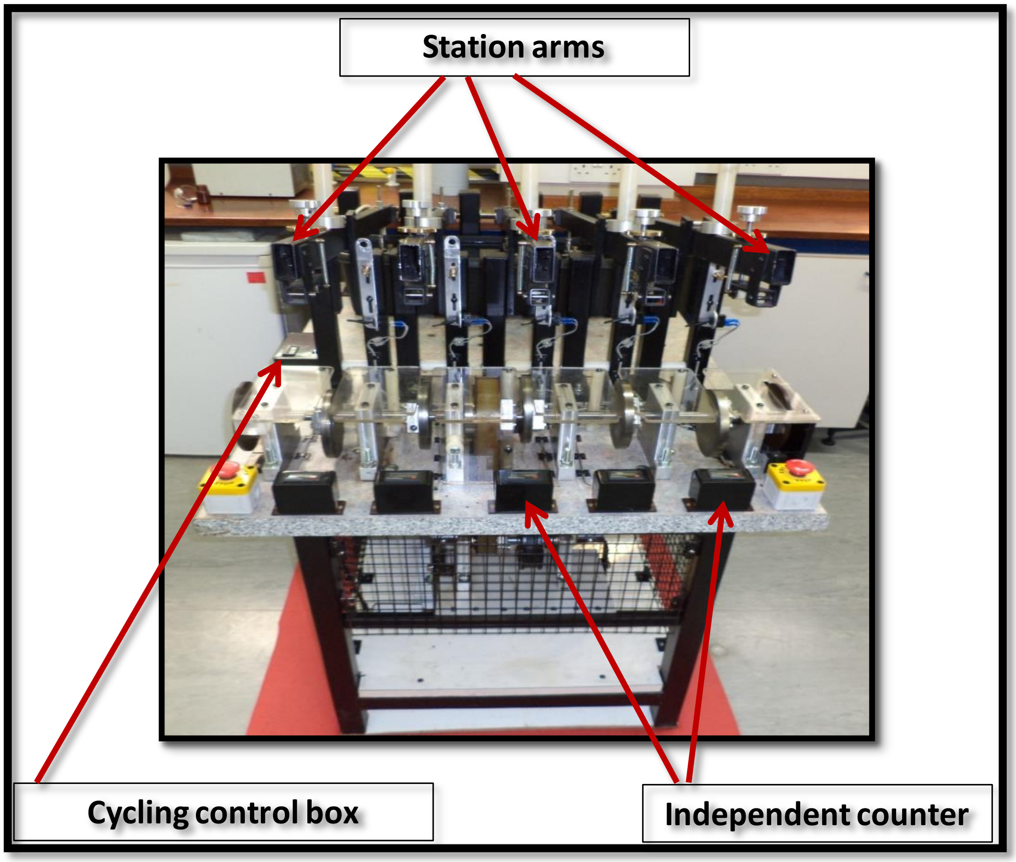

Figure (8-29): Fatigue chewing simulator machine

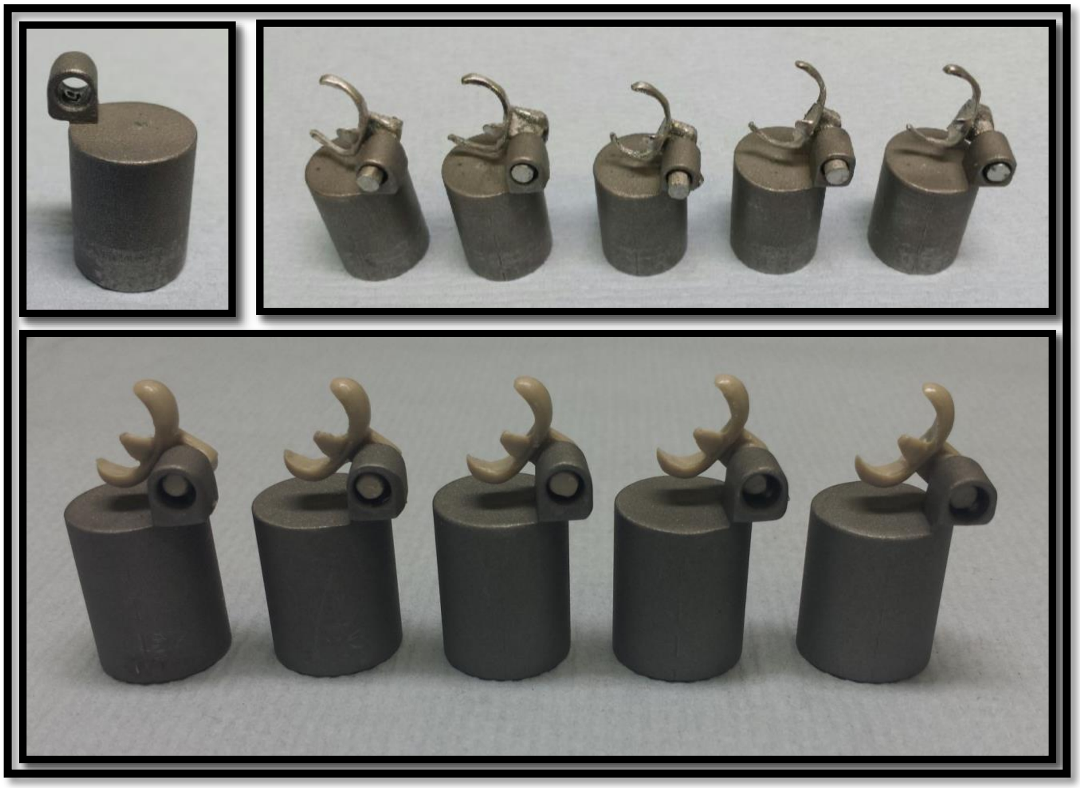

Figure (8-30): PEEK and Co-Cr clasps held by special adjustable clasp holder for cycling test

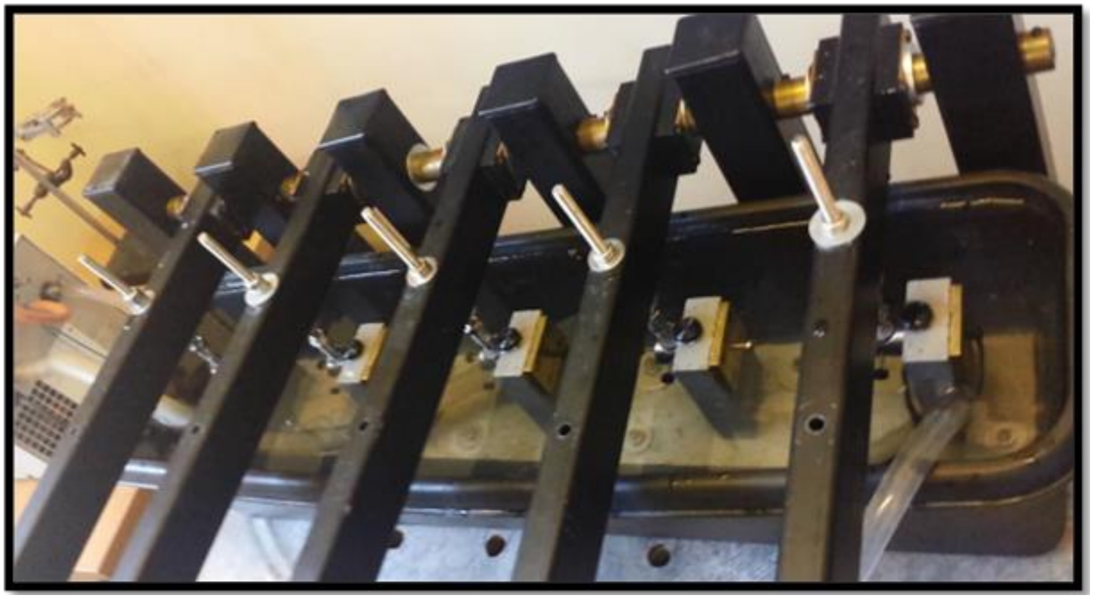

Figure (8-31): Five clasp specimens mounted inside the thermo-cycling water bath tank of the chewing simulator machine

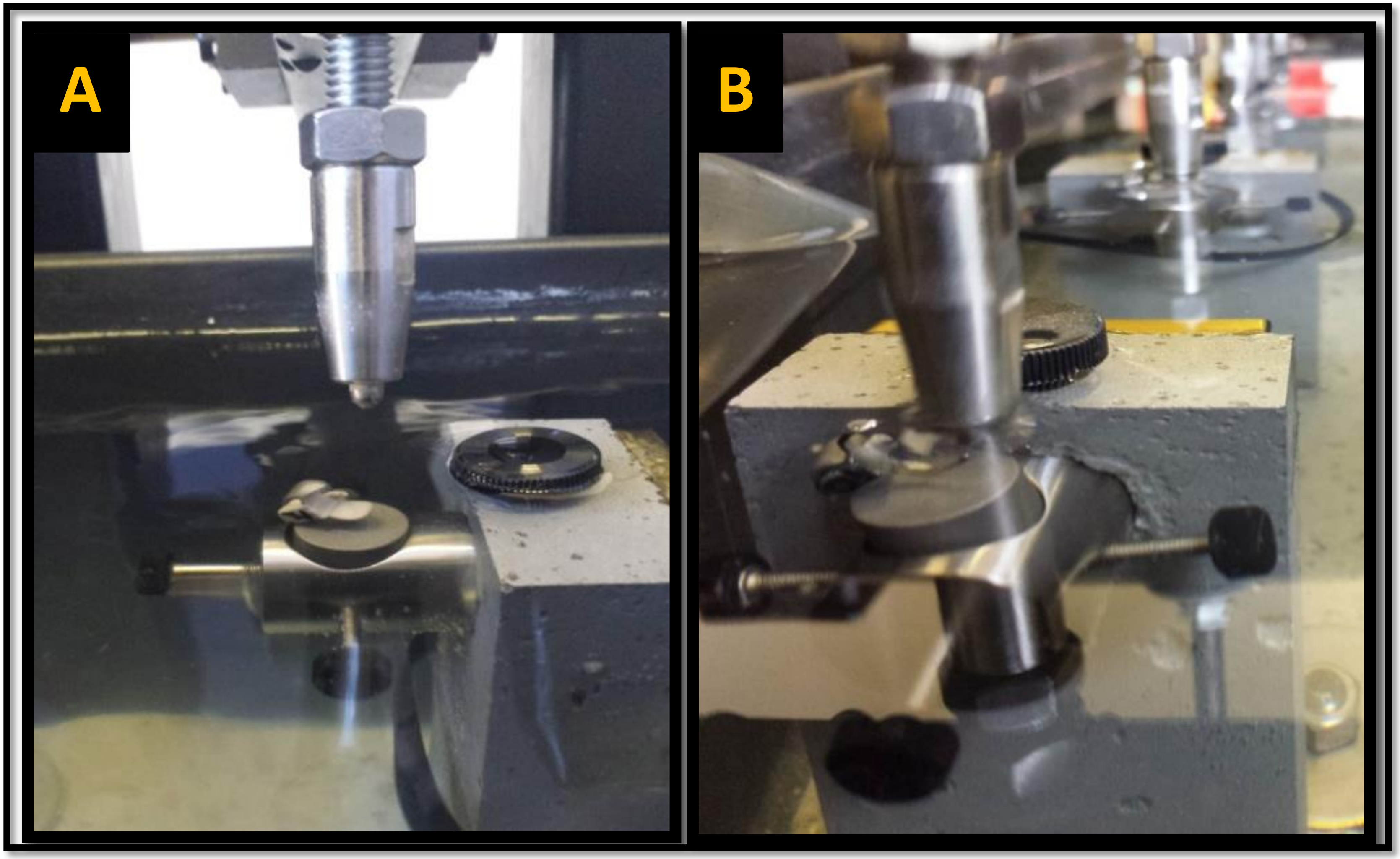

Figure (8-32): Clasps under cycling test: **A.** PEEK clasp **B.** Co-Cr clasp

8.2. Results

The statistical methods used to analyse the results included analysis of variation (ANOVA), and the test performed at a confidence level of 95 % and significant P-value of ($P \leq 0.05$).

The clasps made from PEEK-Optima® thermo-pressed at 200 °C mould temperature, machined PEEK-Juvora™, and the conventionally cast Co-Cr denture material were compared using one-way analysis of variance (ANOVA) and post-hoc tests were conducted to determine the differences in retentive force of the different clasp materials and tooth undercuts among the tested groups, see appendix part (H).

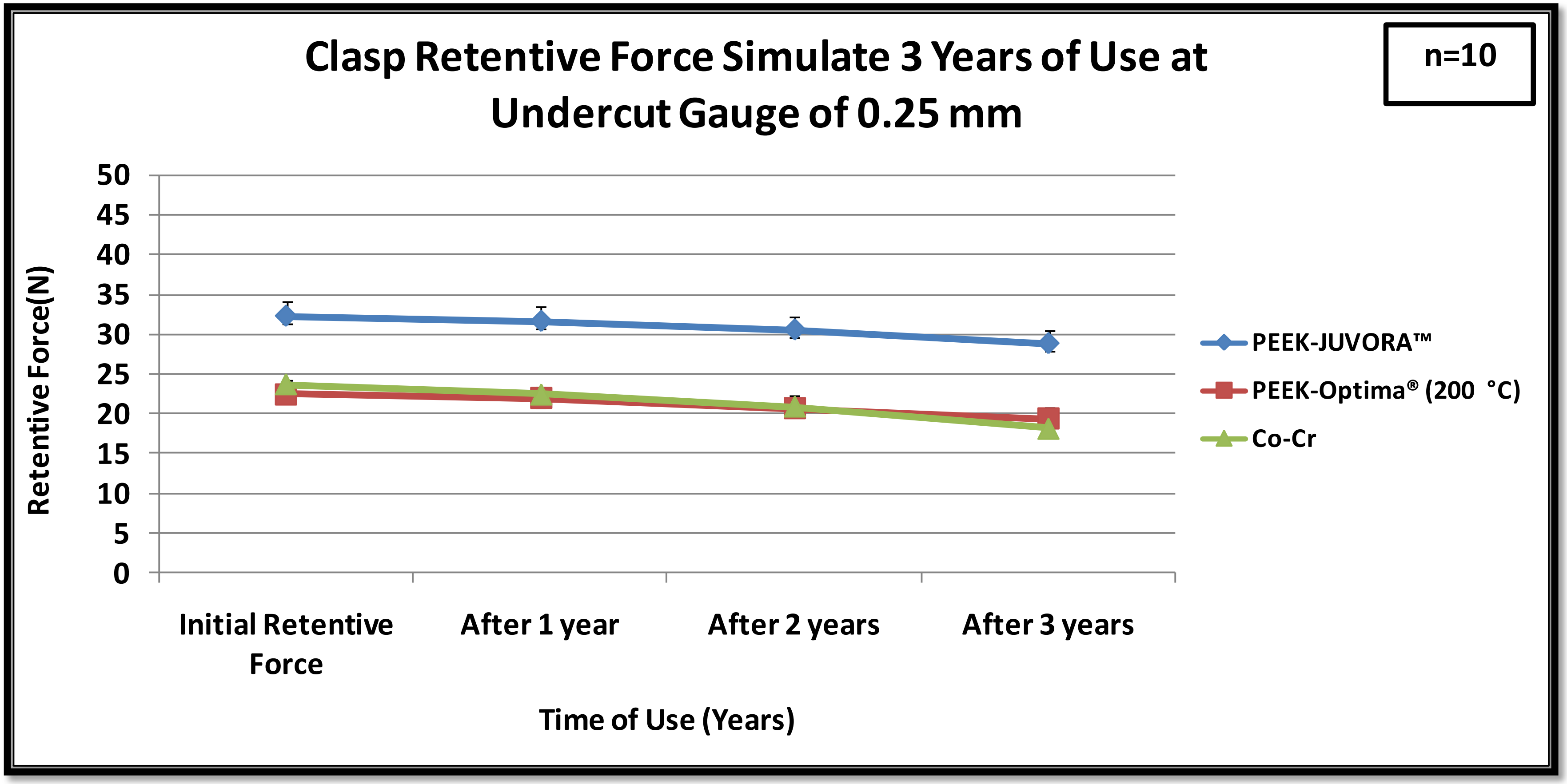

Figure (8-33): Diagram showing the mean distribution of the clasp retentive force of the tested materials over 3 years and at tooth undercut of 0.25 mm

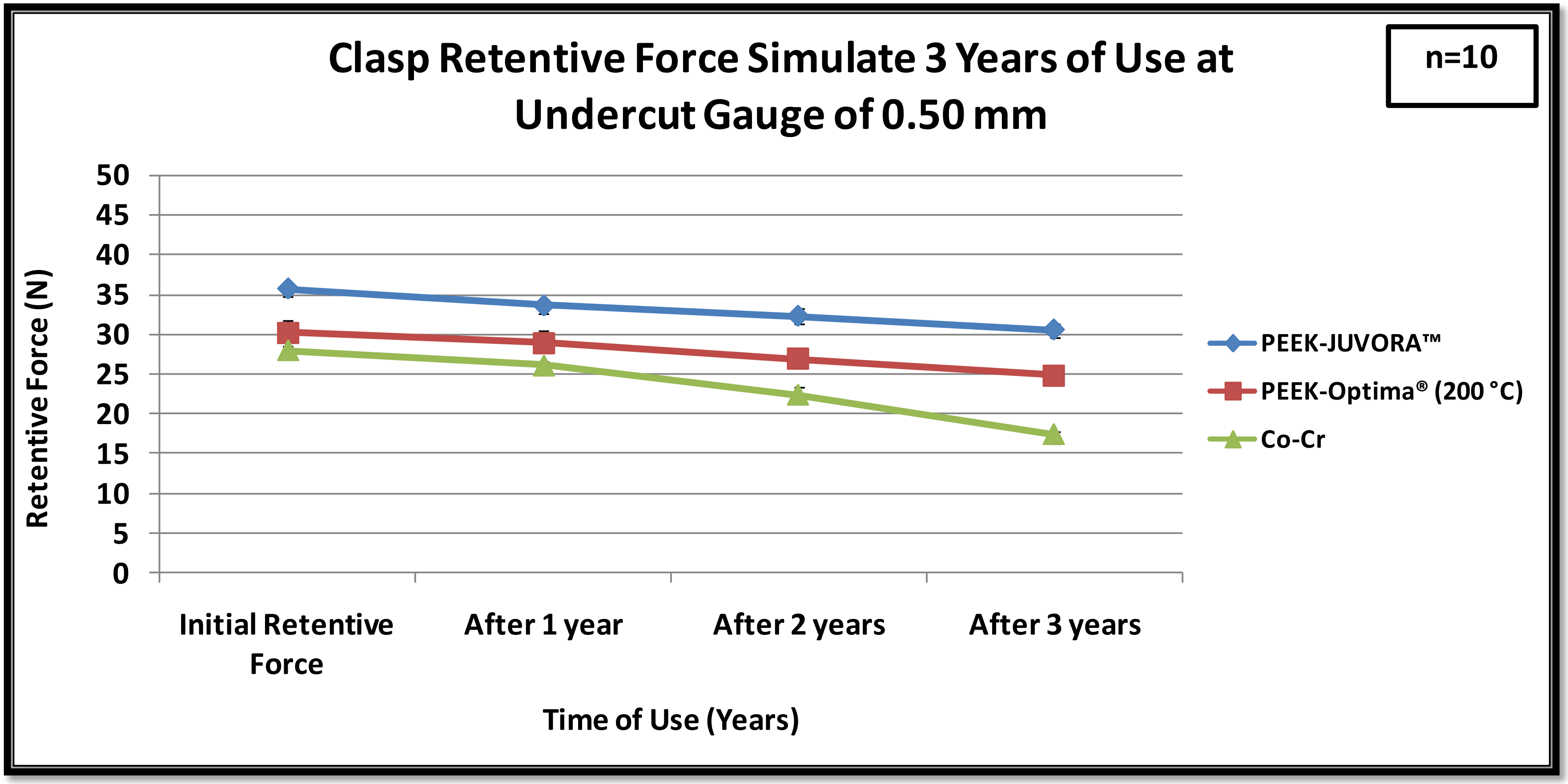

Figure (8-34): Diagram showing the mean distribution of the clasp retentive force of the tested materials over 3 years and at tooth undercut of 0.50 mm

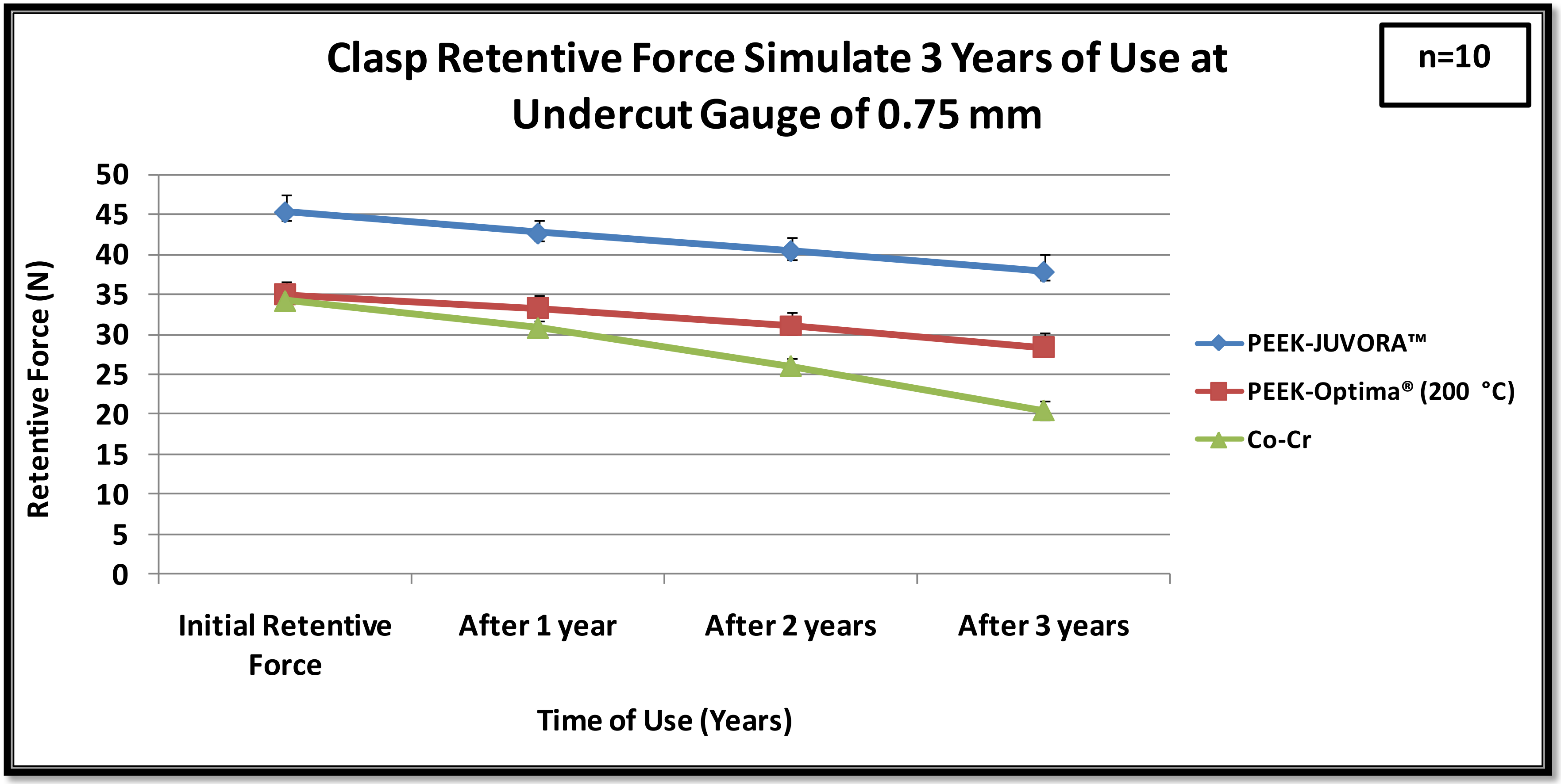

Figure (8-35): Diagram showing the mean distribution of the clasp retentive force of the tested materials over 3 years and at tooth undercut of 0.75 mm

Table (8-1): Fracturing clasp specimen materials over the years of fatigue cycling testing

Clasp Material	Undercut (mm)	No.	Fractured Specimens							
			Initial	Total	After 1 year	Total	After 2 years	Total	After 3 years	Total
PEEK-Juvora™	**0.25**	10	non	10	non	10	non	10	non	10
	0.50	10	non	10	non	10	non	10	non	10
	0.75	10	non	10	non	10	non	10	non	10
PEEK-Optima®	**0.25**	10	non	10	non	10	non	10	non	10
	0.50	10	non	10	non	10	non	10	non	10
	0.75	10	non	10	non	10	non	10	non	10
Co-Cr	**0.25**	10	non	10	non	10	2	8	1	7
	0.50	10	non	10	non	10	2	8	3	5
	0.75	10	non	10	non	10	5	5	2	3

non= non- fractured specimen

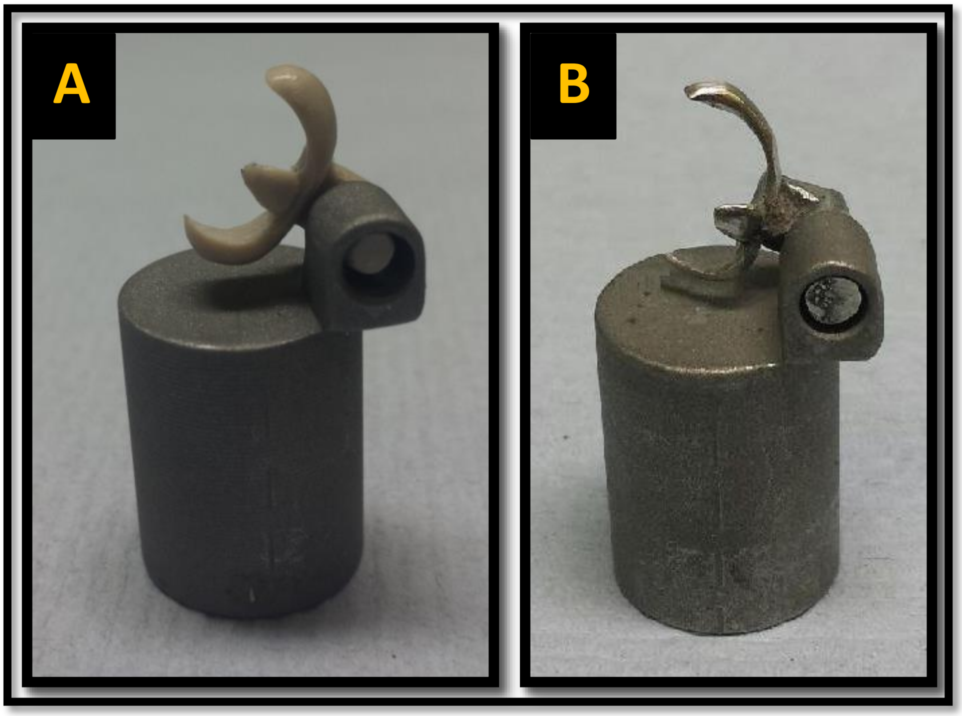

Figure (8-36): At 0.75 mm undercut and after 3 years of insertion/removal cycling testing; **A.** PEEK clasp without fracture; **B.** Co-Cr clasp specimen with fracture

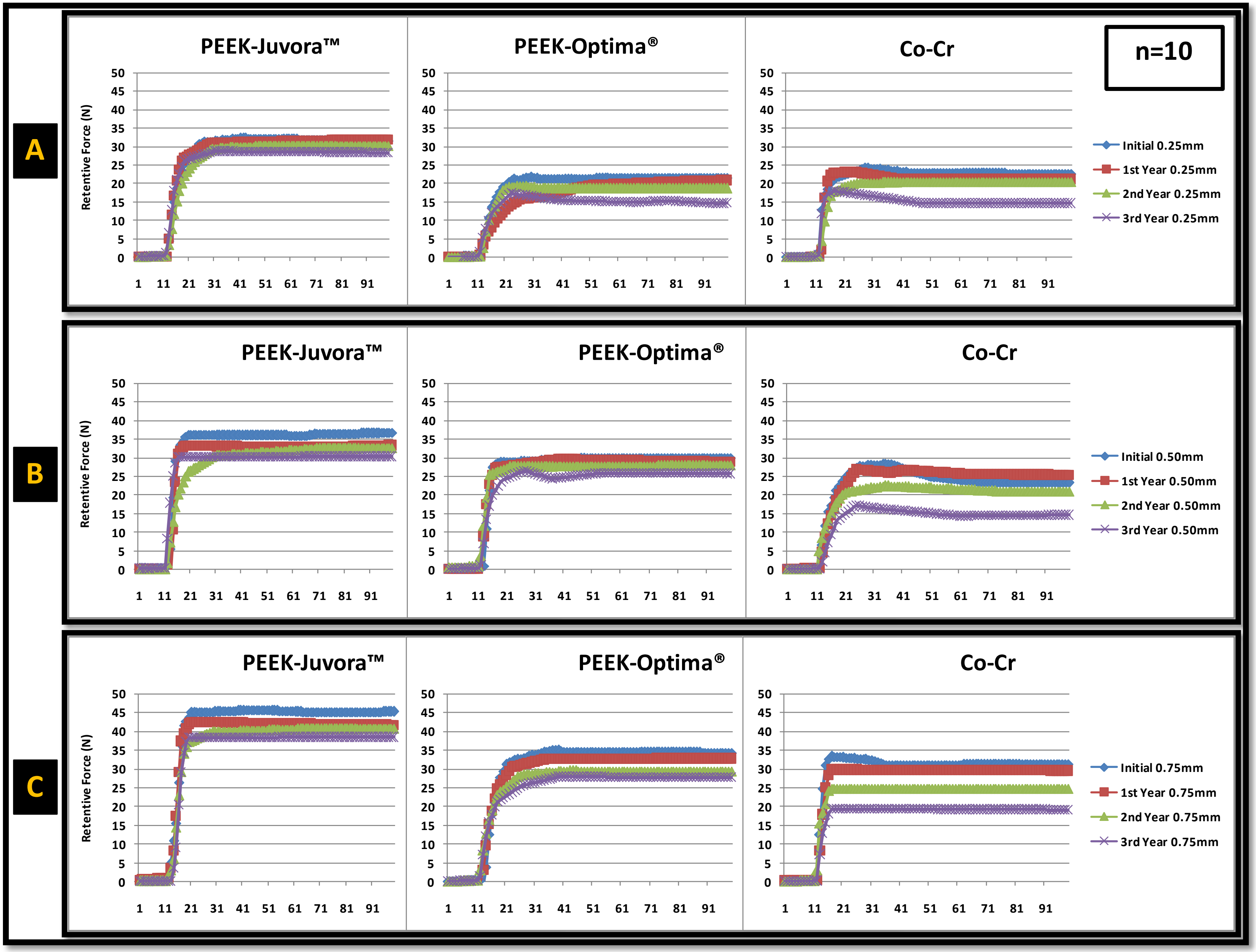

Figure (8-37): Diagram showing the retentive force needed to dislodge the clasps made of different materials over 3 years and at undercuts of **A.** 0.25 mm; **B.** 0.50 mm, and **C.** 0.75 mm

The average of the retentive force was calculated according to the difference between the forces of the Co-Cr clasp tip and the PEEK clasp flange on the abutment tooth undercut. This was measured between the retentive force at the end of each cycle term and the previous one. The averages of the retentive force for each cycle were calculated, in particular at 2200, 4400, and up to 6600 deflection. These cycles equated to the removal/insertion of the molar clasp for the 3 years periods.

The results of the one-way ANOVA for the tested clasps indicated a statistically significant influence of the undercut factor on the retention of the tested clasps ($P \leq 0.001$). Figures (8-33) to (8-35) illustrate the change in the retentive forces of each tested group. They show the changes in retentive force required to remove the PEEK and Co-Cr clasps from the 0.25, 0.50 and 0.75 mm undercuts. The mean initial retentive force for PEEK-Juvora™ clasps at 0.25, 0.50, and 0.75 mm ranged from 32 to 45 N and from 22 to 35 N for PEEK-Optima® respectively at 1.5 mm clasp thickness, while for Co-Cr clasps the range was from 24 to 34 N.

The highest initial retentive force (45 N) was recorded in the PEEK-Juvora™ clasps with 0.75 mm undercut, and the lowest retentive force (22 N) was measured in the PEEK-Optima® clasps with 0.25 mm undercut. There were no failures of any PEEK clasps at any undercuts up to 6600 insertion/removal deflection. On the other hand, most of the Co-Cr clasps with 0.50, and 0.75 mm undercuts failed within the 2nd to 3rd year, at 4400 to 6600 insertion/removal deflection.

PEEK-Juvora™ exhibited the highest retention at the 3 different undercuts over 3 years followed by PEEK-Optima®NI1 at 0.75, and 0.50 mm undercuts over the same cycling period ($P<0.05$). However, the initial retentive force required to dislodge 1.5 mm thick PEEK-Optima® clasps was statistically non-significant ($P>0.05$) compared to the traditional Co-Cr of 0.1 mm thickness at 0.25 mm and 0.75 mm undercut, and also compared to the Co-Cr clasps over the 3 years of testing by insertion/removal cycles, and particularly at the 0.25 mm undercut gauge.

Nevertheless, as the undercut and cycling increased, the Co-Cr clasps exhibited lower retention, in addition to fracturing of some specimens during the cycling period. In contrast, none of the PEEK clasps fractured during the cycling period. However, cycling activation of the Co-Cr clasp decreased the mean initial force of the clasp significantly ($P<0.05$). After the second year, two Co-Cr clasps were fractured, at the 0.25 mm and 0.50 mm undercut, while during the third year another clasp fractured at 0.25 mm and three at 0.50 mm. More clasps fractured at the maximum undercut of 0.75 mm: five clasps in the second year and another 3 during the third year, as shown in table (8-1) and figure (8-36).

Over the tested years, the PEEK-Juvora™ clasps exhibited statistically significant retentive force values ($P<0.05$) at different undercuts except at 0.75 mm undercut between the 1st and 2nd years, and at 0.25 mm between the initial retentive force and the end of the 1st and 2nd years, and between the 1st and 2nd; 2nd and 3rd years values were statistically non-significant ($P>0.05$). Also, the PEEK-Optima® clasps exhibited significant retentive force values ($P<0.05$) at different undercuts except between the initial retentive force and the end of the 1st year at 0.50 and 0.75 mm undercut the value were statistically non-significant ($P>0.05$). On the other hand, the conventional

Co-Cr clasps exhibited a statistically significant decrease in retentive force values at all tested undercuts ($P \leq 0.001$).

8.3. Discussion

Based on the data obtained in this investigation, the novel clasp design made from PEEK material showed significantly higher retention force compared to conventional Co-Cr claps. Tooth shape and clasp design may affect the retentive force, and the clasp retention could be determined by the depth of the undercut available on the tooth (Davenport *et al*., 2001). This study was designed to compare the retentive forces of clasps at 3 different levels of tooth undercut. The 0.25 mm undercut gauge was chosen because it represents the undercut commonly used for Co-Cr clasps, while the 0.50, and 0.75 mm undercuts were selected to simulate the cases where clasps should be placed closer to the gingival margin and need to be deeper for a more aesthetic result. The clasp's length, thickness, section and material influence its flexibility, and a more flexible clasp provides less retention (Davenport *et al*., 2001). In the present study a thickness of 1.5 mm was selected for making the PEEK clasps with a short flange arm.

The results of the present study indicate that the greatest retentive force for PEEK clasps was found in the 1.5 mm thick clasps designed to engage the 0.75 mm undercut, followed by the 0.50 mm clasp undercut. Thermoplastic clasps might achieve clinically acceptable retention at dimensions differing from those of metal clasps, possibly requiring thicker clasp to engage a deeper undercut (Tannous *et al*., 2012). This could be necessary due to the relatively low rigidity of the thermoplastic material compared to metals and alloys (elastic modulus: PEEK 4.0 GPa; and Co-Cr alloy 240 GPa), and may reduce the possibility of traumatic overloading (Turner *et al*., 1999; Kurtz, 2011b).

A few studies have reported on the retentive forces required for clasps retention. One such study stated that 3 to 7.5 N is the retentive force required for adequate retention and functioning of PRDPs, while another study found that 5 N could give an acceptable degree of retention (Frank and Nicholls, 1981; Sato *et al*., 2001b).

In the current study, over a test period representing 3 years, the mean retentive force decreased in milled PEEK-Juvora™ clasps with 1.5 mm thickness from 32 N to 29 N at 0.25 mm undercut gauge; from 36 N to 30 N at 0.50 mm; and from 45 N to 38 N at 0.75 mm. The retentive force of the PEEK-Optima®NI1 clasps thermo-pressed at 200 ˚C mould temperature decreased from 22 N to 19 N at 0.25 mm undercut gauge, from 30 N to 25 N at 0.50 mm, and from 35 N to 28 N at 0.75 mm. Meanwhile retentive force of the conventional Co-Cr clasps decreased from 24 N to 18 N at 0.25 mm undercut gauge, from 28 N to 17 N at 0.50 mm, and from 34 N to 20 N at 0.75 mm. In addition, there was fracturing of specimens during the periodic cycling test starting from the 2nd year and with increased undercut depth. The results show that PEEK thermoplastic material could be used in the fabrication of clasps for RPDs, as they provide adequate retention even after 3 years of simulated use. This may support the finding of Kotake *et a*l., and Kim *et al*., who found in their studies that clasps made of more elastic materials displayed superior resistance to retention loss (Kotake *et al*., 1996; Kim *et al*., 2004).

It could be claimed that bulkier thermoplastic clasp designs would impede self-cleaning and might cause more plaque accumulation. However, the clasps in the present study were designed to engage the undercut with a short flange arm. Besides, some studies have indicated that establishment of a regular recall system for plaque control would provide extra motivation, and avoid damage by the removable partial dentures to the periodontium (Bergman *et al.*, 1995; Mine *et al.*, 2009). In addition, Shimura *et al.* reported that formation of the plaque on the buccal surface is not related to the type or placement of the clasps. They recommended that the guide plane should be as close to the gingival margin as possible to reduce plaque accumulation on the disto-proximal surface (Shimura *et al.*, 2010; Tannous *et al.*, 2012). It seems that more clinical studies are needed to evaluate the effect of these clasps on plaque accumulation on the abutment teeth.

The Co-Cr clasps exhibit some loss of retention. This result appear to disagree with the findings of Rodrigues *et al.*, who reported an increase in retentive force of the Co-Cr clasp during the insertion/removal simulating test (Rodrigues *et al.*, 2002). However, the current finding seems agree with Bridgemana *et al.*, and Kim *et al.*, who also found a decrease in the Co-Cr clasps retention during the simulation test (Bridgemana *et al.*, 1997; Kim *et al.*, 2004). The reduction in Co-Cr clasp retention force may be related to permanent deformation of the metal, as claimed by Ghani and Mahood, and Kim *et al.* in their studies (Ghani and Mahood, 1990; Kim *et al.*, 2004). This result also could be related to the method used to carry out the test. The simulating test and measurement of retentive forces were performed using two different machines, and this could generate torque which may affect the outcome of clasps (Bollenl *et al.*, 1997). However, the entire sample was tested using the same procedures and techniques in order to achieve more consistent results. Furthermore, wear between the crown and the inner surface of the clasp during measurement of the retentive force was limited by duplicating the abutment to be used for each sub-group of specimens at each level.

Results produced under clinical conditions might not be the same, as the periodontal ligaments may allow physiological mobility of natural teeth. In addition, the patient may change the path of insertion or removal of the denture at each cycle. This may lead to greater loads on the abutment tooth, resulting in permanent clasp defects in a short period of time. Therefore, more studies needed to be carried out in conditions closer to clinical situations.

8.4. Conclusion

The present study draws the following conclusions:

1. At 0.25 mm undercut depth, the initial retentive force required to dislodge the 1.5mm thick PEEK-Juvora™ clasp was (32 N), for the PEEK-Optima® clasp (22 N), and for the conventional Co-Cr clasp (24 N).
2. At 0.50 mm undercut depth, the initial retentive force required to dislodge the 1.5mm thick PEEK-Juvora™ clasp was (36 N), for the PEEK-Optima® clasp (30 N), and for the conventional Co-Cr clasp (28 N).
3. At 0.75 mm undercut depth, the initial retentive force required to dislodge the 1.5 mm thick PEEK-Juvora™ clasp was (45 N), for the PEEK-Optima®NI1 clasp (35 N), and for the conventional Co-Cr clasp (34 N).
4. The highest initial retentive force of (45 N) was recorded in the PEEK-Juvora™ clasps with 0.75 mm undercut, and the lowest retentive force, of (22 N), was measured in the PEEK-Optima clasps at 0.25mm undercut.
5. PEEK-Juvora™ showed the highest retention over 3 years and at the 3 different undercuts, followed by PEEK-Optima®NI1 at 0.75 and then 0.50 mm.
6. Over the tested years the conventional Co-Cr clasps showed a significant decrease in retentive force value at different undercuts, additionally to fracturing of specimens within the tested periods.

To sum up, the novel PEEK clasp design illustrated superior retentive force at different tooth undercut values at 1.5 mm thickness in comparison to conventional Co-Cr clasps.

Chapter Nine

Final Discussion
and
Conclusion

Chapter Nine: Final Discussion and Conclusions

After the introduction of cobalt chromium (Co-Cr) and polymethylmethacrylate (PMMA) in dentistry, they became the widely used materials for the fabrication of removable partial denture frameworks (Hsu and Yen, 1998; Van Noort, 2013). The low cost of these restorative denture base materials compared to highly expensive gold restorations contributed to their popularity. Nevertheless, doubts and controversy still remain over the biocompatibility of Cobalt or Chromium based alloys in terms of their long term use in contact with oral tissues (Wataha, 2000; Wataha *et al.*, 2007). The potential systematic effects of these alloys may limit their uses in dentistry due to biological implication such local toxicity, potential allergic reactions, and their mutagenic and carcinogenic effects (Hsu and Yen, 1998; Wataha, 2000). Moreover, Co-Cr partial denture frameworks consist of a major connector and clasps integrated through one piece casting. In the case of clasps with deep undercuts the higher modulus of elasticity produces less deflection since they have limited flexibility. Hence, the retentive forces of the clasps decrease gradually and they exhibit plastic deformation, and fracturing may occur during usage (Yoda *et al.*, 2012). Furthermore, dental practitioners and technicians find these the most difficult to cope with of all the alloys due to the complexity of the casting and polishing procedures, which require the use of special machines and systems (Wataha *et al.*, 2007; Alarcon *et al.*, 2009). PMMA denture base polymer demonstrates poor mechanical properties, dimensional changes and distortion due to polymerization shrinkage as well as the high coefficient of thermal expansion

(Greener *et al*., 1972; Combe and Combe, 1986; Anusavice *et al*., 2013). Additionally, the risks of methylmethacrylate liquid allergic effects on patient bearers' soft tissues and contact dermatitis and reactions among dental technicians are crucial issues (Meding *et al*., 2006).

To sum up, over the last 15 years, Co-Cr alloys and PMMA have during their fabrication and application revealed many characteristics that may do not meet the requirements for a satisfactory denture base.

In recent years, considerable attention has been directed towards the development of new denture materials for load-bearing areas. One major advantage of developing new materials is that it provides the opportunity to improve the mechanical properties for specific applications. There is a difficult philosophical decision for practitioners to make, which should be based on the financial, legal, and technical implications as well as acceptability to patients. In addition, prudent practitioners should avoid the use of denture base materials that may incur biological and mechanical risks. PEEK is a high performance thermoplastic semi-crystalline polymer. To date it has been associated with high performance structural, load-bearing materials and devices in a range of different applications (Cogswell and Leach, 1992; Bakar *et al*., 2003a; Bakar *et al*., 2003b; Kurtz, 2011b). In addition to its superior mechanical properties, PEEK also has other functional properties suitable for biomedical applications and has been most widely used in the load-bearing orthopaedic applications (Akay and Aslan, 1992; Barton *et al*., 1996; Corvelli *et al*., 1997). In addition, a few clinical studies have attempted to use PEEK polymer to fabricate removable dental prostheses as an alternative material to metals and acrylic resins (Costa-Palau *et al*., 2014; Zoidis *et al*., 2015). However, more studies are needed to estimate the efficacy of PEEK polymer as a denture material and as a RPD framework compared to the conventional denture material. Therefore, this study aimed to evaluate the merits of Polyetheretherketone (PEEK) as a new restorative dental material and in particular for the fabrication of removable partial denture frameworks. This involved processing PEEK-Optima®NI1 polymer by denture injection method and machining PEEK-Juvora™ using CAD/CAM production method. These were then compared to the most commonly used and conventional PMMA and Co-Cr alloy denture materials.

1. PEEK polymer is available for medical purposes as granules (PEEK-Optima®NI1) for injection, and as discs (PEEK-Juvora™) for machining. The use of thermo-pressing method requires optimisation of the mould temperature for the injected product. Providers recommend that the moulding temperature should be in the range of 175-205 °C to ensure uniform crystallinity and stability of the moulded parts (Invibio, 2004a). Therefore, the temperature of moulds made of hard diestone gypsum material was optimised in the case of the PEEK-Optima®NI1 (Tg: 143 °C) for thermo-pressing below the PEEK Tg at 100 °C, and above the PEEK Tg at 150, 175, and 200 °C mould temperature. These mould temperatures optimized at 90, 120, 90, and 150 min using the Vecstar furnace setting up at 150, 200 and 250 °C respectively. All the physical and mechanical properties of PEEK-Optima®NI1 were tested at these suggested temperatures.

2. After the optimisation of the mould temperature, the material was thermo-pressed using denture injection method to test the flow percentage and the dimensional accuracy at sample depths of 0.8 and 1 mm. The flow test showed that as the sample depth increased from 0.8 mm to 1 mm, the flow percentage of the thermo-pressed PEEK-Optima® NI1 improved, and under light microscopy, the PEEK-Optima° NI1 that thermo-processed above the PEEK T*g* revealed more crystalline counterparts, particularly at mould temperature of 200 °C, compared to that processed at 100 °C below the PEEK T*g* which exhibited transparency and more amorphous characteristics. The dimensional accuracy of the PEEK sample varied depending on the mould temperature and specimen depth. However, the most constant percentage in terms of thickness was noticed with the PEEK-Optima® thermo-pressed at 200 °C, which increased by about 33 % from the original dimension of 0.8 mm, and by about 32 % in the case of the 1 mm depth sample.

3. Surface topography is of vital importance in denture materials, and the use of thermo-pressed PEEK polymer as a denture material may influence the device's mechanical strength and the ability of microorganisms to colonise it. Processing conditions such as mould temperature may affect the surface topography and thereby contribute to microbial accumulation underneath the denture. A few studies have reported on acceptable surface roughness for denture bases in terms of health considerations. According to Bollenl *et al*. and Radford *et al*., higher concentration of bacterial colonisation could occur in some denture base materials when the surface roughness value is greater than 2.0 µm (Bollenl *et al*., 1997; Radford *et al*., 1999).

Therefore, the surface roughness of the injected PEEK-Optima® at different mould temperatures was estimated as an attempt to predict the microbial colonisation. When as the PEEK-Optima® was thermo-pressed at mould temperatures above the PEEK T*g*, the surface roughness decreased. The lowest mean value, of 1.7 (±0.9) µm, was recorded in the sample group thermo-pressed at 200 °C mould temperatures in comparison to 1.8 (±0.5) µm recorded in the thermo-pressed PMMA.

4. Although the raw material suppliers may provide data sheets and catalogues of these materials' mechanical properties, generally these need interpretation and manipulation before application in a valid design (Jones *et al.*, 1985). Since the primary mode of clinical failure could be determined by the initial mechanical properties of the denture materials, it is possible to make some predictions here. The initial mechanical properties of PEEK polymer could have major bearing on its propensity for clinical failure. For instance, a specific application may need different mechanical property data, for other temperatures, time periods and stresses, from those presented in the data sheets. Whilst PEEK as a biomedical polymer has been suggested for use as a dental prosthesis, no studies have reported on evaluation of PEEK as a denture base material in terms of its various mechanical properties. In addition, with increasing interest in use of the injection moulding process for PEEK applications, there is concern about the strength of the mechanical properties of these materials under different mould temperatures. In terms of material and property selection, the importance of service conditions is illustrated by the influence of processing conditions on the mechanical properties of the unfilled PEEK as a denture base. Since injection moulding conditions might influence the

processing parameters, it is essential to investigate the effects of thermo-pressing conditions on the mechanical performance of the injected material. Therefore, the mechanical properties of the machined PEEK-Juvora™ and thermo-pressed PEEK-Optima®NI1 at different mould temperatures were estimated and evaluated in comparison to those of conventional base materials. Tests of impact strength, flexural properties and tensile strength were carried out to determine the PEEK polymer's properties as a denture material. The Izod impact strength of the PEEK polymer as a denture material was higher than that of the conventional PMMA processed by heat-curing (2.3 KJ/m^2) and thermo-press (2.2 KJ/m^2) techniques. The PEEK-Optima®NI1 samples thermo-pressing at mould temperatures above the PEEK Tg showed the same impact strength range of about 4.8 to 5.3 KJ/m^2, while the PEEK-Juvora™ had lower impact strength of about 4 KJ/m^2. Hence, although the PEEK polymer could be considered as a notch weakening material, its impact strength as a denture material was superior to that of the conventional PMMA.

5. The 4-point bend test was used to evaluate the material flexural properties such as Young's modulus, maximum deflection at maximum load, and the resilience under a maximum load of 100 N. Co-Cr alloy is a conventional base material that was used for comparison in this test, and has exhibited higher Young's modulus value as a denture base than the other tested materials. The thermoplastic PEEK-Juvora™ and PEEK-Optima®NI1 exhibited superior Young's modulus compared to PMMA processed by two techniques. PEEK-Optima®NI1 samples thermo-pressed at different mould temperatures showed the same Young's modulus. However, the maximum bend deflection under the

load of 100 N was noticed with the PMMA sample and the lowest was observed with the Co-Cr sample. The PEEK-Juvora™ sample revealed the lowest bend deflection among the tested groups. Also, the PEEK-Optima® sample thermo-pressed at 200 °C mould temperature had lower bend deflection than the samples thermo-pressed at different mould temperatures. In terms of resilience, and the ability of the material to spring back to its original shape after load removal, the Co-Cr has the lowest resilience ability compared to the PEEK-Juvora™, PEEK-Optima®NI1, and PMMA denture material. However the other thermoplastic materials showed the same ability to spring back to their original shape after force removal. According to Ucar *et al*., high flexibility material may not be the ideal choice as major connector, but high flexibility is crucial for clasp design in RPDs. Hence, flexural modulus and rigidity are more essential than higher deflection rates (Ucar *et al*., 2012).

6. The denture material may elongate under tension load, and return to its original shape and size when unloaded. However, beyond the elastic region there may be a plastic deformation whereby the original form may not be completely regained after unloading. Although PEEK may display elastic behaviour whereby deformations are completely recoverable upon removal of the load, no information or studies are available on the tensile strength of PEEK as a denture base material. Therefore, this study examined the tensile strength of PEEK polymer using different processing methods. Machined PEEK-Juvora™ revealed the highest tensile strength, of about 118 MPa with a maximum deflection of 7 mm at a maximum break load of 585 N. This was superior to that of the PEEK-Optima® thermo-pressed at 150 °C mould temperature, at

96 MPa, and that of the 200 °C thermo-pressed PEEK-Optima®, at 97 MPa, with maximum deflection of 15 mm and 12 mm and at maximum break loads of 557 and 562 N respectively. However, the PEEK polymer exhibited excellent tensile strength compared to the traditional PMMA processed by heat-cured method, at 65 MPa (deflection: 4 mm), and compared to the 68 MPa (deflection: 5 mm) of the thermo-pressed PMMA. These results were obtained at maximum break loads of 439 and 424 N respectively. The PEEK polymer thus demonstrated superior tensile strengrh, and elastic regions with low plastic deformation compared to the PMMA. Furthermore, the flexibility and highly elastic nature of the PEEK polymer could potentially decrease the stress on abutment teeth, which in turn could be advantageous in designing clasps using deep undercuts on the remaining teeth, thus elemination denture pain due to excessive local pressure.

7. Most dental patients of all ages prefer to avoid the use of metal in dental treatment because of the superior aesthetic qualities of non-metal frameworks and their allergy free components. Due to such increased patient expectations, non-metal dentures using thermoplastic materials have recently become a treatment option for patients (Schmalz and Garhammer, 2002; Ruff and Belsito, 2006). Therefore, and as a consequence of the present study's results concerning the superior physical and mechanical properties of PEEK polymer, the study went on to investigate the PEEK-Juvora™ and thermo-pressed PEEK-Optima®NI1 polymer as materials for denture clasp. A novel clasp design was created for the PEEK polymer at different tooth undercuts of 0.25, 0.50, and 0.75 mm. This design was evaluated in comparison with the most popular conventional Co-Cr alloy

clasp design by simulating 3 years' insertion/removal use. Within the current study results, the PEEK-Optima®NI1 thermo-pressed at 200 °C mould temperature above the PEEK T*g* mainly exhibited improved physical and mechanical properties. Therefore, PEEK-Optima®NI1 thermo-pressed at this mould temperature was selected for evaluation the clasp retention test. The highest retention force over 3 years and at 3 different levels of tooth undercut was observed with PEEK-Juvora™. The highest initial retentive force of 45 N was observed with the PEEK-Juvora™ clasps of 0.75 mm undercut depth, followed by the PEEK-Optima®NI1 at 0.75 mm (35 N) and 0.50 mm (30 N). The PEEK clasps exhibited no tendency to fracture at any undercut depths over the tested period. However, the Co-Cr clasps demonstrated lower effectiveness with decreased retentive force values at different undercut depths, additionally to fracturing specimens during the cycling test.

To sum up, the most significant and novel findings of this thesis relate to its demonstration of most superior mechanical properties of PEEK polymer as a denture base material compared to the most commonly used PMMA, and the exceptional retentive force of the innovative clasp design at different depths of tooth undercut compared to the conventional Co-Cr clasp design. These findings indicate the promise offered by PEEK thermoplastic polymer for future use as a denture material.

Chapter Ten

Further Work

Chapter Ten: Further Work

Further studies are needed to consider PEEK as a denture material from the following aspects:

1. Evaluation of the flow and thickness accuracy of thermo-pressed PEEK-Optima®NI1 at different sample depths of 1.5, 2 mm, and 3 mm with PMMA, denture resins and thermoplastic denture polymers.
2. Testing of the shear bond strength of the PEEK-Juvora™ and PEEK-Optima®NI1 to denture teeth and composite resin using different methods such as chemical agents and mechanical retention.
3. Measurement of the retentive force of the dove-wing PEEK clasp design on the premolar teeth.
4. Testing PEEK's retention and stability using the novel dove-wing clasp design as a full palatal RPD framework and palate-free RPD framework.
5. Analyse and evaluate the crystalline percentage and thermal behaviour of PEEK-Optima®NI1 thermo-pressed at different mould temperatures above the PEEK T*g* using Differential Scanning Calorimeter (DSC) and SEM.
6. Measurement of the physical and mechanical properties of PEEK polymer using high temperature resistance bonded investment materials instead of hard diestone material to thermo-press PEEK-Optima®NI1 at different mould temperatures.
7. Measurement of the microbial accumulation and activity on the surfaces of machined PEEK-Juvora™ and thermo-pressed PEEK-Optima®NI1 at mould temperatures above the PEEK T*g*.

Achievements

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1. International Awards

***** BSODR Dental Materials Group Prize and VOCO Dental Biomaterials Prize Award, IADR/PER Congress, Dubrovnik, Croatia (10th September, 2014).

2. National Awards

a. 3 Minute Thesis Competition (3MT), Faculty of Medicine, Dentistry and Health, University of Sheffield, Sheffield, UK (8th June 2015).

b. Certificate of appreciation ”The Achievements of the Iraqi Women in the UK“, The Ambassador of the Republic of of Iraq in the Uk, London, Uk (12th March, 2016).

3. Conference Papers

3.1. Oral Presentations

a. "Determination of Polyetheretherketone (PEEK) Impact Strength as a Denture Material", IADR/PER Congress, Dubrovnik-Croatia (9-13th September, 2014).

b. “Investigating the Surface Roughness of Thermo-pressed Polyetheretherketone (PEEK) as a Denture Base material”, UK Society for Biomaterials (UKSB), 14th Annual Conference and Postgraduate Day, Belfast, UK (25-26th June 2015).

c. “Mechanical Properties of Thermo-pressed Polyetheretherketone as a Denture Material”, British Society for Oral and Dental Research (BSODR), Annual Meeting, Cardiff, UK (14-16th September 2015).

3.2. Poster Presentations

a. “Comparison of Impact Strength of Machined and Thermo-pressed Polyetheretherketone (PEEK) Denture Base Material”, USES Conference, University of Sheffield, Sheffield, UK (24th June, 2014).

b. “The Effect of Processing Conditions on the Flexural Strength of Polyetheretherketone (PEEK) Used as Innovative Denture Base Material”, 2nd International PEEK Conference, Washington DC, USA (23rd-24th April, 2015).

c. “Retentive Force of Novel Polyetheretherketone Clasp Design at Different Undercuts”, IADR/APR General Session and Exhibition, Seoul-Republic of Korea (June 22-25th, 2016).

4. Future Publications

a. Saja A. Muhsin, Paul V. Hatton, Anthony Johnson, Nuno Sereno, and Duncan J. Wood**. “**Determination of Polyetheretherketone (PEEK) Mechanical Properties as a Denture Base Material”

b. Saja A. Muhsin, Paul V. Hatton, Anthony Johnson, Nuno Sereno, and Duncan J. Wood. “Effects of Novel Polyetheretherketone (PEEK) Clasp Design on Retentive Force at Different Tooth Undercuts”.

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RESEARCH AGREEMENT

DATE 01/02/2013

BETWEEN:

(1) **INVIBIO LIMITED**, a company incorporated in England and Wales (registered no: 4088050) whose principal place of business is at Technology Centre, Hillhouse International, Thornton Cleveleys, Lancashire, FY5 4QD ("**Invibio**"); and

(2) **UNIVERSITY OF SHEFFIELD,** whose principal place of business is at University of Sheffield, New Spring House, 231 Glossop Road, Sheffield, S10 2GW, UK ("**UNIVERSITY OF SHEFFIELD**").

THE PARTIES AGREE as follows:

1. PURPOSE OF THE AGREEMENT

1.1 The purpose of the Agreement is a preliminary material suitability assessment ("Study") to be carried out by **UNIVERSITY OF SHEFFIELD**.

1.2 The Study will test Invibio's implantable grade PEEK-OPTIMA polymer (the "Biomaterials") as detailed in Schedule 1. Invibio shall provide **UNIVERSITY OF SHEFFIELD** free of charge with an agreed sample size of the Biomaterials for the purpose of conducting the Study. Should the University of Sheffield wish to extend the scope of the project beyond that outlined Schedule 1 to specifically include an investigation into the behaviour of PEEK frameworks machined through CADCAM using JUVORA® dental discs, then Invibio shall agree to such an extension in scope and shall supply an agreed sample size of JUVORA® dental discs or if necessary milled frames. For the avoidance of doubt, the definition of Biomaterials shall include JUVORA® dental discs.

1.3 In return **UNIVERSITY OF SHEFFIELD** shall inform Invibio in writing of the results of the Study. In the event that **UNIVERSITY OF SHEFFIELD** wishes to publish these results, then Invibio shall be informed in writing, a minimum of 30 days before submission of such proposed publication and shall be provided with a draft of such proposed publication for review and comment.

2. USE OF THE BIOMATERIALS AND SAFETY

2.1 **UNIVERSITY OF SHEFFIELD** shall only use the technical grade Biomaterials for experimental purposes, in connection with the Study. **UNIVERSITY OF SHEFFIELD** shall not sell or otherwise make the Biomaterials available to third parties. **UNIVERSITY OF SHEFFIELD** may not use Biomaterials for clinical use or implant Biomaterials in the human body or incorporate the Biomaterials in any product for implantation into a **human** body **UNIVERSITY OF SHEFFIELD** can alter the physical and chemical properties of the Biomaterial within the remit of the Study, but not outside this remit.

2.2 The parties shall give each other prompt written notice of any adverse facts or issues which come to their attention relating to the safety or efficiency of the Biomaterials.

2.3 From time to time, Invibio may provide consultation services to **UNIVERSITY OF SHEFFIELD** relating to the performance and/or other physical characteristics of the Biomaterials but not to the use to which **UNIVERSITY OF SHEFFIELD** proposes the Biomaterials should be put. Upon information and belief, any information provided by Invibio during the course of its consultation services is an accurate description of the typical characteristics and qualities of the Biomaterials but Invibio makes no warranty to this effect. Invibio disclaims any and all warranties, express or implied, statutory or otherwise, relating to its consultation services. It is **UNIVERSITY OF SHEFFIELD's** exclusive responsibility to satisfy itself that the use to which the Biomaterials may be put will not infringe the rights (including, without limitation, the intellectual property rights) of any third party.

2.4 **UNIVERSITY OF SHEFFIELD** shall ensure that the Study is conducted with all reasonable care and skill and in accordance with the applicable law, scientific practice and ethical regulations.

2.5 **UNIVERSITY OF SHEFFIELD** shall use no polyarylletherketone or similar polymer other than Biomaterials in connection with the Study.

3 WARRANTY AND LIABILITY

3.1 Invibio warrants that the Biomaterials will, when delivered have been manufactured, packaged, handled and stored by Invibio with reasonable skill, competence, care and attention.

3.2 Invibio makes no representations and gives no warranties as to the suitability or otherwise of the Biomaterials for the Study or any other application. For the avoidance of doubt, it shall be the sole responsibility of **UNIVERSITY OF SHEFFIELD** to determine the suitability of the Biomaterials for the Study.

3.3 NEITHER PARTY MAKES ANY WARRANTIES, EXPRESS OR IMPLIED, INCLUDING, WITHOUT LIMITATION, A WARRANTY OF FITNESS FOR A PARTICULAR PURPOSE AND ANY SUCH WARRANTIES WHETHER EXPRESS OF IMPLIED, IN FACT OR BY LAW, ARE EXPRESSLY DISCLAIMED AND NO PARTY SHALL HAVE FURTHER OBLIGATION OR LIABILITY WITH RESPECT TO BIOMATERIALS OR UNIVERSITY OF SHEFFIELD PRODUCTS PROVIDED DURING THE COURSE OF THE STUDY. NEITHER PARTY MAKES ANY WARRANTY TO THE OTHER PARTY'S CUSTOMERS, AGENTS OR ANY THIRD PARTIES INVOLVED IN THE STUDY. NEITHER PARTY HAS AUTHORIZED ANYONE TO MAKE ANY REPRESENTATION OR WARRANTY OTHER THAN AS PROVIDED ABOVE. NEITHER PARTY SHALL IN ANY EVENT BE LIABLE FOR ANY GENERAL, INDIRECT, SPECIAL, CONSEQUENTIAL, PUNITIVE, INCIDENTAL OR SIMILAR DAMAGES, INCLUDING WITHOUT LIMITATION, DAMAGES FOR HARM TO BUSINESS, LOST PROFITS OR LOST SAVINGS, EVEN IF THAT PARTY HAS BEEN ADVISED OF THE POSSIBLITY OF SUCH DAMAGES, REGARDLESS OF THE FORM OF ACTION.

4. CONFIDENTIALITY

4.1 In this Agreement, "Confidential Information" means all information disclosed (by whatever means and whether directly or indirectly) by one Party (the "Disclosing Party") to another Party (the "Receiving Party") in writing and marked as confidential, including, but without limitation, information relating to the Disclosing Party's products, operations, processes, plans or intentions, product information, know-how, design rights, trade secrets, market opportunities and business affairs. Confidential Information also means the said information disclosed orally or visually by Disclosing Party to Receiving Party, identified as confidential at the time of disclosure, and subsequently outlined in writing, confirmed as confidential, and provided to the receiving Party within fourteen (14) days of the disclosure.

4.2 The Receiving Party shall not, at any time:

(a) use Confidential Information other than for the purpose of the Study; or

(b) disclose Confidential Information to any person except in accordance with the terms of this Agreement.

4.3 The Receiving Party shall take reasonable measures to prevent the use or disclosure, other than in accordance with the terms of this Agreement, of Confidential Information.

4.4 Save as required by applicable law or the order of a court of competent jurisdiction, the Receiving Party shall not disclose Confidential Information, without the express written consent of the Disclosing Party, to any third party. However, this obligation shall not apply to any Confidential Information which:

(a) can be shown to the reasonable satisfaction of the Disclosing Party to have already been known to the Receiving Party prior to its receipt from the Disclosing Party; or

(b) is at the date of this Agreement, or at any time after that date becomes, publicly known other than by Receiving Party's breach of this Agreement; or

(c) is lawfully obtained from a third party with full rights of disclosure

4.5 Notwithstanding the provisions of 4.4, the Receiving Party may disclose Confidential Information to its directors, other employees and its subsidiaries or other affiliates to the extent strictly necessary for the purpose of the Study. Before disclosure of Confidential Information to such directors, employees and subsidiaries or affiliates, the Receiving Party shall ensure that such person is fully aware of the Receiving Party's obligations under this letter and shall procure that such person is bound by the obligations of a confidentiality agreement with their employing party.

4.6 The confidentiality provisions of this Agreement shall remain in effect for a period of ten (10) years, or, if earlier until specifically released in writing by an authorised representative of the Disclosing Party, or the Confidential Information (or that portion that is disclosed) becomes publicly known without breach of this Agreement.

5. FINANCING OF THE STUDY AND REPORTING

5.1 The Study shall be financed independently by Invibio and **UNIVERSITY OF SHEFFIELD** depending upon the provision of the required materials and or tests necessary for evaluation.

5.2 Each party shall provide the other party with regular written reports relating to the Study, including reports all test data where applicable. Such written reports shall be treated as Confidential Information and shall not be disclosed to any third party. The parties can meet regularly, formally at least once a quarter, to discuss progress on the Study.

6. INTELLECTUAL PROPERTY RIGHTS

6.1 Invibio is the sole owner of all intellectual property rights in and to the Biomaterials, and **UNIVERSITY OF SHEFFIELD** acknowledges that this Agreement does not operate to vest any right, title or interest in such rights or any other intellectual property rights of Invibio.

6.2 **UNIVERSITY OF SHEFFIELD** is the sole owner of all intellectual property rights in and to **UNIVERSITY OF SHEFFIELD** products and any particular device designs, and Invibio acknowledges that this agreement does not operate to vest any right, title or interest in such rights or any other intellectual property rights of **UNIVERSITY OF SHEFFIELD**.

6.3 All intellectual property whether patentable or not generated during the course of the Study shall vest with the party that developed such intellectual property. Any jointly developed intellectual property generated during the course of the Study shall jointly vest between the parties.

6.4 The rights and obligations of both parties solely regarding jointly developed intellectual property and any commercial exploitation of such jointly developed intellectual property shall be agreed between the parties and incorporated into a commercial agreement. If the parties, acting reasonably, do not agree upon the conditions of such commercial agreement within two months of completion of the Study, then either party, at its own expense, shall be entitled to apply for any and all intellectual property rights in respect of such jointly developed intellectual property and shall grant the other party a non-exclusive, irrevocable, world-wide license to use such jointly developed intellectual property.

6.5 In no event will **UNIVERSITY OF SHEFFIELD** file any patents which could restrict the activities of Invibio in the development, manufacture or sale of Biomaterials and/or related processing technologies, in any field of application.

6.6 In no event will Invibio file any patents which could restrict the activities of **UNIVERSITY OF SHEFFIELD** in the development, manufacture or sale of **UNIVERSITY OF SHEFFIELD** products.

7. DURATION OF THE AGREEMENT

7.1 This Agreement shall come into force on **01/02/2013** and shall remain valid until the earlier of the completion of the Study or **31/03/2016.**

7.2 This Agreement may also be terminated by registered letter by either Party with immediate effect, if the other Party breaches the Agreement in any material manner and fails to remedy such default within thirty days upon receipt of a written notice from the other Party.

7.3 In addition, the Parties may terminate the Agreement by mutual written agreement. :

7.4 An early Termination does not affect the other provisions of this Agreement, especially, but not limited to Clauses 2, 3, 4, 6, 8 and 9.

8. GENERAL

8.1 This Agreement contains the entire agreement between the parties relating to the Study. This Agreement may not be changed, modified, amended or supplemented except by a written instrument signed by both parties. Furthermore, it is the intention of the parties that this Agreement be controlling over additional or different terms of any order, confirmation, invoice or similar document, even if accepted in writing by both parties, and that waivers and amendments shall be effective only if made by non-preprinted agreements clearly understood by both parties to be an amendment or waiver hereof.

8.2 No provision of this Agreement makes one party the agent of the other for any purpose. Neither party has the authority or power to bind, to contract in the name of or to create a liability for the other in any way for any purpose. There is not, as at the date of this Agreement, and never has been, any form of common ownership, common control, common management or any other affiliation between the parties.

9. GOVERNING LAW AND JURISDICTION

This Agreement and all matters arising from or connected with it are governed by English law and the courts of England have exclusive jurisdiction to settle any dispute arising from or connected with this Agreement.

EXECUTED by the parties

Signed by	Signed by
A duly authorised representative of	A duly authorised representative of
INVIBIO LIMITED:	**UNIVERSITY OF SHEFFIELD**
____________ Signature	____________ Signature
JOHN DEVINE. MARKETING & TECHNOLOGY DIRECTOR INVIBIO.	DUNCAN WOOD 26.2.13 SENIOR TEACHER. SCHOOL OF CLINICAL DENTISTRY UNIVERSITY OF SHEFFIELD

Schedule 1

Project details:
The current research to be carried out by the University of Sheffield concerns an evaluation of PEEK as dental material for the fabrication of removable partial denture frameworks.
The production method will initially be via injection moulding with samples produced via CADCAM once optimum design criteria have been defined.
The framework and component design will be optimized to the material behaviour and characteristics. Rigidity of framework connectors, retentive ability of novel design clasps, and resistance to occlusal loading by support elements will be tested. Frameworks will be tested with composite and resin denture teeth in place to reproduce the practical application. The removable partial denture frameworks will be compared to that of a conventional cobalt chromium alloy.

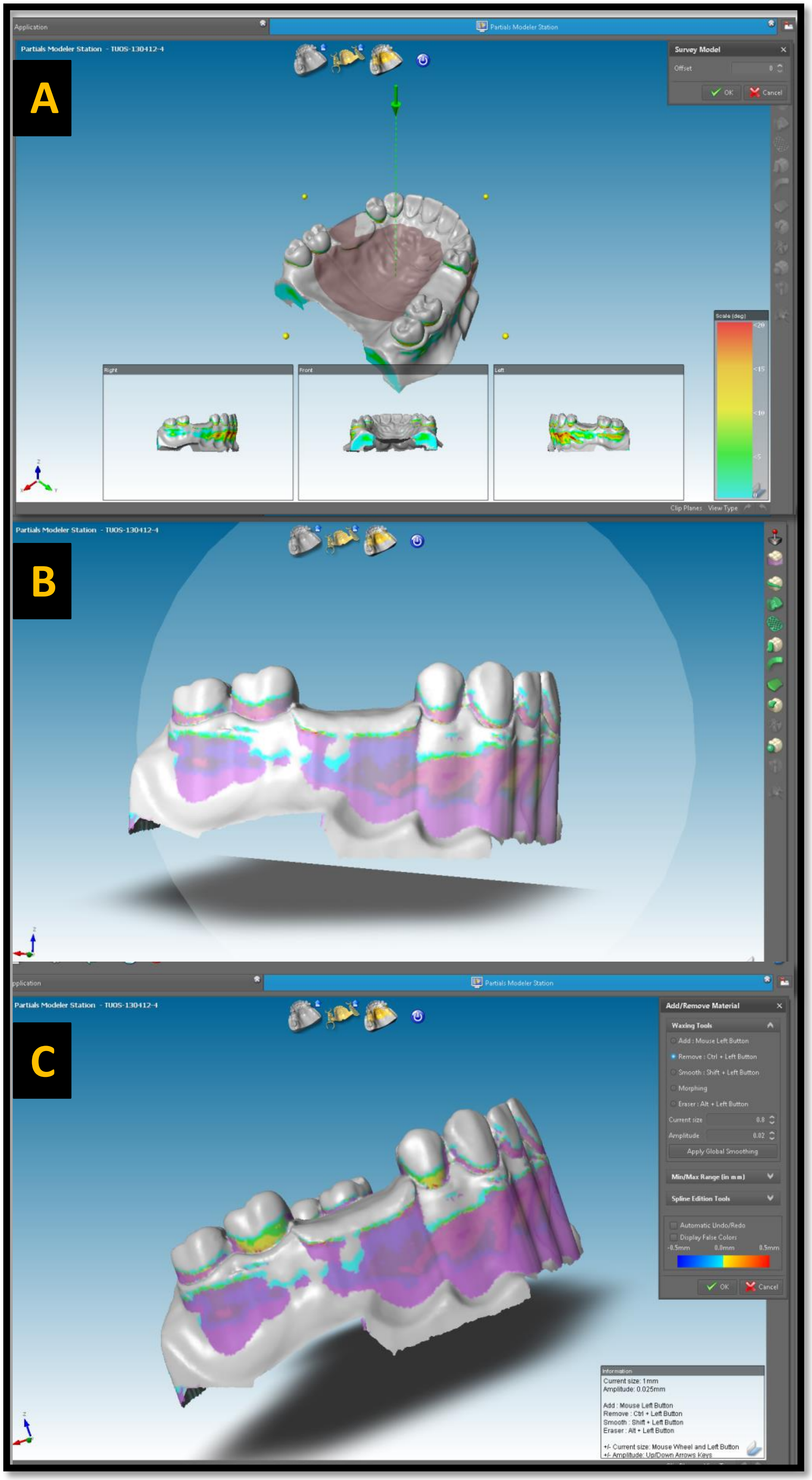
Appendix

Part (A): Software Designing Program for RPD Using DWOS

Table (1): Short description of each step and corresponding icon using DWOS RPD designer

Icon	Step name	Function
	Survey model	Is used to enter the surveying function and to survey the model for the partial design. Also to decide how much of the arch survey model is to be blocked out, figure (1) A.
	Edit blocked out model	Blocking out all the undesirable undercuts, the waxing tool is displayed in purple colour and can be removed in preparation for a clasp to expose all needed areas for the design, figure (1) B & C.
	Add a Clasp	The clasp may be added where needed for the design. (Clasp width, height, offset, reverse path, and damping options could be controlled by this icon in addition to smoothing out the clasp grab by using average distances that are perpendicular from the user placed clasp and the tooth, figure (2) A.
	Add an occlusal rest	Applied to define occlusal rests. The shape, width and thickness can be modified, figure (2) B.
	Add a Bar	To apply bars that connect the clasp with the main component of the partial appliance design, e.g. a grid or palate, figure (2) C.
	Add a palate	Defines the perimeter of a palate for major connector, figure (3) A.
	Add a grid	To apply multiple grids with varying shapes
	Add an inferior bar	To apply an inferior bar that is typically placed upon the underside of the partial design
	Add a finish line	Applied to define the finish line of the partial design, figure (3) B.
	Add support bars	Applied to add extra support bars if desired, during the production of the framework
	Add a pin	Applied to add one or more pins to the design.
	Finish design	Applied when the partial design is completed. This is the last step that will finalise the overall design by collectively combining the individual components into one piece; figure (3) C.

Then the finished RPD framework design (project) is converted into (.Stl) form to be exported to the CAM production devices, figure (4).



Survey Model: Offset 0

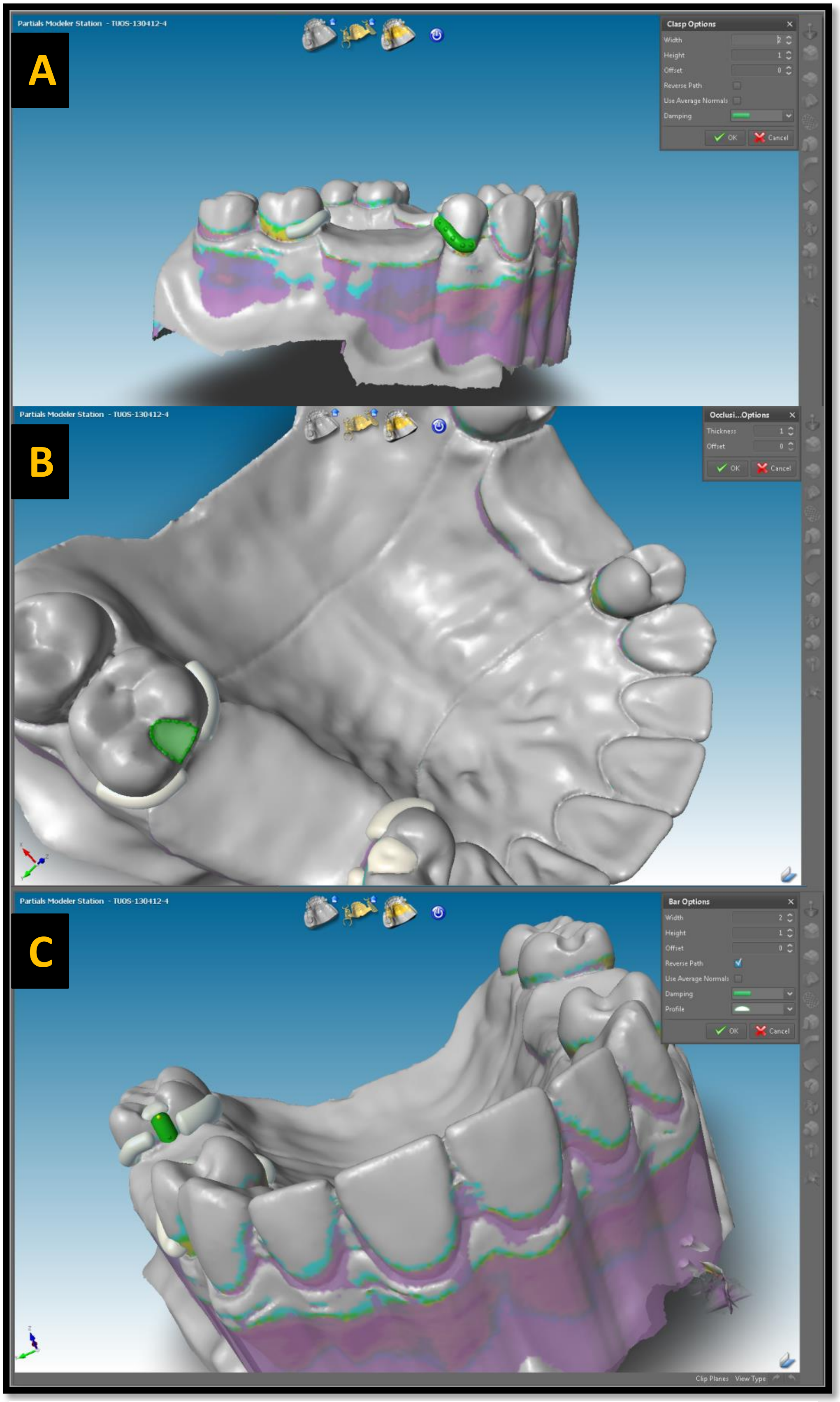
○ Add : Mouse Left Button
● Remove : Ctrl + Left Button
○ Smooth : Shift + Left Button
○ Morphing
○ Eraser : Alt + Left Button
Current size 0.8
Amplitude 0.02
☐ Automatic Undo/Redo
☐ Display False Colors
-0.5mm 0.0mm 0.5mm

Information
Current size: 1mm
Amplitude: 0.025mm

Add : Mouse Left Button
Remove : Ctrl + Left Button
Smooth : Shift + Left Button
Eraser : Alt + Left Button

+/- Current size: Mouse Wheel and Left Button
+/- Amplitude: Up/Down Arrows Keys

Figure (1): A. the arch is surveyed; **B.** blocking out the undesirable undercuts; **C.** exposing the undercut areas needed for the design



Clasp Options
Width 2
Height 1
Offset 0
Reverse Path ☐
Use Average Normals ☐
Damping

Occlusi...Options
Thickness 1
Offset 0

Bar Options
Width 2
Height 1
Offset 0
Reverse Path ☑
Use Average Normals ☐
Damping
Profile

Figure (2): A. clasp added using clasp option icon; **B.** adding occlusal rests; **C.** minor connector added using bar option icon

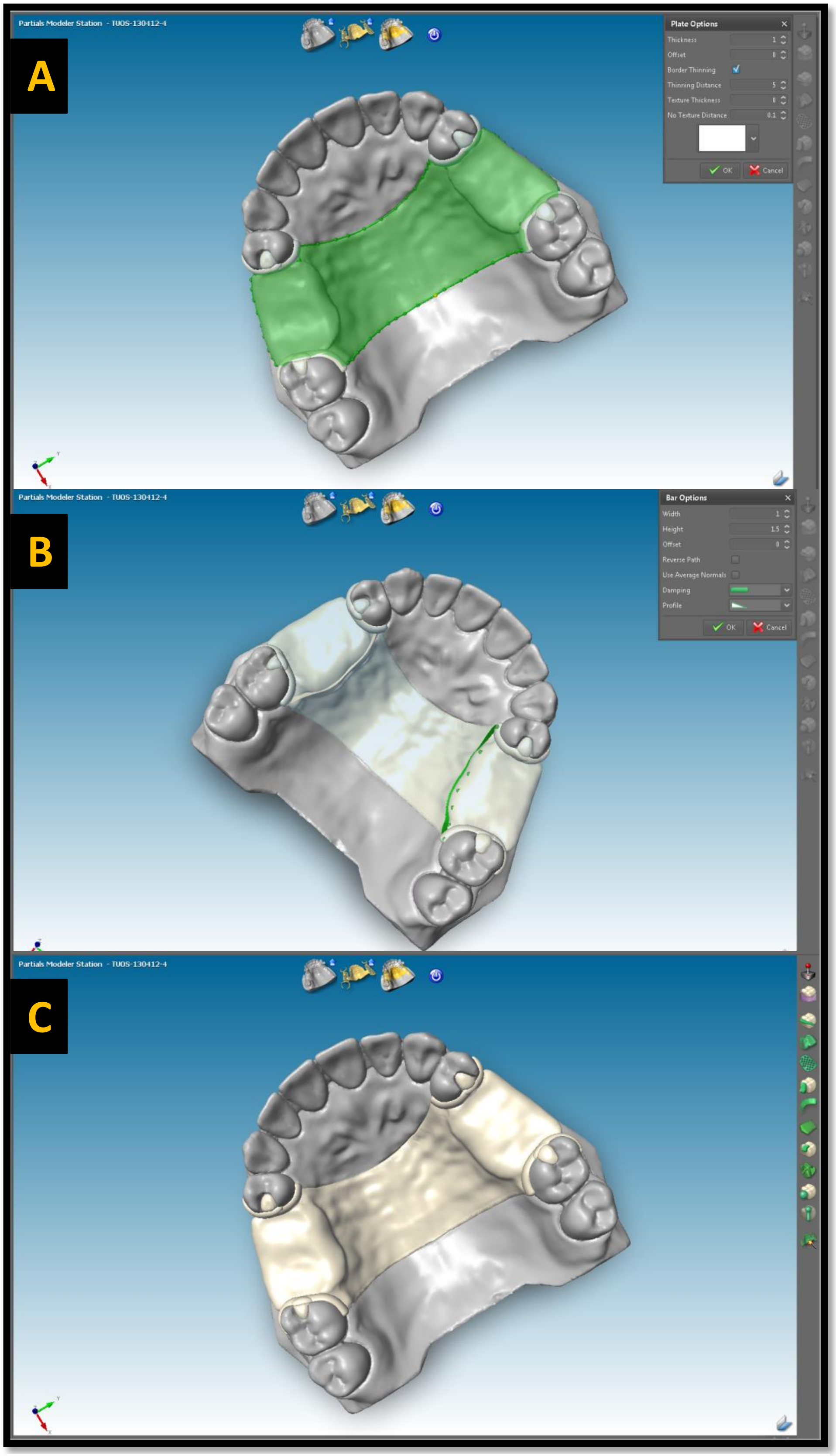
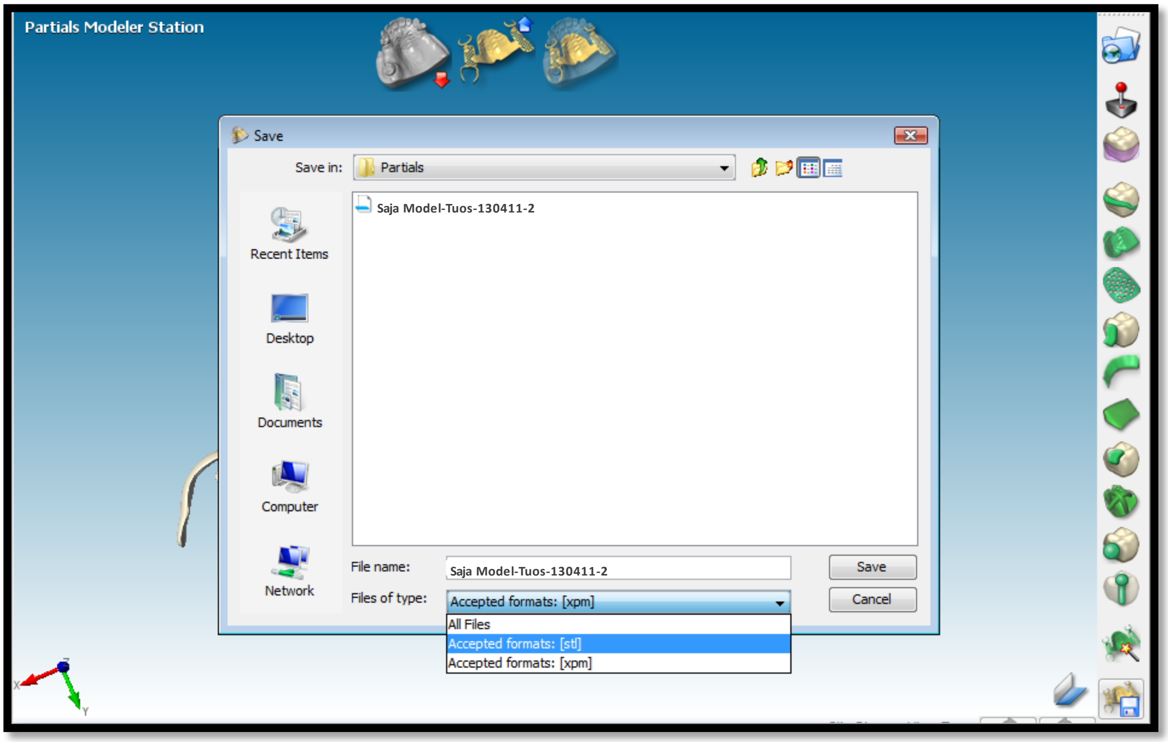


Plate Options
Thickness 1
Offset 0
Border Thinning ☑
Thinning Distance 5
Texture Thickness 0
No Texture Distance 0.1

Bar Options
Width 1
Height 1.5
Offset 0
Reverse Path ☐
Use Average Normals ☐
Damping
Profile

Figure (3): A. adding the palatal major connector; **B.** adding the finishing line to the partial design; **C.** combining the overall design into one piece



Save in: Partials

Saja Model-Tuos-130411-2

File name: Saja Model-Tuos-130411-2

Files of type: Accepted formats: [xpm]

Figure (4): The final project is saved in (.Stl) file form

Statistics

Analysis of the results of this study was conducted using SPSS software (V-22) (Santoso, 2014). These statistical methods included inferential statistical analysis of variation (One way-ANOVA) and Student T-test. Tests were performed at a confidence level of 95 % and significant P-value of (P≤0.05). However, two way ANOVA could be used to reduce type one and two errors.

Part (B): Mould Temperature

Statistics for mould/Furnace monitoring temperature

50C/1h-One thermocouple

Group Statistics

	Temperature	N	Mean	Std. Deviation	Std. Error Mean
Setup50C1h	Furnace	3	73.333	.5774	.3333
	Mould	3	43.333	.8737	.5044

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Setup50C1h	Equal variances assumed	.676	.457	49.619	4	.000	30.0000	.6046	28.3213	31.6787
	Equal variances not assumed			49.619	3.467	.000	30.0000	.6046	28.2145	31.7855

50C/2h-One thermocouple

Group Statistics

	Temperature	N	Mean	Std. Deviation	Std. Error Mean
Setup50C2h	Furnace	3	61.333	.5774	.3333
	Mould	3	45.767	.8083	.4667

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Setup50C2h	Equal variances assumed	.865	.405	27.144	4	.000	15.5667	.5735	13.9744	17.1589
	Equal variances not assumed			27.144	3.619	.000	15.5667	.5735	13.9061	17.2272

50C/3h-One thermocouple

Group Statistics

	Temperature	N	Mean	Std. Deviation	Std. Error Mean
Setup50C3h	Furnace	3	54.333	.5774	.3333
	Mould	3	44.933	.8737	.5044

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Setup50C3h	Equal variances assumed	.676	.457	15.547	4	.000	9.4000	.6046	7.7213	11.0787
	Equal variances not assumed			15.547	3.467	.000	9.4000	.6046	7.6145	11.1855

100C/1h-One thermocouple

Group Statistics

	Temperature	N	Mean	Std. Deviation	Std. Error Mean
Setup100C1h	Furnace	3	110.333	.5774	.3333
	Mould	3	72.000	3.9395	2.2745

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Setup100C1h	Equal variances assumed	7.012	.057	16.675	4	.000	38.3333	2.2988	31.9509	44.7158
	Equal variances not assumed			16.675	2.086	.003	38.3333	2.2988	28.8226	47.8441

100C/2h-One thermocouple

Group Statistics

	Temperature	N	Mean	Std. Deviation	Std. Error Mean
Setup100C2h	Furnace	3	100.000	.0000	.0000
	Mould	3	77.567	.7638	.4410

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Setup100C2h	Equal variances assumed	7.692	.050	50.874	4	.000	22.4333	.4410	21.2090	23.6576
	Equal variances not assumed			50.874	2.000	.000	22.4333	.4410	20.5360	24.3306

100C/3h-One thermocouple

Group Statistics

	Temperature	N	Mean	Std. Deviation	Std. Error Mean
Setup100C3h	Furnace	3	100.000	.0000	.0000
	Mould	3	79.367	1.2220	.7055

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Setup100C3h	Equal variances assumed	7.692	.050	29.245	4	.000	20.6333	.7055	18.6745	22.5922
	Equal variances not assumed			29.245	2.000	.001	20.6333	.7055	17.5977	23.6690

150C/1h-One thermocouple

Group Statistics

	Temperature	N	Mean	Std. Deviation	Std. Error Mean
Setup150C1h	Furnace	3	149.000	1.0000	.5774
	Mould	3	101.600	7.3430	4.2395

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Setup150C1h	Equal variances assumed	10.122	.033	11.078	4	.000	47.4000	4.2786	35.5206	59.2794
	Equal variances not assumed			11.078	2.074	.007	47.4000	4.2786	29.6071	65.1929

150C/2h-One thermocouple

Group Statistics

	Temperature	N	Mean	Std. Deviation	Std. Error Mean
Setup150C2h	Furnace	3	150.000	.0000	.0000
	Mould	3	102.567	8.8274	5.0965

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Setup150C2h	Equal variances assumed	11.320	.028	9.307	4	.001	47.4333	5.0965	33.2831	61.5835
	Equal variances not assumed			9.307	2.000	.011	47.4333	5.0965	25.5048	69.3619

150C/3h-One thermocouple

Group Statistics

	Temperature	N	Mean	Std. Deviation	Std. Error Mean
Setup150C3h	Furnace	3	150.000	.0000	.0000
	Mould	3	103.067	6.9551	4.0155

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Setup150C3h	Equal variances assumed	11.594	.027	11.688	4	.000	46.9333	4.0155	35.7844	58.0822
	Equal variances not assumed			11.688	2.000	.007	46.9333	4.0155	29.6559	64.2107

200C/1h-One thermocouple

Group Statistics

	Temperature	N	Mean	Std. Deviation	Std. Error Mean
Setup200C1h	Furnace	3	200.000	.0000	.0000
	Mould	3	131.133	.8963	.5175

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Setup200C1h	Equal variances assumed	15.563	.017	133.083	4	.000	68.8667	.5175	67.4299	70.3034
	Equal variances not assumed			133.083	2.000	.000	68.8667	.5175	66.6402	71.0932

200C/2h-One thermocouple

Group Statistics

	Temperature	N	Mean	Std. Deviation	Std. Error Mean
Setup200C2h	Furnace	3	200.000	.0000	.0000
	Mould	3	155.933	.5686	.3283

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Setup200C2h	Equal variances assumed	9.563	.036	134.229	4	.000	44.0667	.3283	43.1552	44.9782
	Equal variances not assumed			134.229	2.000	.000	44.0667	.3283	42.6541	45.4792

200C/3h-One thermocouple

Group Statistics

	Temperature	N	Mean	Std. Deviation	Std. Error Mean
Setup200C3h	Furnace	3	200.000	.0000	.0000
	Mould	3	168.867	.2517	.1453

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Setup200C3h	Equal variances assumed	5.953	.071	214.274	4	.000	31.1333	.1453	30.7299	31.5367
	Equal variances not assumed			214.274	2.000	.000	31.1333	.1453	30.5082	31.7585

250C/1h-One thermocouple

Group Statistics

	Temperature	N	Mean	Std. Deviation	Std. Error Mean
Setup250C1h	Furnace	3	250.000	.0000	.0000
	Mould	3	208.333	.5774	.3333

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Setup250C1h	Equal variances assumed	16.000	.016	125.000	4	.000	41.6667	.3333	40.7412	42.5921
	Equal variances not assumed			125.000	2.000	.000	41.6667	.3333	40.2324	43.1009

250C/2h-One thermocouple

Group Statistics

	Temperature	N	Mean	Std. Deviation	Std. Error Mean
Setup250C2h	Furnace	3	250.000	.0000	.0000
	Mould	3	220.333	.5774	.3333

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Setup250C2h	Equal variances assumed	16.000	.016	89.000	4	.000	29.6667	.3333	28.7412	30.5921
	Equal variances not assumed			89.000	2.000	.000	29.6667	.3333	28.2324	31.1009

250C/3h-One thermocouple

Group Statistics

	Temperature	N	Mean	Std. Deviation	Std. Error Mean
Setup250C3h	Furnace	3	250.000	.0000	.0000
	Mould	3	225.667	.5774	.3333

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Setup250C3h	Equal variances assumed	16.000	.016	73.000	4	.000	24.3333	.3333	23.4079	25.2588
	Equal variances not assumed			73.000	2.000	.000	24.3333	.3333	22.8991	25.7676

300C/1h-One thermocouple

Group Statistics

	Temperature	N	Mean	Std. Deviation	Std. Error Mean
Setup300C1h	Furnace	3	300.000	.0000	.0000
	Mould	3	209.667	.5774	.3333

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Setup300C1h	Equal variances assumed	16.000	.016	271.000	4	.000	90.3333	.3333	89.4079	91.2588
	Equal variances not assumed			271.000	2.000	.000	90.3333	.3333	88.8991	91.7676

300C/2h-One thermocouple

Group Statistics

	Temperature	N	Mean	Std. Deviation	Std. Error Mean
Setup300C2h	Furnace	3	300.000	.0000	.0000
	Mould	3	243.333	.5774	.3333

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Setup300C2h	Equal variances assumed	16.000	.016	170.000	4	.000	56.6667	.3333	55.7412	57.5921
	Equal variances not assumed			170.000	2.000	.000	56.6667	.3333	55.2324	58.1009

300C/3h-One thermocouple

Group Statistics

	Temperature	N	Mean	Std. Deviation	Std. Error Mean
Setup300C3h	Furnace	3	300.000	.0000	.0000
	Mould	3	263.667	.5774	.3333

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Setup300C3h	Equal variances assumed	16.000	.016	109.000	4	.000	36.3333	.3333	35.4079	37.2588
	Equal variances not assumed			109.000	2.000	.000	36.3333	.3333	34.8991	37.7676

Multi-thermocouples

Between-Subjects Factors

		Value Label	N
LocationTemperature	1.00	Room T	5
	2.00	Furnace T	5
	3.00	Flask-enterance T	5
	4.00	Posterior mould region T	5
	5.00	Middle mould region T	5
	6.00	Anterior mould region T	5
	7.00	Premolar region T	5
	8.00	Molar region T	5

Descriptive Statistics

Dependent Variable: Tat90minof150setfurnace

LocationTemperature	Mean	Std. Deviation	N
Room T	16.9080	1.85816	5
Furnace T	128.9140	.80276	5
Flask-enterance T	105.4680	1.48710	5
Posterior mould region T	104.5740	1.63191	5
Middle mould region T	105.0540	1.61376	5
Anterior mould region T	104.2400	1.64578	5
Premolar region T	102.9680	1.70939	5
Molar region T	102.6320	1.71002	5
Total	96.3447	31.54077	40

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Tat90minof150setfurnace

F	df1	df2	Sig.
.830	7	32	.571

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + LocationTemperature

1. Grand Mean

Dependent Variable: Tat90minof150setfurnace

Mean	Std. Error	95% Confidence Interval	
		Lower Bound	Upper Bound
96.345	.251	95.834	96.856

2. LocationTemperature

Dependent Variable: Tat90minof150setfurnace

LocationTemperature	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Room T	16.908	.709	15.463	18.353
Furnace T	128.914	.709	127.469	130.359
Flask-enterance T	105.468	.709	104.023	106.913
Posterior mould region T	104.574	.709	103.129	106.019
Middle mould region T	105.054	.709	103.609	106.499
Anterior mould region T	104.240	.709	102.795	105.685
Premolar region T	102.968	.709	101.523	104.413
Molar region T	102.632	.709	101.187	104.077

Between-Subjects Factors

		Value Label	N
LocationTemperature	1.00	Room T	5
	2.00	Furnace T	5
	3.00	Flask-enterance T	5
	4.00	Posterior mould region T	5
	5.00	Middle mould region T	5
	6.00	Anterior mould region T	5
	7.00	Premolar region T	5
	8.00	Molar region T	5

Multiple Comparisons

Dependent Variable: Tat90minof150setfurnace

Tukey HSD

		Mean Difference			95% Confidence Interval	
(I) LocationTemperature	(J) LocationTemperature	(I-J)	Std. Error	Sig.	Lower Bound	Upper Bound
Room T	Furnace T	-112.0060-*	1.00327	.000	-115.2559-	-108.7561-
	Flask-enterance T	-88.5600-*	1.00327	.000	-91.8099-	-85.3101-
	Posterior mould region T	-87.6660-*	1.00327	.000	-90.9159-	-84.4161-
	Middle mould region T	-88.1460-*	1.00327	.000	-91.3959-	-84.8961-
	Anterior mould region T	-87.3320-*	1.00327	.000	-90.5819-	-84.0821-
	Premolar region T	-86.0600-*	1.00327	.000	-89.3099-	-82.8101-
	Molar region T	-85.7240-*	1.00327	.000	-88.9739-	-82.4741-
Furnace T	Room T	112.0060*	1.00327	.000	108.7561	115.2559
	Flask-enterance T	23.4460*	1.00327	.000	20.1961	26.6959
	Posterior mould region T	24.3400*	1.00327	.000	21.0901	27.5899
	Middle mould region T	23.8600*	1.00327	.000	20.6101	27.1099
	Anterior mould region T	24.6740*	1.00327	.000	21.4241	27.9239
	Premolar region T	25.9460*	1.00327	.000	22.6961	29.1959
	Molar region T	26.2820*	1.00327	.000	23.0321	29.5319
Flask-enterance T	Room T	88.5600*	1.00327	.000	85.3101	91.8099
	Furnace T	-23.4460-*	1.00327	.000	-26.6959-	-20.1961-
	Posterior mould region T	.8940	1.00327	.985	-2.3559-	4.1439
	Middle mould region T	.4140	1.00327	1.000	-2.8359-	3.6639
	Anterior mould region T	1.2280	1.00327	.919	-2.0219-	4.4779
	Premolar region T	2.5000	1.00327	.235	-.7499-	5.7499
	Molar region T	2.8360	1.00327	.124	-.4139-	6.0859
Posterior mould region T	Room T	87.6660*	1.00327	.000	84.4161	90.9159
	Furnace T	-24.3400-*	1.00327	.000	-27.5899-	-21.0901-
	Flask-enterance T	-.8940-	1.00327	.985	-4.1439-	2.3559
	Middle mould region T	-.4800-	1.00327	1.000	-3.7299-	2.7699
	Anterior mould region T	.3340	1.00327	1.000	-2.9159-	3.5839
	Premolar region T	1.6060	1.00327	.746	-1.6439-	4.8559
	Molar region T	1.9420	1.00327	.538	-1.3079-	5.1919
Middle mould region T	Room T	88.1460*	1.00327	.000	84.8961	91.3959
	Furnace T	-23.8600-*	1.00327	.000	-27.1099-	-20.6101-
	Flask-enterance T	-.4140-	1.00327	1.000	-3.6639-	2.8359
	Posterior mould region T	.4800	1.00327	1.000	-2.7699-	3.7299
	Anterior mould region T	.8140	1.00327	.991	-2.4359-	4.0639
	Premolar region T	2.0860	1.00327	.449	-1.1639-	5.3359
	Molar region T	2.4220	1.00327	.269	-.8279-	5.6719
Anterior mould region T	Room T	87.3320*	1.00327	.000	84.0821	90.5819
	Furnace T	-24.6740-*	1.00327	.000	-27.9239-	-21.4241-
	Flask-enterance T	-1.2280-	1.00327	.919	-4.4779-	2.0219
	Posterior mould region T	-.3340-	1.00327	1.000	-3.5839-	2.9159
	Middle mould region T	-.8140-	1.00327	.991	-4.0639-	2.4359
	Premolar region T	1.2720	1.00327	.904	-1.9779-	4.5219
	Molar region T	1.6080	1.00327	.745	-1.6419-	4.8579
Premolar region T	Room T	86.0600*	1.00327	.000	82.8101	89.3099
	Furnace T	-25.9460-*	1.00327	.000	-29.1959-	-22.6961-
	Flask-enterance T	-2.5000-	1.00327	.235	-5.7499-	.7499
	Posterior mould region T	-1.6060-	1.00327	.746	-4.8559-	1.6439
	Middle mould region T	-2.0860-	1.00327	.449	-5.3359-	1.1639
	Anterior mould region T	-1.2720-	1.00327	.904	-4.5219-	1.9779
	Molar region T	.3360	1.00327	1.000	-2.9139-	3.5859
Molar region T	Room T	85.7240*	1.00327	.000	82.4741	88.9739
	Furnace T	-26.2820-*	1.00327	.000	-29.5319-	-23.0321-
	Flask-enterance T	-2.8360-	1.00327	.124	-6.0859-	.4139
	Posterior mould region T	-1.9420-	1.00327	.538	-5.1919-	1.3079
	Middle mould region T	-2.4220-	1.00327	.269	-5.6719-	.8279
	Anterior mould region T	-1.6080-	1.00327	.745	-4.8579-	1.6419
	Premolar region T	-.3360-	1.00327	1.000	-3.5859-	2.9139

Based on observed means.

The error term is Mean Square(Error) = 2.516.

*. The mean difference is significant at the .05 level.

Between-Subjects Factors

		Value Label	N
LocationTemperature	1.00	Room T	5
	2.00	Furnace T	5
	3.00	Flask-enterance T	5
	4.00	Posterior mould region T	5
	5.00	Middle mould region T	5
	6.00	Anterior mould region T	5
	7.00	Premolar region T	5
	8.00	Molar region T	5

Descriptive Statistics

Dependent Variable: Tat120minof200setfurnace

LocationTemperature	Mean	Std. Deviation	N
Room T	17.7140	.81304	5
Furnace T	173.6220	.94028	5
Flask-enterance T	150.0700	2.26230	5
Posterior mould region T	150.5480	2.02768	5
Middle mould region T	151.0060	2.37511	5
Anterior mould region T	150.1700	2.06467	5
Premolar region T	148.9320	1.99699	5
Molar region T	148.5940	1.99877	5
Total	136.3320	46.11922	40

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Tat120minof200setfurnace

F	df1	df2	Sig.
.417	7	32	.885

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + LocationTemperature

1. Grand Mean

Dependent Variable: Tat120minof200setfurnace

		95% Confidence Interval	
Mean	Std. Error	Lower Bound	Upper Bound
136.332	.299	135.722	136.942

2. LocationTemperature

Dependent Variable: Tat120minof200setfurnace

			95% Confidence Interval	
LocationTemperature	Mean	Std. Error	Lower Bound	Upper Bound
Room T	17.714	.846	15.990	19.438
Furnace T	173.622	.846	171.898	175.346
Flask-enterance T	150.070	.846	148.346	151.794
Posterior mould region T	150.548	.846	148.824	152.272
Middle mould region T	151.006	.846	149.282	152.730
Anterior mould region T	150.170	.846	148.446	151.894
Premolar region T	148.932	.846	147.208	150.656
Molar region T	148.594	.846	146.870	150.318

Multiple Comparisons

Dependent Variable: Tat120minof200setfurnace

Tukey HSD

(I) LocationTemperature	(J) LocationTemperature	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Room T	Furnace T	-155.9080-*	1.19711	.000	-159.7858-	-152.0302-
	Flask-enterance T	-132.3560-*	1.19711	.000	-136.2338-	-128.4782-
	Posterior mould region T	-132.8340-*	1.19711	.000	-136.7118-	-128.9562-
	Middle mould region T	-133.2920-*	1.19711	.000	-137.1698-	-129.4142-
	Anterior mould region T	-132.4560-*	1.19711	.000	-136.3338-	-128.5782-
	Premolar region T	-131.2180-*	1.19711	.000	-135.0958-	-127.3402-
	Molar region T	-130.8800-*	1.19711	.000	-134.7578-	-127.0022-
Furnace T	Room T	155.9080*	1.19711	.000	152.0302	159.7858
	Flask-enterance T	23.5520*	1.19711	.000	19.6742	27.4298
	Posterior mould region T	23.0740*	1.19711	.000	19.1962	26.9518
	Middle mould region T	22.6160*	1.19711	.000	18.7382	26.4938
	Anterior mould region T	23.4520*	1.19711	.000	19.5742	27.3298
	Premolar region T	24.6900*	1.19711	.000	20.8122	28.5678
	Molar region T	25.0280*	1.19711	.000	21.1502	28.9058
Flask-enterance T	Room T	132.3560*	1.19711	.000	128.4782	136.2338
	Furnace T	-23.5520-*	1.19711	.000	-27.4298-	-19.6742-
	Posterior mould region T	-.4780-	1.19711	1.000	-4.3558-	3.3998
	Middle mould region T	-.9360-	1.19711	.993	-4.8138-	2.9418
	Anterior mould region T	-.1000-	1.19711	1.000	-3.9778-	3.7778
	Premolar region T	1.1380	1.19711	.978	-2.7398-	5.0158
	Molar region T	1.4760	1.19711	.916	-2.4018-	5.3538
Posterior mould region T	Room T	132.8340*	1.19711	.000	128.9562	136.7118
	Furnace T	-23.0740-*	1.19711	.000	-26.9518-	-19.1962-
	Flask-enterance T	.4780	1.19711	1.000	-3.3998-	4.3558
	Middle mould region T	-.4580-	1.19711	1.000	-4.3358-	3.4198
	Anterior mould region T	.3780	1.19711	1.000	-3.4998-	4.2558
	Premolar region T	1.6160	1.19711	.872	-2.2618-	5.4938
	Molar region T	1.9540	1.19711	.728	-1.9238-	5.8318
Middle mould region T	Room T	133.2920*	1.19711	.000	129.4142	137.1698
	Furnace T	-22.6160-*	1.19711	.000	-26.4938-	-18.7382-
	Flask-enterance T	.9360	1.19711	.993	-2.9418-	4.8138
	Posterior mould region T	.4580	1.19711	1.000	-3.4198-	4.3358
	Anterior mould region T	.8360	1.19711	.996	-3.0418-	4.7138
	Premolar region T	2.0740	1.19711	.667	-1.8038-	5.9518
	Molar region T	2.4120	1.19711	.488	-1.4658-	6.2898
Anterior mould region T	Room T	132.4560*	1.19711	.000	128.5782	136.3338
	Furnace T	-23.4520-*	1.19711	.000	-27.3298-	-19.5742-
	Flask-enterance T	.1000	1.19711	1.000	-3.7778-	3.9778
	Posterior mould region T	-.3780-	1.19711	1.000	-4.2558-	3.4998
	Middle mould region T	-.8360-	1.19711	.996	-4.7138-	3.0418
	Premolar region T	1.2380	1.19711	.965	-2.6398-	5.1158
	Molar region T	1.5760	1.19711	.886	-2.3018-	5.4538
Premolar region T	Room T	131.2180*	1.19711	.000	127.3402	135.0958
	Furnace T	-24.6900-*	1.19711	.000	-28.5678-	-20.8122-
	Flask-enterance T	-1.1380-	1.19711	.978	-5.0158-	2.7398
	Posterior mould region T	-1.6160-	1.19711	.872	-5.4938-	2.2618
	Middle mould region T	-2.0740-	1.19711	.667	-5.9518-	1.8038
	Anterior mould region T	-1.2380-	1.19711	.965	-5.1158-	2.6398
	Molar region T	.3380	1.19711	1.000	-3.5398-	4.2158
Molar region T	Room T	130.8800*	1.19711	.000	127.0022	134.7578
	Furnace T	-25.0280-*	1.19711	.000	-28.9058-	-21.1502-
	Flask-enterance T	-1.4760-	1.19711	.916	-5.3538-	2.4018
	Posterior mould region T	-1.9540-	1.19711	.728	-5.8318-	1.9238
	Middle mould region T	-2.4120-	1.19711	.488	-6.2898-	1.4658
	Anterior mould region T	-1.5760-	1.19711	.886	-5.4538-	2.3018
	Premolar region T	-.3380-	1.19711	1.000	-4.2158-	3.5398

Based on observed means.

The error term is Mean Square(Error) = 3.583.

*. The mean difference is significant at the .05 level.

Between-Subjects Factors

		Value Label	N
LocationTemperature	1.00	Room T	5
	2.00	Furnace T	5
	3.00	Flask-entrance T	5
	4.00	Posterior mould region T	5
	5.00	Middle mould region T	5
	6.00	Anterior mould region T	5
	7.00	Premolar mould region T	5
	8.00	Molar mould region T	5

Descriptive Statistics

Dependent Variable: Tat15minof250setfurnace

LocationTemperature	Mean	Std. Deviation	N
Room T	17.1960	.59374	5
Furnace T	179.2700	8.55636	5
Flask-entrance T	62.0540	6.93829	5
Posterior mould region T	46.1500	6.70263	5
Middle mould region T	47.1280	6.64127	5
Anterior mould region T	43.1480	6.59766	5
Premolar mould region T	35.3000	5.93501	5
Molar mould region T	33.2520	5.91922	5
Total	57.9373	48.37668	40

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Tat15minof250setfurnace

F	df1	df2	Sig.
3.777	7	32	.004

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + LocationTemperature

1. Grand Mean

Dependent Variable: Tat15minof250setfurnace

		95% Confidence Interval	
Mean	Std. Error	Lower Bound	Upper Bound
57.937	1.007	55.886	59.989

2. LocationTemperature

Dependent Variable: Tat15minof250setfurnace

			95% Confidence Interval	
LocationTemperature	Mean	Std. Error	Lower Bound	Upper Bound
Room T	17.196	2.848	11.394	22.998
Furnace T	179.270	2.848	173.468	185.072
Flask-entrance T	62.054	2.848	56.252	67.856
Posterior mould region T	46.150	2.848	40.348	51.952
Middle mould region T	47.128	2.848	41.326	52.930
Anterior mould region T	43.148	2.848	37.346	48.950
Premolar mould region T	35.300	2.848	29.498	41.102
Molar mould region T	33.252	2.848	27.450	39.054

Multiple Comparisons

Dependent Variable: Tat15minof250setfurnace

Games-Howell

(I) LocationTemperature	(J) LocationTemperature	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Room T	Furnace T	-162.0740-*	3.83572	.000	-181.8949-	-142.2531-
	Flask-entrance T	-44.8580-*	3.11424	.001	-60.9072-	-28.8088-
	Posterior mould region T	-28.9540-*	3.00925	.005	-44.4535-	-13.4545-
	Middle mould region T	-29.9320-*	2.98191	.004	-45.2883-	-14.5757-
	Anterior mould region T	-25.9520-*	2.96249	.007	-41.2065-	-10.6975-
	Premolar mould region T	-18.1040-*	2.66747	.019	-31.8115-	-4.3965-
	Molar mould region T	-16.0560-*	2.66044	.029	-29.7266-	-2.3854-
Furnace T	Room T	162.0740*	3.83572	.000	142.2531	181.8949
	Flask-entrance T	117.2160*	4.92648	.000	97.4967	136.9353
	Posterior mould region T	133.1200*	4.86079	.000	113.5869	152.6531
	Middle mould region T	132.1420*	4.84392	.000	112.6546	151.6294
	Anterior mould region T	136.1220*	4.83199	.000	116.6664	155.5776
	Premolar mould region T	143.9700*	4.65695	.000	124.9240	163.0160
	Molar mould region T	146.0180*	4.65292	.000	126.9800	165.0560
Flask-entrance T	Room T	44.8580*	3.11424	.001	28.8088	60.9072
	Furnace T	-117.2160-*	4.92648	.000	-136.9353-	-97.4967-
	Posterior mould region T	15.9040	4.31428	.071	-1.1735-	32.9815
	Middle mould region T	14.9260	4.29526	.093	-2.0795-	31.9315
	Anterior mould region T	18.9060*	4.28180	.028	1.9510	35.8610
	Premolar mould region T	26.7540*	4.08324	.003	10.4917	43.0163
	Molar mould region T	28.8020*	4.07865	.002	12.5545	45.0495
Posterior mould region T	Room T	28.9540*	3.00925	.005	13.4545	44.4535
	Furnace T	-133.1200-*	4.86079	.000	-152.6531-	-113.5869-
	Flask-entrance T	-15.9040-	4.31428	.071	-32.9815-	1.1735
	Middle mould region T	-.9780-	4.21976	1.000	-17.6764-	15.7204
	Anterior mould region T	3.0020	4.20605	.994	-13.6429-	19.6469
	Premolar mould region T	10.8500	4.00374	.244	-5.0556-	26.7556
	Molar mould region T	12.8980	3.99906	.129	-2.9918-	28.7878
Middle mould region T	Room T	29.9320*	2.98191	.004	14.5757	45.2883
	Furnace T	-132.1420-*	4.84392	.000	-151.6294-	-112.6546-
	Flask-entrance T	-14.9260-	4.29526	.093	-31.9315-	2.0795
	Posterior mould region T	.9780	4.21976	1.000	-15.7204-	17.6764
	Anterior mould region T	3.9800	4.18654	.970	-12.5867-	20.5467
	Premolar mould region T	11.8280	3.98324	.177	-3.9872-	27.6432
	Molar mould region T	13.8760	3.97853	.092	-1.9230-	29.6750
Anterior mould region T	Room T	25.9520*	2.96249	.007	10.6975	41.2065
	Furnace T	-136.1220-*	4.83199	.000	-155.5776-	-116.6664-
	Flask-entrance T	-18.9060-*	4.28180	.028	-35.8610-	-1.9510-
	Posterior mould region T	-3.0020-	4.20605	.994	-19.6469-	13.6429
	Middle mould region T	-3.9800-	4.18654	.970	-20.5467-	12.5867
	Premolar mould region T	7.8480	3.96872	.544	-7.9035-	23.5995
	Molar mould region T	9.8960	3.96400	.314	-5.8392-	25.6312
Premolar mould region T	Room T	18.1040*	2.66747	.019	4.3965	31.8115
	Furnace T	-143.9700-*	4.65695	.000	-163.0160-	-124.9240-
	Flask-entrance T	-26.7540-*	4.08324	.003	-43.0163-	-10.4917-
	Posterior mould region T	-10.8500-	4.00374	.244	-26.7556-	5.0556
	Middle mould region T	-11.8280-	3.98324	.177	-27.6432-	3.9872
	Anterior mould region T	-7.8480-	3.96872	.544	-23.5995-	7.9035
	Molar mould region T	2.0480	3.74864	.999	-12.7858-	16.8818
Molar mould region T	Room T	16.0560*	2.66044	.029	2.3854	29.7266
	Furnace T	-146.0180-*	4.65292	.000	-165.0560-	-126.9800-
	Flask-entrance T	-28.8020-*	4.07865	.002	-45.0495-	-12.5545-
	Posterior mould region T	-12.8980-	3.99906	.129	-28.7878-	2.9918
	Middle mould region T	-13.8760-	3.97853	.092	-29.6750-	1.9230
	Anterior mould region T	-9.8960-	3.96400	.314	-25.6312-	5.8392
	Premolar mould region T	-2.0480-	3.74864	.999	-16.8818-	12.7858

Based on observed means.

The error term is Mean Square(Error) = 40.566.

*. The mean difference is significant at the .05 level.

Between-Subjects Factors

		Value Label	N
LocationTemperature	1.00	Room T	5
	2.00	Furnace T	5
	3.00	Flask-enterance T	5
	4.00	Posterior mould region T	5
	5.00	Middle mould region T	5
	6.00	Anterior mould region T	5
	7.00	Premolar region T	5
	8.00	Molar region T	5

Descriptive Statistics

Dependent Variable: Tat90minsof250setfurnace

LocationTemperature	Mean	Std. Deviation	N
Room T	17.8540	.60941	5
Furnace T	214.0320	1.41436	5
Flask-enterance T	176.8080	2.99379	5
Posterior mould region T	176.0500	2.65455	5
Middle mould region T	176.5860	3.51216	5
Anterior mould region T	175.0320	2.72679	5
Premolar region T	172.0960	2.46368	5
Molar region T	171.3520	2.43747	5
Total	159.9762	56.02360	40

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Tat90minsof250setfurnace

F	df1	df2	Sig.
.865	7	32	.544

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + LocationTemperature

1. Grand Mean

Dependent Variable: Tat90minsof250setfurnace

		95% Confidence Interval	
Mean	Std. Error	Lower Bound	Upper Bound
159.976	.396	159.170	160.783

2. LocationTemperature

Dependent Variable: Tat90minsof250setfurnace

			95% Confidence Interval	
LocationTemperature	Mean	Std. Error	Lower Bound	Upper Bound
Room T	17.854	1.120	15.573	20.135
Furnace T	214.032	1.120	211.751	216.313
Flask-enterance T	176.808	1.120	174.527	179.089
Posterior mould region T	176.050	1.120	173.769	178.331
Middle mould region T	176.586	1.120	174.305	178.867
Anterior mould region T	175.032	1.120	172.751	177.313
Premolar region T	172.096	1.120	169.815	174.377
Molar region T	171.352	1.120	169.071	173.633

Multiple Comparisons

Dependent Variable: Tat90minsof250setfurnace

Tukey HSD

(I) LocationTemperature	(J) LocationTemperature	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Room T	Furnace T	-196.1780-*	1.58371	.000	-201.3081-	-191.0479-
	Flask-enterance T	-158.9540-*	1.58371	.000	-164.0841-	-153.8239-
	Posterior mould region T	-158.1960-*	1.58371	.000	-163.3261-	-153.0659-
	Middle mould region T	-158.7320-*	1.58371	.000	-163.8621-	-153.6019-
	Anterior mould region T	-157.1780-*	1.58371	.000	-162.3081-	-152.0479-
	Premolar region T	-154.2420-*	1.58371	.000	-159.3721-	-149.1119-
	Molar region T	-153.4980-*	1.58371	.000	-158.6281-	-148.3679-
Furnace T	Room T	196.1780*	1.58371	.000	191.0479	201.3081
	Flask-enterance T	37.2240*	1.58371	.000	32.0939	42.3541
	Posterior mould region T	37.9820*	1.58371	.000	32.8519	43.1121
	Middle mould region T	37.4460*	1.58371	.000	32.3159	42.5761
	Anterior mould region T	39.0000*	1.58371	.000	33.8699	44.1301
	Premolar region T	41.9360*	1.58371	.000	36.8059	47.0661
	Molar region T	42.6800*	1.58371	.000	37.5499	47.8101
Flask-enterance T	Room T	158.9540*	1.58371	.000	153.8239	164.0841
	Furnace T	-37.2240-*	1.58371	.000	-42.3541-	-32.0939-
	Posterior mould region T	.7580	1.58371	1.000	-4.3721-	5.8881
	Middle mould region T	.2220	1.58371	1.000	-4.9081-	5.3521
	Anterior mould region T	1.7760	1.58371	.947	-3.3541-	6.9061
	Premolar region T	4.7120	1.58371	.090	-.4181-	9.8421
	Molar region T	5.4560*	1.58371	.031	.3259	10.5861
Posterior mould region T	Room T	158.1960*	1.58371	.000	153.0659	163.3261
	Furnace T	-37.9820-*	1.58371	.000	-43.1121-	-32.8519-
	Flask-enterance T	-.7580-	1.58371	1.000	-5.8881-	4.3721
	Middle mould region T	-.5360-	1.58371	1.000	-5.6661-	4.5941
	Anterior mould region T	1.0180	1.58371	.998	-4.1121-	6.1481
	Premolar region T	3.9540	1.58371	.233	-1.1761-	9.0841
	Molar region T	4.6980	1.58371	.092	-.4321-	9.8281
Middle mould region T	Room T	158.7320*	1.58371	.000	153.6019	163.8621
	Furnace T	-37.4460-*	1.58371	.000	-42.5761-	-32.3159-
	Flask-enterance T	-.2220-	1.58371	1.000	-5.3521-	4.9081
	Posterior mould region T	.5360	1.58371	1.000	-4.5941-	5.6661
	Anterior mould region T	1.5540	1.58371	.974	-3.5761-	6.6841
	Premolar region T	4.4900	1.58371	.122	-.6401-	9.6201
	Molar region T	5.2340*	1.58371	.043	.1039	10.3641
Anterior mould region T	Room T	157.1780*	1.58371	.000	152.0479	162.3081
	Furnace T	-39.0000-*	1.58371	.000	-44.1301-	-33.8699-
	Flask-enterance T	-1.7760-	1.58371	.947	-6.9061-	3.3541
	Posterior mould region T	-1.0180-	1.58371	.998	-6.1481-	4.1121
	Middle mould region T	-1.5540-	1.58371	.974	-6.6841-	3.5761
	Premolar region T	2.9360	1.58371	.590	-2.1941-	8.0661
	Molar region T	3.6800	1.58371	.312	-1.4501-	8.8101
Premolar region T	Room T	154.2420*	1.58371	.000	149.1119	159.3721
	Furnace T	-41.9360-*	1.58371	.000	-47.0661-	-36.8059-
	Flask-enterance T	-4.7120-	1.58371	.090	-9.8421-	.4181
	Posterior mould region T	-3.9540-	1.58371	.233	-9.0841-	1.1761
	Middle mould region T	-4.4900-	1.58371	.122	-9.6201-	.6401
	Anterior mould region T	-2.9360-	1.58371	.590	-8.0661-	2.1941
	Molar region T	.7440	1.58371	1.000	-4.3861-	5.8741
Molar region T	Room T	153.4980*	1.58371	.000	148.3679	158.6281
	Furnace T	-42.6800-*	1.58371	.000	-47.8101-	-37.5499-
	Flask-enterance T	-5.4560-*	1.58371	.031	-10.5861-	-.3259-
	Posterior mould region T	-4.6980-	1.58371	.092	-9.8281-	.4321
	Middle mould region T	-5.2340-*	1.58371	.043	-10.3641-	-.1039-
	Anterior mould region T	-3.6800-	1.58371	.312	-8.8101-	1.4501
	Premolar region T	-.7440-	1.58371	1.000	-5.8741-	4.3861

Based on observed means.

The error term is Mean Square(Error) = 6.270.

*. The mean difference is significant at the .05 level.

Between-Subjects Factors

		Value Label	N
LocationTemperature	1.00	Room T	5
	2.00	Furnace T	5
	3.00	Flask-enterance T	5
	4.00	Posterior mould region T	5
	5.00	Middle mould region T	5
	6.00	Anterior mould region T	5
	7.00	Premolar region T	5
	8.00	Molar region T	5

Descriptive Statistics

Dependent Variable: Tat150minsof250setfurnace

LocationTemperature	Mean	Std. Deviation	N
Room T	18.5900	1.15709	5
Furnace T	221.7520	1.55973	5
Flask-enterance T	199.0620	3.43685	5
Posterior mould region T	200.9260	3.01236	5
Middle mould region T	202.2640	2.86030	5
Anterior mould region T	200.7460	2.95124	5
Premolar region T	199.5780	2.98448	5
Molar region T	199.2840	2.91103	5
Total	180.2753	62.35287	40

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Tat150minsof250setfurnace

F	df1	df2	Sig.
.678	7	32	.689

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + LocationTemperature

1. Grand Mean

Dependent Variable: Tat150minsof250setfurnace

		95% Confidence Interval	
Mean	Std. Error	Lower Bound	Upper Bound
180.275	.429	179.401	181.149

2. LocationTemperature

Dependent Variable: Tat150minsof250setfurnace

			95% Confidence Interval	
LocationTemperature	Mean	Std. Error	Lower Bound	Upper Bound
Room T	18.590	1.214	16.118	21.062
Furnace T	221.752	1.214	219.280	224.224
Flask-enterance T	199.062	1.214	196.590	201.534
Posterior mould region T	200.926	1.214	198.454	203.398
Middle mould region T	202.264	1.214	199.792	204.736
Anterior mould region T	200.746	1.214	198.274	203.218
Premolar region T	199.578	1.214	197.106	202.050
Molar region T	199.284	1.214	196.812	201.756

Multiple Comparisons

Dependent Variable: Tat150minsof250setfurnace

Tukey HSD

(I) LocationTemperature	(J) LocationTemperature	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Room T	Furnace T	-203.1620-*	1.71654	.000	-208.7224-	-197.6016-
	Flask-enterance T	-180.4720-*	1.71654	.000	-186.0324-	-174.9116-
	Posterior mould region T	-182.3360-*	1.71654	.000	-187.8964-	-176.7756-
	Middle mould region T	-183.6740-*	1.71654	.000	-189.2344-	-178.1136-
	Anterior mould region T	-182.1560-*	1.71654	.000	-187.7164-	-176.5956-
	Premolar region T	-180.9880-*	1.71654	.000	-186.5484-	-175.4276-
	Molar region T	-180.6940-*	1.71654	.000	-186.2544-	-175.1336-
Furnace T	Room T	203.1620*	1.71654	.000	197.6016	208.7224
	Flask-enterance T	22.6900*	1.71654	.000	17.1296	28.2504
	Posterior mould region T	20.8260*	1.71654	.000	15.2656	26.3864
	Middle mould region T	19.4880*	1.71654	.000	13.9276	25.0484
	Anterior mould region T	21.0060*	1.71654	.000	15.4456	26.5664
	Premolar region T	22.1740*	1.71654	.000	16.6136	27.7344
	Molar region T	22.4680*	1.71654	.000	16.9076	28.0284
Flask-enterance T	Room T	180.4720*	1.71654	.000	174.9116	186.0324
	Furnace T	-22.6900-*	1.71654	.000	-28.2504-	-17.1296-
	Posterior mould region T	-1.8640-	1.71654	.955	-7.4244-	3.6964
	Middle mould region T	-3.2020-	1.71654	.583	-8.7624-	2.3584
	Anterior mould region T	-1.6840-	1.71654	.974	-7.2444-	3.8764
	Premolar region T	-.5160-	1.71654	1.000	-6.0764-	5.0444
	Molar region T	-.2220-	1.71654	1.000	-5.7824-	5.3384
Posterior mould region T	Room T	182.3360*	1.71654	.000	176.7756	187.8964
	Furnace T	-20.8260-*	1.71654	.000	-26.3864-	-15.2656-
	Flask-enterance T	1.8640	1.71654	.955	-3.6964-	7.4244
	Middle mould region T	-1.3380-	1.71654	.993	-6.8984-	4.2224
	Anterior mould region T	.1800	1.71654	1.000	-5.3804-	5.7404
	Premolar region T	1.3480	1.71654	.993	-4.2124-	6.9084
	Molar region T	1.6420	1.71654	.977	-3.9184-	7.2024
Middle mould region T	Room T	183.6740*	1.71654	.000	178.1136	189.2344
	Furnace T	-19.4880-*	1.71654	.000	-25.0484-	-13.9276-
	Flask-enterance T	3.2020	1.71654	.583	-2.3584-	8.7624
	Posterior mould region T	1.3380	1.71654	.993	-4.2224-	6.8984
	Anterior mould region T	1.5180	1.71654	.985	-4.0424-	7.0784
	Premolar region T	2.6860	1.71654	.767	-2.8744-	8.2464
	Molar region T	2.9800	1.71654	.665	-2.5804-	8.5404
Anterior mould region T	Room T	182.1560*	1.71654	.000	176.5956	187.7164
	Furnace T	-21.0060-*	1.71654	.000	-26.5664-	-15.4456-
	Flask-enterance T	1.6840	1.71654	.974	-3.8764-	7.2444
	Posterior mould region T	-.1800-	1.71654	1.000	-5.7404-	5.3804
	Middle mould region T	-1.5180-	1.71654	.985	-7.0784-	4.0424
	Premolar region T	1.1680	1.71654	.997	-4.3924-	6.7284
	Molar region T	1.4620	1.71654	.988	-4.0984-	7.0224
Premolar region T	Room T	180.9880*	1.71654	.000	175.4276	186.5484
	Furnace T	-22.1740-*	1.71654	.000	-27.7344-	-16.6136-
	Flask-enterance T	.5160	1.71654	1.000	-5.0444-	6.0764
	Posterior mould region T	-1.3480-	1.71654	.993	-6.9084-	4.2124
	Middle mould region T	-2.6860-	1.71654	.767	-8.2464-	2.8744
	Anterior mould region T	-1.1680-	1.71654	.997	-6.7284-	4.3924
	Molar region T	.2940	1.71654	1.000	-5.2664-	5.8544
Molar region T	Room T	180.6940*	1.71654	.000	175.1336	186.2544
	Furnace T	-22.4680-*	1.71654	.000	-28.0284-	-16.9076-
	Flask-enterance T	.2220	1.71654	1.000	-5.3384-	5.7824
	Posterior mould region T	-1.6420-	1.71654	.977	-7.2024-	3.9184
	Middle mould region T	-2.9800-	1.71654	.665	-8.5404-	2.5804
	Anterior mould region T	-1.4620-	1.71654	.988	-7.0224-	4.0984
	Premolar region T	-.2940-	1.71654	1.000	-5.8544-	5.2664

Based on observed means.

The error term is Mean Square(Error) = 7.366.

*. The mean difference is significant at the .05 level.

Part (C): Flow and Thickness

UNIANOVA Flow0.8mm BY Materials

Between-Subjects Factors

		Value Label	N
Materials	1.00	PMMA (Heat-Cured)	10
	2.00	PMMA (Thermo-press)	10
	3.00	PEEK-Optima® (100°C)	10
	4.00	PEEK-Optima® (150°C)	10
	5.00	PEEK-Optima® (175°C)	10
	6.00	PEEK-Optima® (200°C)	10

Descriptive Statistics

Dependent Variable: Flow0.8mm

Materials	Mean	Std. Deviation	N
PMMA (Heat-Cured)	100.0000	.00000	10
PMMA (Thermo-press)	95.0708	5.41492	10
PEEK-Optima® (100°C)	99.3083	1.10121	10
PEEK-Optima® (150°C)	87.5208	7.69255	10
PEEK-Optima® (175°C)	74.2500	7.88334	10
PEEK-Optima® (200°C)	84.0333	12.20984	10
Total	90.0306	11.44630	60

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Flow0.8mm

F	df1	df2	Sig.
8.350	5	54	.000

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Materials

1. Grand Mean

Dependent Variable: Flow0.8mm

		95% Confidence Interval	
Mean	Std. Error	Lower Bound	Upper Bound
90.031	.914	88.198	91.864

2. Materials

Dependent Variable: Flow0.8mm

			95% Confidence Interval	
Materials	Mean	Std. Error	Lower Bound	Upper Bound
PMMA (Heat-Cured)	100.000	2.240	95.510	104.490
PMMA (Thermo-press)	95.071	2.240	90.581	99.561
PEEK-Optima® (100°C)	99.308	2.240	94.818	103.798
PEEK-Optima® (150°C)	87.521	2.240	83.031	92.011
PEEK-Optima® (175°C)	74.250	2.240	69.760	78.740
PEEK-Optima® (200°C)	84.033	2.240	79.543	88.523

Multiple Comparisons

Dependent Variable: Flow0.8mm

Games-Howell

		Mean Difference			95% Confidence Interval	
(I) Materials	(J) Materials	(I-J)	Std. Error	Sig.	Lower Bound	Upper Bound
PMMA (Heat-Cured)	PMMA (Thermo-press)	4.9292	1.71235	.130	-1.1534-	11.0117
	PEEK-Optima® (100°C)	.6917	.34823	.416	-.5453-	1.9286
	PEEK-Optima® (150°C)	12.4792*	2.43260	.006	3.8382	21.1201
	PEEK-Optima® (175°C)	25.7500*	2.49293	.000	16.8947	34.6053
	PEEK-Optima® (200°C)	15.9667*	3.86109	.022	2.2515	29.6819
PMMA (Thermo-press)	PMMA (Heat-Cured)	-4.9292-	1.71235	.130	-11.0117-	1.1534
	PEEK-Optima® (100°C)	-4.2375-	1.74740	.236	-10.3391-	1.8641
	PEEK-Optima® (150°C)	7.5500	2.97484	.170	-2.0235-	17.1235
	PEEK-Optima® (175°C)	20.8208*	3.02437	.000	11.0718	30.5699
	PEEK-Optima® (200°C)	11.0375	4.22376	.165	-3.0721-	25.1471
PEEK-Optima® (100°C)	PMMA (Heat-Cured)	-.6917-	.34823	.416	-1.9286-	.5453
	PMMA (Thermo-press)	4.2375	1.74740	.236	-1.8641-	10.3391
	PEEK-Optima® (150°C)	11.7875*	2.45740	.008	3.1353	20.4397
	PEEK-Optima® (175°C)	25.0583*	2.51713	.000	16.1922	33.9245
	PEEK-Optima® (200°C)	15.2750*	3.87676	.028	1.5536	28.9964
PEEK-Optima® (150°C)	PMMA (Heat-Cured)	-12.4792-*	2.43260	.006	-21.1201-	-3.8382-
	PMMA (Thermo-press)	-7.5500-	2.97484	.170	-17.1235-	2.0235
	PEEK-Optima® (100°C)	-11.7875-*	2.45740	.008	-20.4397-	-3.1353-
	PEEK-Optima® (175°C)	13.2708*	3.48313	.014	2.2006	24.3411
	PEEK-Optima® (200°C)	3.4875	4.56350	.970	-11.3168-	18.2918
PEEK-Optima® (175°C)	PMMA (Heat-Cured)	-25.7500-*	2.49293	.000	-34.6053-	-16.8947-
	PMMA (Thermo-press)	-20.8208-*	3.02437	.000	-30.5699-	-11.0718-
	PEEK-Optima® (100°C)	-25.0583-*	2.51713	.000	-33.9245-	-16.1922-
	PEEK-Optima® (150°C)	-13.2708-*	3.48313	.014	-24.3411-	-2.2006-
	PEEK-Optima® (200°C)	-9.7833-	4.59595	.323	-24.6650-	5.0983
PEEK-Optima® (200°C)	PMMA (Heat-Cured)	-15.9667-*	3.86109	.022	-29.6819-	-2.2515-
	PMMA (Thermo-press)	-11.0375-	4.22376	.165	-25.1471-	3.0721
	PEEK-Optima® (100°C)	-15.2750-*	3.87676	.028	-28.9964-	-1.5536-
	PEEK-Optima® (150°C)	-3.4875-	4.56350	.970	-18.2918-	11.3168
	PEEK-Optima® (175°C)	9.7833	4.59595	.323	-5.0983-	24.6650

Based on observed means.

The error term is Mean Square(Error) = 50.156.

*. The mean difference is significant at the .05 level.

UNIANOVA Flow1mm BY Thermo-pressed Materials

Between-Subjects Factors

		Value Label	N
ThermopressedMaterials	1.00	PMMA (Thermo-press)	10
	2.00	PEEK-Optima® (100°C)	10
	3.00	PEEK-Optima® (150°C)	10
	4.00	PEEK-Optima® (175°C)	10
	5.00	PEEK-Optima® (200°C)	10

Descriptive Statistics

Dependent Variable: Flow1mm

ThermopressedMaterials	Mean	Std. Deviation	N
PMMA (Thermo-press)	100.0000	.00000	10
PEEK-Optima® (100°C)	99.4000	1.27039	10
PEEK-Optima® (150°C)	97.3625	2.26641	10
PEEK-Optima® (175°C)	95.1125	1.82130	10
PEEK-Optima® (200°C)	98.6000	1.36411	10
Total	98.0950	2.29260	50

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Flow1mm

F	df1	df2	Sig.
3.693	4	45	.011

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + ThermopressedMaterials

1. ThermopressedMaterials

Dependent Variable: Flow1mm

			95% Confidence Interval	
ThermopressedMaterials	Mean	Std. Error	Lower Bound	Upper Bound
PMMA (Thermo-press)	100.000	.488	99.016	100.984
PEEK-Optima® (100°C)	99.400	.488	98.416	100.384
PEEK-Optima® (150°C)	97.362	.488	96.379	98.346
PEEK-Optima® (175°C)	95.112	.488	94.129	96.096
PEEK-Optima® (200°C)	98.600	.488	97.616	99.584

2. Grand Mean

Dependent Variable: Flow1mm

		95% Confidence Interval	
Mean	Std. Error	Lower Bound	Upper Bound
98.095	.218	97.655	98.535

Multiple Comparisons

Dependent Variable: Flow1mm

Games-Howell

					95% Confidence Interval	
(I) ThermopressedMaterials	(J) ThermopressedMaterials	Mean Difference (I-J)	Std. Error	Sig.	Lower Bound	Upper Bound
PMMA (Thermo-press)	PEEK-Optima® (100°C)	.6000	.40173	.590	-.7509-	1.9509
	PEEK-Optima® (150°C)	2.6375*	.71670	.031	.2275	5.0475
	PEEK-Optima® (175°C)	4.8875*	.57595	.000	2.9508	6.8242
	PEEK-Optima® (200°C)	1.4000	.43137	.059	-.0505-	2.8505
PEEK-Optima® (100°C)	PMMA (Thermo-press)	-.6000-	.40173	.590	-1.9509-	.7509
	PEEK-Optima® (150°C)	2.0375	.82161	.151	-.5190-	4.5940
	PEEK-Optima® (175°C)	4.2875*	.70221	.000	2.1374	6.4376
	PEEK-Optima® (200°C)	.8000	.58947	.661	-.9834-	2.5834
PEEK-Optima® (150°C)	PMMA (Thermo-press)	-2.6375-*	.71670	.031	-5.0475-	-.2275-
	PEEK-Optima® (100°C)	-2.0375-	.82161	.151	-4.5940-	.5190
	PEEK-Optima® (175°C)	2.2500	.91944	.150	-.5437-	5.0437
	PEEK-Optima® (200°C)	-1.2375-	.83650	.590	-3.8258-	1.3508
PEEK-Optima® (175°C)	PMMA (Thermo-press)	-4.8875-*	.57595	.000	-6.8242-	-2.9508-
	PEEK-Optima® (100°C)	-4.2875-*	.70221	.000	-6.4376-	-2.1374-
	PEEK-Optima® (150°C)	-2.2500-	.91944	.150	-5.0437-	.5437
	PEEK-Optima® (200°C)	-3.4875-*	.71958	.001	-5.6815-	-1.2935-
PEEK-Optima® (200°C)	PMMA (Thermo-press)	-1.4000-	.43137	.059	-2.8505-	.0505
	PEEK-Optima® (100°C)	-.8000-	.58947	.661	-2.5834-	.9834
	PEEK-Optima® (150°C)	1.2375	.83650	.590	-1.3508-	3.8258
	PEEK-Optima® (175°C)	3.4875*	.71958	.001	1.2935	5.6815

Based on observed means.

The error term is Mean Square(Error) = 2.386.

*. The mean difference is significant at the .05 level.

UNIANOVA Flow Percentage 0.8 & 1mm BY Thermo-pressed Materials

Between-Subjects Factors

		Value Label	N
ThermopressedMaterials	1.00	PMMA at 0.8mm	10
	2.00	PMMA at 1mm	10
	3.00	PEEK-Optima® at 0.8mm (100°C)	10
	4.00	PEEK-Optima® at 1mm (100°C)	10
	5.00	PEEK-Optima® at 0.8mm (150°C)	10
	6.00	PEEK-Optima® at 1mm (150°C)	10
	7.00	PEEK-Optima® at 0.8mm (175°C)	10
	8.00	PEEK-Optima® at 1mm (175°C)	10
	9.00	PEEK-Optima® at 0.8mm (200°C)	10
	10.00	PEEK-Optima® at 1 mm (200°C)	10

Descriptive Statistics

Dependent Variable: FlowPercentage

ThermopressedMaterials	Mean	Std. Deviation	N
PMMA at 0.8mm	95.0708	5.41492	10
PMMA at 1mm	100.0000	.00000	10
PEEK-Optima® at 0.8mm (100°C)	99.3083	1.10121	10
PEEK-Optima® at 1mm (100°C)	99.4000	1.27039	10
PEEK-Optima® at 0.8mm (150°C)	87.5208	7.69255	10
PEEK-Optima® at 1mm (150°C)	97.3625	2.26641	10
PEEK-Optima® at 0.8mm (175°C)	74.2500	7.88334	10
PEEK-Optima® at 1mm (175°C)	95.1125	1.82130	10
PEEK-Optima® at 0.8mm (200°C)	84.0333	12.20984	10
PEEK-Optima® at 1 mm (200°C)	98.6000	1.36411	10
Total	93.0658	9.70482	100

Levene's Test of Equality of Error Variances[a]

Dependent Variable: FlowPercentage

F	df1	df2	Sig.
9.949	9	90	.000

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + ThermopressedMaterials

1. Grand Mean

Dependent Variable: FlowPercentage

Mean	Std. Error	95% Confidence Interval	
		Lower Bound	Upper Bound
93.066	.559	91.955	94.177

2. ThermopressedMaterials

Dependent Variable: FlowPercentage

ThermopressedMaterials	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
PMMA at 0.8mm	95.071	1.769	91.557	98.585
PMMA at 1mm	100.000	1.769	96.486	103.514
PEEK-Optima® at 0.8mm (100°C)	99.308	1.769	95.794	102.822
PEEK-Optima® at 1mm (100°C)	99.400	1.769	95.886	102.914
PEEK-Optima® at 0.8mm (150°C)	87.521	1.769	84.007	91.035
PEEK-Optima® at 1mm (150°C)	97.363	1.769	93.848	100.877
PEEK-Optima® at 0.8mm (175°C)	74.250	1.769	70.736	77.764
PEEK-Optima® at 1mm (175°C)	95.112	1.769	91.598	98.627
PEEK-Optima® at 0.8mm (200°C)	84.033	1.769	80.519	87.547
PEEK-Optima® at 1 mm (200°C)	98.600	1.769	95.086	102.114

Multiple Comparisons

Dependent Variable: FlowPercentage

Games-Howell

(I) ThermopressedMaterials	(J) ThermopressedMaterials	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
PMMA at 0.8mm	PMMA at 1mm	-4.9292-	1.71235	.237	-11.8773-	2.0189
	PEEK-Optima® at 0.8mm (100°C)	-4.2375-	1.74740	.401	-11.1955-	2.7205
	PEEK-Optima® at 1mm (100°C)	-4.3292-	1.75884	.383	-11.2937-	2.6354
	PEEK-Optima® at 0.8mm (150°C)	7.5500	2.97484	.318	-3.2677-	18.3677
	PEEK-Optima® at 1mm (150°C)	-2.2917-	1.85629	.951	-9.3661-	4.7828
	PEEK-Optima® at 0.8mm (175°C)	20.8208*	3.02437	.000	9.8025	31.8391
	PEEK-Optima® at 1mm (175°C)	-.0417-	1.80661	1.000	-7.0489-	6.9656
	PEEK-Optima® at 0.8mm (200°C)	11.0375	4.22376	.303	-4.9762-	27.0512
	PEEK-Optima® at 1 mm (200°C)	-3.5292-	1.76585	.617	-10.4985-	3.4401
PMMA at 1mm	PMMA at 0.8mm	4.9292	1.71235	.237	-2.0189-	11.8773
	PEEK-Optima® at 0.8mm (100°C)	.6917	.34823	.625	-.7213-	2.1047
	PEEK-Optima® at 1mm (100°C)	.6000	.40173	.866	-1.0301-	2.2301
	PEEK-Optima® at 0.8mm (150°C)	12.4792*	2.43260	.012	2.6085	22.3498
	PEEK-Optima® at 1mm (150°C)	2.6375	.71670	.083	-.2706-	5.5456
	PEEK-Optima® at 0.8mm (175°C)	25.7500*	2.49293	.000	15.6346	35.8654
	PEEK-Optima® at 1mm (175°C)	4.8875*	.57595	.000	2.5505	7.2245
	PEEK-Optima® at 0.8mm (200°C)	15.9667*	3.86109	.045	.2997	31.6336
	PEEK-Optima® at 1 mm (200°C)	1.4000	.43137	.148	-.3503-	3.1503
PEEK-Optima® at 0.8mm (100°C)	PMMA at 0.8mm	4.2375	1.74740	.401	-2.7205-	11.1955
	PMMA at 1mm	-.6917-	.34823	.625	-2.1047-	.7213
	PEEK-Optima® at 1mm (100°C)	-.0917-	.53165	1.000	-2.0026-	1.8193
	PEEK-Optima® at 0.8mm (150°C)	11.7875*	2.45740	.017	1.9127	21.6623
	PEEK-Optima® at 1mm (150°C)	1.9458	.79682	.375	-1.0496-	4.9413
	PEEK-Optima® at 0.8mm (175°C)	25.0583*	2.51713	.000	14.9389	35.1777
	PEEK-Optima® at 1mm (175°C)	4.1958*	.67304	.001	1.7172	6.6744
	PEEK-Optima® at 0.8mm (200°C)	15.2750	3.87676	.057	-.3935-	30.9435
	PEEK-Optima® at 1 mm (200°C)	.7083	.55439	.946	-1.2904-	2.7070
PEEK-Optima® at 1mm (100°C)	PMMA at 0.8mm	4.3292	1.75884	.383	-2.6354-	11.2937
	PMMA at 1mm	-.6000-	.40173	.866	-2.2301-	1.0301
	PEEK-Optima® at 0.8mm (100°C)	.0917	.53165	1.000	-1.8193-	2.0026
	PEEK-Optima® at 0.8mm (150°C)	11.8792*	2.46555	.016	2.0017	21.7566
	PEEK-Optima® at 1mm (150°C)	2.0375	.82161	.352	-1.0095-	5.0845
	PEEK-Optima® at 0.8mm (175°C)	25.1500*	2.52509	.000	15.0282	35.2718
	PEEK-Optima® at 1mm (175°C)	4.2875*	.70221	.000	1.7322	6.8428
	PEEK-Optima® at 0.8mm (200°C)	15.3667	3.88193	.056	-.3027-	31.0360
	PEEK-Optima® at 1 mm (200°C)	.8000	.58947	.925	-1.3148-	2.9148
PEEK-Optima® at 0.8mm (150°C)	PMMA at 0.8mm	-7.5500-	2.97484	.318	-18.3677-	3.2677
	PMMA at 1mm	-12.4792-*	2.43260	.012	-22.3498-	-2.6085-
	PEEK-Optima® at 0.8mm (100°C)	-11.7875-*	2.45740	.017	-21.6623-	-1.9127-
	PEEK-Optima® at 1mm (100°C)	-11.8792-*	2.46555	.016	-21.7566-	-2.0017-
	PEEK-Optima® at 1mm (150°C)	-9.8417-	2.53598	.052	-19.7649-	.0815
	PEEK-Optima® at 0.8mm (175°C)	13.2708*	3.48313	.032	.7815	25.7602
	PEEK-Optima® at 1mm (175°C)	-7.5917-	2.49985	.184	-17.4864-	2.3031
	PEEK-Optima® at 0.8mm (200°C)	3.4875	4.56350	.998	-13.2572-	20.2322
	PEEK-Optima® at 1 mm (200°C)	-11.0792-*	2.47055	.026	-20.9585-	-1.1998-
PEEK-Optima® at 1mm (150°C)	PMMA at 0.8mm	2.2917	1.85629	.951	-4.7828-	9.3661
	PMMA at 1mm	-2.6375-	.71670	.083	-5.5456-	.2706
	PEEK-Optima® at 0.8mm (100°C)	-1.9458-	.79682	.375	-4.9413-	1.0496
	PEEK-Optima® at 1mm (100°C)	-2.0375-	.82161	.352	-5.0845-	1.0095
	PEEK-Optima® at 0.8mm (150°C)	9.8417	2.53598	.052	-.0815-	19.7649

	PEEK-Optima® at 0.8mm (175°C)	23.1125*	2.59391	.000	12.9477	33.2773
	PEEK-Optima® at 1mm (175°C)	2.2500	.91944	.358	-1.0656-	5.5656
	PEEK-Optima® at 0.8mm (200°C)	13.3292	3.92704	.115	-2.3540-	29.0123
	PEEK-Optima® at 1 mm (200°C)	-1.2375-	.83650	.881	-4.3194-	1.8444
PEEK-Optima® at 0.8mm (175°C)	PMMA at 0.8mm	-20.8208-*	3.02437	.000	-31.8391-	-9.8025-
	PMMA at 1mm	-25.7500-*	2.49293	.000	-35.8654-	-15.6346-
	PEEK-Optima® at 0.8mm (100°C)	-25.0583-*	2.51713	.000	-35.1777-	-14.9389-
	PEEK-Optima® at 1mm (100°C)	-25.1500-*	2.52509	.000	-35.2718-	-15.0282-
	PEEK-Optima® at 0.8mm (150°C)	-13.2708-*	3.48313	.032	-25.7602-	-.7815-
	PEEK-Optima® at 1mm (150°C)	-23.1125-*	2.59391	.000	-33.2773-	-12.9477-
	PEEK-Optima® at 1mm (175°C)	-20.8625-*	2.55860	.000	-31.0006-	-10.7244-
	PEEK-Optima® at 0.8mm (200°C)	-9.7833-	4.59595	.535	-26.6116-	7.0450
	PEEK-Optima® at 1 mm (200°C)	-24.3500-*	2.52998	.000	-34.4736-	-14.2264-
PEEK-Optima® at 1mm (175°C)	PMMA at 0.8mm	.0417	1.80661	1.000	-6.9656-	7.0489
	PMMA at 1mm	-4.8875-*	.57595	.000	-7.2245-	-2.5505-
	PEEK-Optima® at 0.8mm (100°C)	-4.1958-*	.67304	.001	-6.6744-	-1.7172-
	PEEK-Optima® at 1mm (100°C)	-4.2875-*	.70221	.000	-6.8428-	-1.7322-
	PEEK-Optima® at 0.8mm (150°C)	7.5917	2.49985	.184	-2.3031-	17.4864
	PEEK-Optima® at 1mm (150°C)	-2.2500-	.91944	.358	-5.5656-	1.0656
	PEEK-Optima® at 0.8mm (175°C)	20.8625*	2.55860	.000	10.7244	31.0006
	PEEK-Optima® at 0.8mm (200°C)	11.0792	3.90381	.245	-4.5954-	26.7537
	PEEK-Optima® at 1 mm (200°C)	-3.4875-*	.71958	.005	-6.0929-	-.8821-
PEEK-Optima® at 0.8mm (200°C)	PMMA at 0.8mm	-11.0375-	4.22376	.303	-27.0512-	4.9762
	PMMA at 1mm	-15.9667-*	3.86109	.045	-31.6336-	-.2997-
	PEEK-Optima® at 0.8mm (100°C)	-15.2750-	3.87676	.057	-30.9435-	.3935
	PEEK-Optima® at 1mm (100°C)	-15.3667-	3.88193	.056	-31.0360-	.3027
	PEEK-Optima® at 0.8mm (150°C)	-3.4875-	4.56350	.998	-20.2322-	13.2572
	PEEK-Optima® at 1mm (150°C)	-13.3292-	3.92704	.115	-29.0123-	2.3540
	PEEK-Optima® at 0.8mm (175°C)	9.7833	4.59595	.535	-7.0450-	26.6116
	PEEK-Optima® at 1mm (175°C)	-11.0792-	3.90381	.245	-26.7537-	4.5954
	PEEK-Optima® at 1 mm (200°C)	-14.5667-	3.88511	.074	-30.2366-	1.1032
PEEK-Optima® at 1 mm (200°C)	PMMA at 0.8mm	3.5292	1.76585	.617	-3.4401-	10.4985
	PMMA at 1mm	-1.4000-	.43137	.148	-3.1503-	.3503
	PEEK-Optima® at 0.8mm (100°C)	-.7083-	.55439	.946	-2.7070-	1.2904
	PEEK-Optima® at 1mm (100°C)	-.8000-	.58947	.925	-2.9148-	1.3148
	PEEK-Optima® at 0.8mm (150°C)	11.0792*	2.47055	.026	1.1998	20.9585
	PEEK-Optima® at 1mm (150°C)	1.2375	.83650	.881	-1.8444-	4.3194
	PEEK-Optima® at 0.8mm (175°C)	24.3500*	2.52998	.000	14.2264	34.4736
	PEEK-Optima® at 1mm (175°C)	3.4875*	.71958	.005	.8821	6.0929
	PEEK-Optima® at 0.8mm (200°C)	14.5667	3.88511	.074	-1.1032-	30.2366

Based on observed means.

The error term is Mean Square(Error) = 31.286.

*. The mean difference is significant at the .05 level.

Thickness
UNIANOVA Thickness BY Materials (at 0.8mm)

Between-Subjects Factors

		Value Label	N
Materials	1.00	PMMA (Heat-Cured)	240
	2.00	PMMA (Thermo-press)	221
	3.00	PEEK-Optima® (100°C)	227
	4.00	PEEK-Optima® (150°C)	182
	5.00	PEEK-Optima® (175°C)	153
	6.00	PEEK-Optima® (200°C)	176

Descriptive Statistics

Dependent Variable: Thickness

Materials	Mean	Std. Deviation	N
PMMA (Heat-Cured)	1.1399	.16546	240
PMMA (Thermo-press)	1.0212	.17164	221
PEEK-Optima® (100°C)	1.1249	.16458	227
PEEK-Optima® (150°C)	1.0881	.09921	182
PEEK-Optima® (175°C)	.9806	.07954	153
PEEK-Optima® (200°C)	1.0661	.11951	176
Total	1.0762	.15291	1199

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Thickness

F	df1	df2	Sig.
18.448	5	1193	.000

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Materials

1. Grand Mean

Dependent Variable: Thickness

		95% Confidence Interval	
Mean	Std. Error	Lower Bound	Upper Bound
1.070	.004	1.062	1.078

2. Materials

Dependent Variable: Thickness

			95% Confidence Interval	
Materials	Mean	Std. Error	Lower Bound	Upper Bound
PMMA (Heat-Cured)	1.140	.009	1.122	1.158
PMMA (Thermo-press)	1.021	.010	1.002	1.040
PEEK-Optima® (100°C)	1.125	.009	1.106	1.144
PEEK-Optima® (150°C)	1.088	.011	1.067	1.109
PEEK-Optima® (175°C)	.981	.012	.958	1.003
PEEK-Optima® (200°C)	1.066	.011	1.045	1.087

Multiple Comparisons

Dependent Variable: Thickness
Games-Howell

(I) Materials	(J) Materials	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
PMMA (Heat-Cured)	PMMA (Thermo-press)	.1187*	.01573	.000	.0736	.1637
	PEEK-Optima® (100°C)	.0150	.01528	.924	-.0288-	.0587
	PEEK-Optima® (150°C)	.0518*	.01297	.001	.0146	.0889
	PEEK-Optima® (175°C)	.1593*	.01247	.000	.1236	.1950
	PEEK-Optima® (200°C)	.0737*	.01397	.000	.0337	.1138
PMMA (Thermo-press)	PMMA (Heat-Cured)	-.1187-*	.01573	.000	-.1637-	-.0736-
	PEEK-Optima® (100°C)	-.1037-*	.01589	.000	-.1492-	-.0582-
	PEEK-Optima® (150°C)	-.0669-*	.01369	.000	-.1061-	-.0277-
	PEEK-Optima® (175°C)	.0406*	.01322	.027	.0028	.0785
	PEEK-Optima® (200°C)	-.0449-*	.01464	.028	-.0868-	-.0030-
PEEK-Optima® (100°C)	PMMA (Heat-Cured)	-.0150-	.01528	.924	-.0587-	.0288
	PMMA (Thermo-press)	.1037*	.01589	.000	.0582	.1492
	PEEK-Optima® (150°C)	.0368	.01317	.060	-.0009-	.0745
	PEEK-Optima® (175°C)	.1443*	.01268	.000	.1080	.1806
	PEEK-Optima® (200°C)	.0588*	.01416	.001	.0182	.0993
PEEK-Optima® (150°C)	PMMA (Heat-Cured)	-.0518-*	.01297	.001	-.0889-	-.0146-
	PMMA (Thermo-press)	.0669*	.01369	.000	.0277	.1061
	PEEK-Optima® (100°C)	-.0368-	.01317	.060	-.0745-	.0009
	PEEK-Optima® (175°C)	.1075*	.00977	.000	.0795	.1355
	PEEK-Optima® (200°C)	.0220	.01163	.410	-.0114-	.0553
PEEK-Optima® (175°C)	PMMA (Heat-Cured)	-.1593-*	.01247	.000	-.1950-	-.1236-
	PMMA (Thermo-press)	-.0406-*	.01322	.027	-.0785-	-.0028-
	PEEK-Optima® (100°C)	-.1443-*	.01268	.000	-.1806-	-.1080-
	PEEK-Optima® (150°C)	-.1075-*	.00977	.000	-.1355-	-.0795-
	PEEK-Optima® (200°C)	-.0855-*	.01107	.000	-.1173-	-.0538-
PEEK-Optima® (200°C)	PMMA (Heat-Cured)	-.0737-*	.01397	.000	-.1138-	-.0337-
	PMMA (Thermo-press)	.0449*	.01464	.028	.0030	.0868
	PEEK-Optima® (100°C)	-.0588-*	.01416	.001	-.0993-	-.0182-
	PEEK-Optima® (150°C)	-.0220-	.01163	.410	-.0553-	.0114
	PEEK-Optima® (175°C)	.0855*	.01107	.000	.0538	.1173

Based on observed means.
The error term is Mean Square(Error) = .020.
*. The mean difference is significant at the .05 level.

UNIANOVA Thicknessat1mmdepthspecimen BY Thermo-pressed Materials

Between-Subjects Factors

		Value Label	N
ThermopressedMaterials	1.00	PMMA (Thermo-press)	240
	2.00	PEEK-Optima® (100°C)	240
	3.00	PEEK-Optima® (150°C)	240
	4.00	PEEK-Optima® (175°C)	240
	5.00	PEEK-Optima® (200°C)	240

Descriptive Statistics

Dependent Variable: Thicknessat1mmdepthspecimen

ThermopressedMaterials	Mean	Std. Deviation	N
PMMA (Thermo-press)	1.3190	.07119	240
PEEK-Optima® (100°C)	1.3428	.09888	240
PEEK-Optima® (150°C)	1.3268	.08159	240
PEEK-Optima® (175°C)	1.3151	.07943	240
PEEK-Optima® (200°C)	1.3183	.07872	240
Total	1.3244	.08294	1200

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Thicknessat1mmdepthspecimen

F	df1	df2	Sig.
9.075	4	1195	.000

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + ThermopressedMaterials

1. Grand Mean

Dependent Variable: Thicknessat1mmdepthspecimen

Mean	Std. Error	95% Confidence Interval	
		Lower Bound	Upper Bound
1.324	.002	1.320	1.329

2. ThermopressedMaterials

Dependent Variable: Thicknessat1mmdepthspecimen

ThermopressedMaterials	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
PMMA (Thermo-press)	1.319	.005	1.309	1.329
PEEK-Optima® (100°C)	1.343	.005	1.332	1.353
PEEK-Optima® (150°C)	1.327	.005	1.316	1.337
PEEK-Optima® (175°C)	1.315	.005	1.305	1.326
PEEK-Optima® (200°C)	1.318	.005	1.308	1.329

Multiple Comparisons

Dependent Variable: Thicknessat1mmdepthspecimen

Games-Howell

(I) ThermopressedMaterials	(J) ThermopressedMaterials	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
PMMA (Thermo-press)	PEEK-Optima® (100°C)	-.0238-*	.00786	.022	-.0454-	-.0023-
	PEEK-Optima® (150°C)	-.0078-	.00699	.796	-.0270-	.0113
	PEEK-Optima® (175°C)	.0039	.00689	.980	-.0150-	.0227
	PEEK-Optima® (200°C)	.0007	.00685	1.000	-.0181-	.0195
PEEK-Optima® (100°C)	PMMA (Thermo-press)	.0238*	.00786	.022	.0023	.0454
	PEEK-Optima® (150°C)	.0160	.00827	.302	-.0067-	.0386
	PEEK-Optima® (175°C)	.0277*	.00819	.007	.0053	.0501
	PEEK-Optima® (200°C)	.0245*	.00816	.023	.0022	.0469
PEEK-Optima® (150°C)	PMMA (Thermo-press)	.0078	.00699	.796	-.0113-	.0270
	PEEK-Optima® (100°C)	-.0160-	.00827	.302	-.0386-	.0067
	PEEK-Optima® (175°C)	.0117	.00735	.503	-.0084-	.0318
	PEEK-Optima® (200°C)	.0085	.00732	.771	-.0115-	.0286
PEEK-Optima® (175°C)	PMMA (Thermo-press)	-.0039-	.00689	.980	-.0227-	.0150
	PEEK-Optima® (100°C)	-.0277-*	.00819	.007	-.0501-	-.0053-
	PEEK-Optima® (150°C)	-.0117-	.00735	.503	-.0318-	.0084
	PEEK-Optima® (200°C)	-.0032-	.00722	.992	-.0229-	.0166
PEEK-Optima® (200°C)	PMMA (Thermo-press)	-.0007-	.00685	1.000	-.0195-	.0181
	PEEK-Optima® (100°C)	-.0245-*	.00816	.023	-.0469-	-.0022-
	PEEK-Optima® (150°C)	-.0085-	.00732	.771	-.0286-	.0115
	PEEK-Optima® (175°C)	.0032	.00722	.992	-.0166-	.0229

Based on observed means.

The error term is Mean Square(Error) = .007.

*. The mean difference is significant at the .05 level.

UNIANOVA Thickness BY Thermo-pressed Materials (Between 0.8& 1mm)

Between-Subjects Factors

		Value Label	N
ThermopressedMaterials	1.00	PMMA at 0.8mm	221
	2.00	PMMA at 1mm	240
	3.00	PEEK-Optima® at 0.8mm (100°C)	227
	4.00	PEEK-Optima® at 1mm (100°C)	240
	5.00	PEEK-Optima® at 0.8mm (150°C)	182
	6.00	PEEK-Optima® at 1mm (150°C)	240
	7.00	PEEK-Optima® at 0.8mm (175°C)	38
	8.00	PEEK-Optima® at 1mm (175°C)	240
	9.00	PEEK-Optima® at 0.8mm (200°C)	176
	10.00	PEEK-Optima® at 1 mm (200°C)	35

Descriptive Statistics

Dependent Variable: Thickness

ThermopressedMaterials	Mean	Std. Deviation	N
PMMA at 0.8mm	1.0212	.17164	221
PMMA at 1mm	1.3190	.07119	240
PEEK-Optima® at 0.8mm (100°C)	1.1249	.16458	227
PEEK-Optima® at 1mm (100°C)	1.3428	.09888	240
PEEK-Optima® at 0.8mm (150°C)	1.0881	.09921	182
PEEK-Optima® at 1mm (150°C)	1.3268	.08159	240
PEEK-Optima® at 0.8mm (175°C)	.9831	.07460	38
PEEK-Optima® at 1mm (175°C)	1.3151	.07943	240
PEEK-Optima® at 0.8mm (200°C)	1.0661	.11951	176
PEEK-Optima® at 1 mm (200°C)	1.3075	.07351	35
Total	1.2087	.17312	1839

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Thickness

F	df1	df2	Sig.
19.734	9	1829	.000

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + ThermopressedMaterials

1. Grand Mean

Dependent Variable: Thickness

Mean	Std. Error	95% Confidence Interval	
		Lower Bound	Upper Bound
1.189	.003	1.183	1.196

2. ThermopressedMaterials

Dependent Variable: Thickness

ThermopressedMaterials	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
PMMA at 0.8mm	1.021	.008	1.006	1.036
PMMA at 1mm	1.319	.007	1.305	1.333
PEEK-Optima® at 0.8mm (100°C)	1.125	.008	1.110	1.140
PEEK-Optima® at 1mm (100°C)	1.343	.007	1.328	1.357
PEEK-Optima® at 0.8mm (150°C)	1.088	.008	1.071	1.105
PEEK-Optima® at 1mm (150°C)	1.327	.007	1.312	1.341
PEEK-Optima® at 0.8mm (175°C)	.983	.019	.947	1.019
PEEK-Optima® at 1mm (175°C)	1.315	.007	1.301	1.330
PEEK-Optima® at 0.8mm (200°C)	1.066	.009	1.049	1.083
PEEK-Optima® at 1 mm (200°C)	1.307	.019	1.270	1.345

Multiple Comparisons

Dependent Variable: Thickness

Games-Howell

(I) ThermopressedMaterials	(J) ThermopressedMaterials	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
PMMA at 0.8mm	PMMA at 1mm	-.2978-*	.01243	.000	-.3374-	-.2581-
	PEEK-Optima® at 0.8mm (100°C)	-.1037-*	.01589	.000	-.1542-	-.0531-
	PEEK-Optima® at 1mm (100°C)	-.3216-*	.01319	.000	-.3636-	-.2796-
	PEEK-Optima® at 0.8mm (150°C)	-.0669-*	.01369	.000	-.1105-	-.0233-
	PEEK-Optima® at 1mm (150°C)	-.3056-*	.01269	.000	-.3460-	-.2652-
	PEEK-Optima® at 0.8mm (175°C)	.0381	.01673	.411	-.0158-	.0921
	PEEK-Optima® at 1mm (175°C)	-.2939-*	.01263	.000	-.3342-	-.2536-
	PEEK-Optima® at 0.8mm (200°C)	-.0449-	.01464	.070	-.0915-	.0017
	PEEK-Optima® at 1 mm (200°C)	-.2863-*	.01696	.000	-.3411-	-.2314-
PMMA at 1mm	PMMA at 0.8mm	.2978*	.01243	.000	.2581	.3374
	PEEK-Optima® at 0.8mm (100°C)	.1941*	.01185	.000	.1563	.2319
	PEEK-Optima® at 1mm (100°C)	-.0238-	.00786	.077	-.0488-	.0012
	PEEK-Optima® at 0.8mm (150°C)	.2309*	.00867	.000	.2033	.2585
	PEEK-Optima® at 1mm (150°C)	-.0078-	.00699	.982	-.0301-	.0144
	PEEK-Optima® at 0.8mm (175°C)	.3359*	.01295	.000	.2930	.3788
	PEEK-Optima® at 1mm (175°C)	.0039	.00689	1.000	-.0180-	.0258
	PEEK-Optima® at 0.8mm (200°C)	.2529*	.01011	.000	.2206	.2851
	PEEK-Optima® at 1 mm (200°C)	.0115	.01325	.997	-.0326-	.0556
PEEK-Optima® at 0.8mm (100°C)	PMMA at 0.8mm	.1037*	.01589	.000	.0531	.1542
	PMMA at 1mm	-.1941-*	.01185	.000	-.2319-	-.1563-
	PEEK-Optima® at 1mm (100°C)	-.2179-*	.01265	.000	-.2582-	-.1776-
	PEEK-Optima® at 0.8mm (150°C)	.0368	.01317	.142	-.0051-	.0787
	PEEK-Optima® at 1mm (150°C)	-.2019-*	.01213	.000	-.2405-	-.1633-
	PEEK-Optima® at 0.8mm (175°C)	.1418*	.01630	.000	.0891	.1945

	PEEK-Optima® at 1mm (175°C)	-.2939-*	.01263	.000	-.3342-	-.2536-
	PEEK-Optima® at 0.8mm (200°C)	-.0449-	.01464	.070	-.0915-	.0017
	PEEK-Optima® at 1 mm (200°C)	-.2863-*	.01696	.000	-.3411-	-.2314-
PMMA at 1mm	PMMA at 0.8mm	.2978*	.01243	.000	.2581	.3374
	PEEK-Optima® at 0.8mm (100°C)	.1941*	.01185	.000	.1563	.2319
	PEEK-Optima® at 1mm (100°C)	-.0238-	.00786	.077	-.0488-	.0012
	PEEK-Optima® at 0.8mm (150°C)	.2309*	.00867	.000	.2033	.2585
	PEEK-Optima® at 1mm (150°C)	-.0078-	.00699	.982	-.0301-	.0144
	PEEK-Optima® at 0.8mm (175°C)	.3359*	.01295	.000	.2930	.3788
	PEEK-Optima® at 1mm (175°C)	.0039	.00689	1.000	-.0180-	.0258
	PEEK-Optima® at 0.8mm (200°C)	.2529*	.01011	.000	.2206	.2851
	PEEK-Optima® at 1 mm (200°C)	.0115	.01325	.997	-.0326-	.0556
PEEK-Optima® at 0.8mm (100°C)	PMMA at 0.8mm	.1037*	.01589	.000	.0531	.1542
	PMMA at 1mm	-.1941-*	.01185	.000	-.2319-	-.1563-
	PEEK-Optima® at 1mm (100°C)	-.2179-*	.01265	.000	-.2582-	-.1776-
	PEEK-Optima® at 0.8mm (150°C)	.0368	.01317	.142	-.0051-	.0787
	PEEK-Optima® at 1mm (150°C)	-.2019-*	.01213	.000	-.2405-	-.1633-
	PEEK-Optima® at 0.8mm (175°C)	.1418*	.01630	.000	.0891	.1945
	PEEK-Optima® at 1mm (175°C)	-.1902-*	.01207	.000	-.2287-	-.1518-
	PEEK-Optima® at 0.8mm (200°C)	.0588*	.01416	.002	.0137	.1038
	PEEK-Optima® at 1 mm (200°C)	-.1826-*	.01654	.000	-.2361-	-.1290-
PEEK-Optima® at 1mm (100°C)	PMMA at 0.8mm	.3216*	.01319	.000	.2796	.3636
	PMMA at 1mm	.0238	.00786	.077	-.0012-	.0488
	PEEK-Optima® at 0.8mm (100°C)	.2179*	.01265	.000	.1776	.2582
	PEEK-Optima® at 0.8mm (150°C)	.2547*	.00974	.000	.2237	.2857

	PEEK-Optima® at 1mm (150°C)	.0160	.00827	.647	-.0103-	.0423
	PEEK-Optima® at 0.8mm (175°C)	.3597*	.01368	.000	.3147	.4047
	PEEK-Optima® at 1mm (175°C)	.0277*	.00819	.027	.0017	.0537
	PEEK-Optima® at 0.8mm (200°C)	.2767*	.01104	.000	.2415	.3119
	PEEK-Optima® at 1 mm (200°C)	.0353	.01397	.277	-.0108-	.0814
PEEK-Optima® at 0.8mm (150°C)	PMMA at 0.8mm	.0669*	.01369	.000	.0233	.1105
	PMMA at 1mm	-.2309-*	.00867	.000	-.2585-	-.2033-
	PEEK-Optima® at 0.8mm (100°C)	-.0368-	.01317	.142	-.0787-	.0051
	PEEK-Optima® at 1mm (100°C)	-.2547-*	.00974	.000	-.2857-	-.2237-
	PEEK-Optima® at 1mm (150°C)	-.2387-*	.00905	.000	-.2675-	-.2099-
	PEEK-Optima® at 0.8mm (175°C)	.1050*	.01416	.000	.0587	.1513
	PEEK-Optima® at 1mm (175°C)	-.2270-*	.00896	.000	-.2556-	-.1985-
	PEEK-Optima® at 0.8mm (200°C)	.0220	.01163	.676	-.0151-	.0590
	PEEK-Optima® at 1 mm (200°C)	-.2194-*	.01444	.000	-.2668-	-.1720-
PEEK-Optima® at 1mm (150°C)	PMMA at 0.8mm	.3056*	.01269	.000	.2652	.3460
	PMMA at 1mm	.0078	.00699	.982	-.0144-	.0301
	PEEK-Optima® at 0.8mm (100°C)	.2019*	.01213	.000	.1633	.2405
	PEEK-Optima® at 1mm (100°C)	-.0160-	.00827	.647	-.0423-	.0103
	PEEK-Optima® at 0.8mm (150°C)	.2387*	.00905	.000	.2099	.2675
	PEEK-Optima® at 0.8mm (175°C)	.3437*	.01320	.000	.3001	.3873
	PEEK-Optima® at 1mm (175°C)	.0117	.00735	.852	-.0117-	.0351
	PEEK-Optima® at 0.8mm (200°C)	.2607*	.01043	.000	.2274	.2940
	PEEK-Optima® at 1 mm (200°C)	.0193	.01350	.910	-.0255-	.0641
PEEK-Optima® at 0.8mm (175°C)	PMMA at 0.8mm	-.0381-	.01673	.411	-.0921-	.0158
	PMMA at 1mm	-.3359-*	.01295	.000	-.3788-	-.2930-
	PEEK-Optima® at 0.8mm (100°C)	-.1418-*	.01630	.000	-.1945-	-.0891-
	PEEK-Optima® at 1mm (100°C)	-.3597-*	.01368	.000	-.4047-	-.3147-
	PEEK-Optima® at 0.8mm (150°C)	-.1050-*	.01416	.000	-.1513-	-.0587-
	PEEK-Optima® at 1mm (150°C)	-.3437-*	.01320	.000	-.3873-	-.3001-
	PEEK-Optima® at 1mm (175°C)	-.3320-*	.01314	.000	-.3755-	-.2886-
	PEEK-Optima® at 0.8mm (200°C)	-.0830-*	.01509	.000	-.1321-	-.0340-
	PEEK-Optima® at 1 mm (200°C)	-.3244-*	.01735	.000	-.3810-	-.2677-
PEEK-Optima® at 1mm (175°C)	PMMA at 0.8mm	.2939*	.01263	.000	.2536	.3342
	PMMA at 1mm	-.0039-	.00689	1.000	-.0258-	.0180
	PEEK-Optima® at 0.8mm (100°C)	.1902*	.01207	.000	.1518	.2287
	PEEK-Optima® at 1mm (100°C)	-.0277-*	.00819	.027	-.0537-	-.0017-
	PEEK-Optima® at 0.8mm (150°C)	.2270*	.00896	.000	.1985	.2556
	PEEK-Optima® at 1mm (150°C)	-.0117-	.00735	.852	-.0351-	.0117
	PEEK-Optima® at 0.8mm (175°C)	.3320*	.01314	.000	.2886	.3755
	PEEK-Optima® at 0.8mm (200°C)	.2490*	.01037	.000	.2159	.2821
	PEEK-Optima® at 1 mm (200°C)	.0076	.01344	1.000	-.0370-	.0523
PEEK-Optima® at 0.8mm (200°C)	PMMA at 0.8mm	.0449	.01464	.070	-.0017-	.0915
	PMMA at 1mm	-.2529-*	.01011	.000	-.2851-	-.2206-
	PEEK-Optima® at 0.8mm (100°C)	-.0588-*	.01416	.002	-.1038-	-.0137-
	PEEK-Optima® at 1mm (100°C)	-.2767-*	.01104	.000	-.3119-	-.2415-
	PEEK-Optima® at 0.8mm (150°C)	-.0220-	.01163	.676	-.0590-	.0151
	PEEK-Optima® at 1mm (150°C)	-.2607-*	.01043	.000	-.2940-	-.2274-
	PEEK-Optima® at 0.8mm (175°C)	.0830*	.01509	.000	.0340	.1321
	PEEK-Optima® at 1mm (175°C)	-.2490-*	.01037	.000	-.2821-	-.2159-
	PEEK-Optima® at 1 mm (200°C)	-.2414-*	.01535	.000	-.2914-	-.1913-
PEEK-Optima® at 1 mm (200°C)	PMMA at 0.8mm	.2863*	.01696	.000	.2314	.3411
	PMMA at 1mm	-.0115-	.01325	.997	-.0556-	.0326
	PEEK-Optima® at 0.8mm (100°C)	.1826*	.01654	.000	.1290	.2361
	PEEK-Optima® at 1mm (100°C)	-.0353-	.01397	.277	-.0814-	.0108
	PEEK-Optima® at 0.8mm (150°C)	.2194*	.01444	.000	.1720	.2668
	PEEK-Optima® at 1mm (150°C)	-.0193-	.01350	.910	-.0641-	.0255

Part (D): Surface Roughness

Diestone mould material

```
T-TEST GROUPS=Materials(1 2)
  /MISSING=ANALYSIS
  /VARIABLES=PMMAHC
  /CRITERIA=CI(.95).
```

T-Test

Group Statistics

	GroupNumber	N	Mean	Std. Deviation	Std. Error Mean
PEEK100	Before	220	1.3105	.76421	.05152
	After	220	1.4687	.49421	.03332

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
PEEK100	Equal variances assumed	.237	.626	-2.578-	438	.010	-.15820-	.06136	-.27879-	-.03761-
	Equal variances not assumed			-2.578-	374.910	.010	-.15820-	.06136	-.27885-	-.03755-

Group Statistics

	GroupNumber	N	Mean	Std. Deviation	Std. Error Mean
PEEK150	Before	220	1.2804	.46484	.03134
	After	220	1.5331	.29885	.02015

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
PEEK150	Equal variances assumed	20.490	.000	-6.784-	438	.000	-.25274-	.03726	-.32596-	-.17951-
	Equal variances not assumed			-6.784-	373.622	.000	-.25274-	.03726	-.32600-	-.17948-

Group Statistics

	GroupNumber	N	Mean	Std. Deviation	Std. Error Mean
PEEK175	Before	220	1.1351	.37035	.02497
	After	220	1.5150	.35805	.02414

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
PEEK175	Equal variances assumed	.929	.336	-10.940-	438	.000	-.37994-	.03473	-.44820-	-.31168-
	Equal variances not assumed			-10.940-	437.502	.000	-.37994-	.03473	-.44820-	-.31168-

Group Statistics

	GroupNumber	N	Mean	Std. Deviation	Std. Error Mean
PEEK200	Before	220	1.1042	.26735	.01802
	After	220	1.5273	.25603	.01726

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
PEEK200	Equal variances assumed	.072	.789	-16.956-	438	.000	-.42317-	.02496	-.47222-	-.37412-
	Equal variances not assumed			-16.956-	437.183	.000	-.42317-	.02496	-.47222-	-.37412-

Group Statistics

	GroupNumber	N	Mean	Std. Deviation	Std. Error Mean
PMMAHC	Before	220	1.7420	.30124	.02031
	After	220	1.6089	.22917	.01545

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
PMMAHC	Equal variances assumed	5.612	.018	5.219	438	.000	.13318	.02552	.08302	.18333
	Equal variances not assumed			5.219	408.890	.000	.13318	.02552	.08301	.18334

Group Statistics

	GroupNumber	N	Mean	Std. Deviation	Std. Error Mean
PMMAInj	Before	220	1.6939	.26224	.01768
	After	220	1.5868	.23001	.01551

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
PMMAInj	Equal variances assumed	3.669	.056	4.556	438	.000	.10714	.02352	.06091	.15336
	Equal variances not assumed			4.556	430.677	.000	.10714	.02352	.06091	.15336

Tested Polymer Material

Between-Subjects Factors

		Value Label	N
Materials	1.00	PMMA-Hc	220
	2.00	PMMA (thermo-pressed)	220
	3.00	PEEK-Optima (100 °C)	220
	4.00	PEEK-Optima (150 °C)	220
	5.00	PEEK-Optima (175 °C)	220
	6.00	PEEK-Optima (200 °C)	220

Descriptive Statistics

Dependent Variable: Ra

Materials	Mean	Std. Deviation	N
PMMA-Hc	1.7162	.60429	220
PMMA (thermo-pressed)	1.8090	.52565	220
PEEK-Optima (100 °C)	3.2774	2.29709	220
PEEK-Optima (150 °C)	1.9582	1.40838	220
PEEK-Optima (175 °C)	1.7585	.68726	220
PEEK-Optima (200 °C)	1.6627	.88904	220
Total	2.0303	1.35696	1320

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Ra

F	df1	df2	Sig.
94.569	5	1314	.000

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Materials

1. Grand Mean

Dependent Variable: Ra

Mean	Std. Error	95% Confidence Interval	
		Lower Bound	Upper Bound
2.030	.034	1.964	2.097

2. Materials

Dependent Variable: Ra

Materials	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
PMMA-Hc	1.716	.083	1.553	1.880
PMMA (thermo-pressed)	1.809	.083	1.646	1.972
PEEK-Optima (100 °C)	3.277	.083	3.114	3.441
PEEK-Optima (150 °C)	1.958	.083	1.795	2.122
PEEK-Optima (175 °C)	1.759	.083	1.595	1.922
PEEK-Optima (200 °C)	1.663	.083	1.499	1.826

Multiple Comparisons

Dependent Variable: Ra

Games-Howell

(I) Materials	(J) Materials	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
PMMA-Hc	PMMA (thermo-pressed)	-.0928-	.05400	.520	-.2474-	.0617
	PEEK-Optima (100 °C)	-1.5612-*	.16014	.000	-2.0211-	-1.1013-
	PEEK-Optima (150 °C)	-.2421-	.10332	.180	-.5384-	.0543
	PEEK-Optima (175 °C)	-.0423-	.06170	.983	-.2190-	.1343
	PEEK-Optima (200 °C)	.0535	.07247	.977	-.1541-	.2611
PMMA (thermo-pressed)	PMMA-Hc	.0928	.05400	.520	-.0617-	.2474
	PEEK-Optima (100 °C)	-1.4684-*	.15887	.000	-1.9247-	-1.0120-
	PEEK-Optima (150 °C)	-.1492-	.10135	.682	-.4401-	.1416
	PEEK-Optima (175 °C)	.0505	.05833	.954	-.1165-	.2175
	PEEK-Optima (200 °C)	.1463	.06963	.289	-.0532-	.3458
PEEK-Optima (100 °C)	PMMA-Hc	1.5612*	.16014	.000	1.1013	2.0211
	PMMA (thermo-pressed)	1.4684*	.15887	.000	1.0120	1.9247
	PEEK-Optima (150 °C)	1.3191*	.18166	.000	.7987	1.8396
	PEEK-Optima (175 °C)	1.5189*	.16165	.000	1.0547	1.9830
	PEEK-Optima (200 °C)	1.6147*	.16606	.000	1.1382	2.0912
PEEK-Optima (150 °C)	PMMA-Hc	.2421	.10332	.180	-.0543-	.5384
	PMMA (thermo-pressed)	.1492	.10135	.682	-.1416-	.4401
	PEEK-Optima (100 °C)	-1.3191-*	.18166	.000	-1.8396-	-.7987-
	PEEK-Optima (175 °C)	.1997	.10566	.410	-.1032-	.5027
	PEEK-Optima (200 °C)	.2955	.11229	.092	-.0261-	.6172
PEEK-Optima (175 °C)	PMMA-Hc	.0423	.06170	.983	-.1343-	.2190
	PMMA (thermo-pressed)	-.0505-	.05833	.954	-.2175-	.1165
	PEEK-Optima (100 °C)	-1.5189-*	.16165	.000	-1.9830-	-1.0547-
	PEEK-Optima (150 °C)	-.1997-	.10566	.410	-.5027-	.1032
	PEEK-Optima (200 °C)	.0958	.07576	.804	-.1211-	.3127
PEEK-Optima (200 °C)	PMMA-Hc	-.0535-	.07247	.977	-.2611-	.1541
	PMMA (thermo-pressed)	-.1463-	.06963	.289	-.3458-	.0532
	PEEK-Optima (100 °C)	-1.6147-*	.16606	.000	-2.0912-	-1.1382-
	PEEK-Optima (150 °C)	-.2955-	.11229	.092	-.6172-	.0261
	PEEK-Optima (175 °C)	-.0958-	.07576	.804	-.3127-	.1211

Based on observed means.

The error term is Mean Square(Error) = 1.527.

*. The mean difference is significant at the .05 level.

Polymer materiasl and Die stone after heating

```
T-TEST GROUPS=Materials(1 2)
  /MISSING=ANALYSIS
  /VARIABLES=PMMAHC
  /CRITERIA=CI(.95).
```

T-Test

Group Statistics

	Materials	N	Mean	Std. Deviation	Std. Error Mean
PMMAHC	Diestone After Heating	220	1.6089	.22917	.01545
	Denture Polymer Material	220	1.7162	.60429	.04074

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
PMMAHC	Equal variances assumed	87.951	.000	-2.463-	438	.014	-.10730-	.04357	-.19294-	-.02167-
	Equal variances not assumed			-2.463-	280.720	.014	-.10730-	.04357	-.19307-	-.02153-

Group Statistics

	Materials	N	Mean	Std. Deviation	Std. Error Mean
PMMAThermopressed	Diestone After Heating	220	1.5868	.23001	.01551
	Denture Polymer Material	220	1.8090	.52565	.03544

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
PMMAThermopressed	Equal variances assumed	40.501	.000	-5.745-	438	.000	-.22225-	.03868	-.29828-	-.14623-
	Equal variances not assumed			-5.745-	299.898	.000	-.22225-	.03868	-.29838-	-.14613-

Group Statistics

	Materials	N	Mean	Std. Deviation	Std. Error Mean
PEEK100C	Diestone After Heating	220	1.4687	.49421	.03332
	Denture Polymer Material	220	3.2774	2.29709	.15487

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
PEEK100C	Equal variances assumed	181.261	.000	-11.417-	438	.000	-1.80864-	.15841	-2.11999-	-1.49730-
	Equal variances not assumed			-11.417-	239.231	.000	-1.80864-	.15841	-2.12071-	-1.49658-

Group Statistics

	Materials	N	Mean	Std. Deviation	Std. Error Mean
PEEK150C	Diestone After Heating	220	1.5331	.29885	.02015
	Denture Polymer Material	220	1.9582	1.40838	.09495

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
PEEK150C	Equal variances assumed	157.196	.000	-4.379-	438	.000	-.42510-	.09707	-.61588-	-.23433-
	Equal variances not assumed			-4.379-	238.681	.000	-.42510-	.09707	-.61632-	-.23389-

Group Statistics

	Materials	N	Mean	Std. Deviation	Std. Error Mean
PEEK175C	Diestone After Heating	220	1.5150	.35805	.02414
	Denture Polymer Material	220	1.7585	.68726	.04634

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
PEEK175C	Equal variances assumed	41.780	.000	-4.660-	438	.000	-.24346-	.05225	-.34614-	-.14077-
	Equal variances not assumed			-4.660-	329.725	.000	-.24346-	.05225	-.34624-	-.14068-

Group Statistics

	Materials	N	Mean	Std. Deviation	Std. Error Mean
PEEK200C	Diestone After Heating	220	1.5273	.25603	.01726
	Denture Polymer Material	220	1.6627	.88904	.05994

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
PEEK200C	Equal variances assumed	223.838	.000	-2.170-	438	.031	-.13535-	.06237	-.25794-	-.01276-
	Equal variances not assumed			-2.170-	255.079	.031	-.13535-	.06237	-.25819-	-.01251-

Part (E): Impact Strength

Between-Subjects Factors

		Value Label	N
Materials	1.00	PMMA-HC	10
	2.00	PMMA-Inj(40C)	10
	3.00	PEEK-Optima-Inj(100)	10
	4.00	PEEK-Optima-Inj(150)	10
	5.00	PEEK-Optima-Inj(175)	10
	6.00	PEEK-Optima-Inj(200)	10
	7.00	PEEK-Juvora(milling)	10

Descriptive Statistics

Dependent Variable: ImpactStrength

Materials	Mean	Std. Deviation	N
PMMA-HC	2.2709	.16642	10
PMMA-Inj(40C)	2.1903	.10843	10
PEEK-Optima-Inj(100)	5.7325	.41814	10
PEEK-Optima-Inj(150)	5.0226	.39563	10
PEEK-Optima-Inj(175)	5.3020	.48543	10
PEEK-Optima-Inj(200)	4.8387	.40321	10
PEEK-Juvora(milling)	3.9953	1.01278	10
Total	4.1932	1.42772	70

Levene's Test of Equality of Error Variances[a]

Dependent Variable: ImpactStrength

F	df1	df2	Sig.
10.737	6	63	.000

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Materials

1. Grand Mean

Dependent Variable: ImpactStrength

		95% Confidence Interval	
Mean	Std. Error	Lower Bound	Upper Bound
4.193	.061	4.072	4.314

2. Materials

Dependent Variable: ImpactStrength

			95% Confidence Interval	
Materials	Mean	Std. Error	Lower Bound	Upper Bound
PMMA-HC	2.271	.160	1.951	2.591
PMMA-Inj(40C)	2.190	.160	1.870	2.510
PEEK-Optima-Inj(100)	5.733	.160	5.413	6.053
PEEK-Optima-Inj(150)	5.023	.160	4.703	5.343
PEEK-Optima-Inj(175)	5.302	.160	4.982	5.622
PEEK-Optima-Inj(200)	4.839	.160	4.519	5.159
PEEK-Juvora(milling)	3.995	.160	3.675	4.315

Multiple Comparisons

Dependent Variable: ImpactStrength

Games-Howell

(I) Materials	(J) Materials	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
PMMA-HC	PMMA-Inj(40C)	.0807	.06281	.849	-.1308-	.2921
	PEEK-Optima-Inj(100)	-3.4616-*	.14232	.000	-3.9613-	-2.9619-
	PEEK-Optima-Inj(150)	-2.7516-*	.13573	.000	-3.2261-	-2.2772-
	PEEK-Optima-Inj(175)	-3.0311-*	.16228	.000	-3.6072-	-2.4550-
	PEEK-Optima-Inj(200)	-2.5678-*	.13794	.000	-3.0507-	-2.0849-
	PEEK-Juvora(milling)	-1.7244-*	.32457	.005	-2.9138-	-.5350-
PMMA-Inj(40C)	PMMA-HC	-.0807-	.06281	.849	-.2921-	.1308
	PEEK-Optima-Inj(100)	-3.5423-*	.13660	.000	-4.0352-	-3.0494-
	PEEK-Optima-Inj(150)	-2.8323-*	.12972	.000	-3.2991-	-2.3655-
	PEEK-Optima-Inj(175)	-3.1117-*	.15729	.000	-3.6829-	-2.5406-
	PEEK-Optima-Inj(200)	-2.6484-*	.13203	.000	-3.1240-	-2.1729-
	PEEK-Juvora(milling)	-1.8051-*	.32210	.004	-2.9933-	-.6168-
PEEK-Optima-Inj(100)	PMMA-HC	3.4616*	.14232	.000	2.9619	3.9613
	PMMA-Inj(40C)	3.5423*	.13660	.000	3.0494	4.0352
	PEEK-Optima-Inj(150)	.7100*	.18203	.015	.1082	1.3117
	PEEK-Optima-Inj(175)	.4305	.20260	.381	-.2406-	1.1017
	PEEK-Optima-Inj(200)	.8938*	.18369	.002	.2868	1.5009
	PEEK-Juvora(milling)	1.7372*	.34649	.004	.5242	2.9502
PEEK-Optima-Inj(150)	PMMA-HC	2.7516*	.13573	.000	2.2772	3.2261
	PMMA-Inj(40C)	2.8323*	.12972	.000	2.3655	3.2991
	PEEK-Optima-Inj(100)	-.7100-*	.18203	.015	-1.3117-	-.1082-
	PEEK-Optima-Inj(175)	-.2794-	.19803	.789	-.9369-	.3780
	PEEK-Optima-Inj(200)	.1839	.17863	.940	-.4064-	.7742
	PEEK-Juvora(milling)	1.0272	.34384	.117	-.1818-	2.2363
PEEK-Optima-Inj(175)	PMMA-HC	3.0311*	.16228	.000	2.4550	3.6072
	PMMA-Inj(40C)	3.1117*	.15729	.000	2.5406	3.6829
	PEEK-Optima-Inj(100)	-.4305-	.20260	.381	-1.1017-	.2406
	PEEK-Optima-Inj(150)	.2794	.19803	.789	-.3780-	.9369
	PEEK-Optima-Inj(200)	.4633	.19955	.288	-.1987-	1.1252
	PEEK-Juvora(milling)	1.3066*	.35516	.034	.0790	2.5343
PEEK-Optima-Inj(200)	PMMA-HC	2.5678*	.13794	.000	2.0849	3.0507
	PMMA-Inj(40C)	2.6484*	.13203	.000	2.1729	3.1240
	PEEK-Optima-Inj(100)	-.8938-*	.18369	.002	-1.5009-	-.2868-
	PEEK-Optima-Inj(150)	-.1839-	.17863	.940	-.7742-	.4064
	PEEK-Optima-Inj(175)	-.4633-	.19955	.288	-1.1252-	.1987
PEEK-Juvora(milling)	PMMA-HC	1.7244*	.32457	.005	.5350	2.9138
	PMMA-Inj(40C)	1.8051*	.32210	.004	.6168	2.9933
	PEEK-Optima-Inj(100)	-1.7372-*	.34649	.004	-2.9502-	-.5242-
	PEEK-Optima-Inj(150)	-1.0272-	.34384	.117	-2.2363-	.1818
	PEEK-Optima-Inj(175)	-1.3066-*	.35516	.034	-2.5343-	-.0790-
	PEEK-Optima-Inj(200)	-.8434-	.34472	.261	-2.0537-	.3670

Based on observed means.

The error term is Mean Square(Error) = .256.

*. The mean difference is significant at the .05 level.

Between-Subjects Factors

		Value Label	N
Materials	1.00	PMMA-HC	10
	2.00	PMMA-Inj(40C)	10
	3.00	PEEK-Optima-Inj(100)	10
	4.00	PEEK-Optima-Inj(150)	10
	5.00	PEEK-Optima-Inj(175)	10
	6.00	PEEK-Optima-Inj(200)	10
	7.00	PEEK-Juvora(milling)	10

Descriptive Statistics

Dependent Variable: AbsorbedEnergy

Materials	Mean	Std. Deviation	N
PMMA-HC	.0634	.00439	10
PMMA-Inj(40C)	.0735	.00415	10
PEEK-Optima-Inj(100)	.1739	.01201	10
PEEK-Optima-Inj(150)	.1563	.01330	10
PEEK-Optima-Inj(175)	.1688	.01699	10
PEEK-Optima-Inj(200)	.1496	.01180	10
PEEK-Juvora(milling)	.1226	.02876	10
Total	.1297	.04446	70

Levene's Test of Equality of Error Variances[a]

Dependent Variable: AbsorbedEnergy

F	df1	df2	Sig.
10.406	6	63	.000

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Materials

1. Grand Mean

Dependent Variable: AbsorbedEnergy

		95% Confidence Interval	
Mean	Std. Error	Lower Bound	Upper Bound
.130	.002	.126	.133

2. Materials

Dependent Variable: AbsorbedEnergy

			95% Confidence Interval	
Materials	Mean	Std. Error	Lower Bound	Upper Bound
PMMA-HC	.063	.005	.054	.073
PMMA-Inj(40C)	.073	.005	.064	.083
PEEK-Optima-Inj(100)	.174	.005	.164	.183
PEEK-Optima-Inj(150)	.156	.005	.147	.166
PEEK-Optima-Inj(175)	.169	.005	.159	.178
PEEK-Optima-Inj(200)	.150	.005	.140	.159
PEEK-Juvora(milling)	.123	.005	.113	.132

Multiple Comparisons

Dependent Variable: AbsorbedEnergy

Games-Howell

(I) Materials	(J) Materials	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
PMMA-HC	PMMA-Inj(40C)	-.0100-*	.00191	.001	-.0163-	-.0037-
	PEEK-Optima-Inj(100)	-.1104-*	.00404	.000	-.1247-	-.0962-
	PEEK-Optima-Inj(150)	-.0929-*	.00443	.000	-.1086-	-.0771-
	PEEK-Optima-Inj(175)	-.1054-*	.00555	.000	-.1254-	-.0853-
	PEEK-Optima-Inj(200)	-.0862-*	.00398	.000	-.1002-	-.0721-
	PEEK-Juvora(milling)	-.0592-*	.00920	.001	-.0930-	-.0254-
PMMA-Inj(40C)	PMMA-HC	.0100*	.00191	.001	.0037	.0163
	PEEK-Optima-Inj(100)	-.1004-*	.00402	.000	-.1147-	-.0862-
	PEEK-Optima-Inj(150)	-.0829-*	.00441	.000	-.0986-	-.0671-
	PEEK-Optima-Inj(175)	-.0953-*	.00553	.000	-.1154-	-.0753-
	PEEK-Optima-Inj(200)	-.0761-*	.00395	.000	-.0902-	-.0621-
	PEEK-Juvora(milling)	-.0492-*	.00919	.005	-.0829-	-.0154-
PEEK-Optima-Inj(100)	PMMA-HC	.1104*	.00404	.000	.0962	.1247
	PMMA-Inj(40C)	.1004*	.00402	.000	.0862	.1147
	PEEK-Optima-Inj(150)	.0176	.00567	.075	-.0012-	.0363
	PEEK-Optima-Inj(175)	.0051	.00658	.985	-.0170-	.0271
	PEEK-Optima-Inj(200)	.0243*	.00532	.004	.0067	.0419
	PEEK-Juvora(milling)	.0513*	.00986	.003	.0168	.0857
PEEK-Optima-Inj(150)	PMMA-HC	.0929*	.00443	.000	.0771	.1086
	PMMA-Inj(40C)	.0829*	.00441	.000	.0671	.0986
	PEEK-Optima-Inj(100)	-.0176-	.00567	.075	-.0363-	.0012
	PEEK-Optima-Inj(175)	-.0125-	.00682	.546	-.0352-	.0102
	PEEK-Optima-Inj(200)	.0067	.00562	.888	-.0119-	.0253
	PEEK-Juvora(milling)	.0337	.01002	.060	-.0011-	.0684
PEEK-Optima-Inj(175)	PMMA-HC	.1054*	.00555	.000	.0853	.1254
	PMMA-Inj(40C)	.0953*	.00553	.000	.0753	.1154
	PEEK-Optima-Inj(100)	-.0051-	.00658	.985	-.0271-	.0170
	PEEK-Optima-Inj(150)	.0125	.00682	.546	-.0102-	.0352
	PEEK-Optima-Inj(200)	.0192	.00654	.107	-.0027-	.0411
	PEEK-Juvora(milling)	.0462*	.01056	.008	.0103	.0820
PEEK-Optima-Inj(200)	PMMA-HC	.0862*	.00398	.000	.0721	.1002
	PMMA-Inj(40C)	.0761*	.00395	.000	.0621	.0902
	PEEK-Optima-Inj(100)	-.0243-*	.00532	.004	-.0419-	-.0067-
	PEEK-Optima-Inj(150)	-.0067-	.00562	.888	-.0253-	.0119
	PEEK-Optima-Inj(175)	-.0192-	.00654	.107	-.0411-	.0027
	PEEK-Juvora(milling)	.0270	.00983	.168	-.0074-	.0614
PEEK-Juvora(milling)	PMMA-HC	.0592*	.00920	.001	.0254	.0930
	PMMA-Inj(40C)	.0492*	.00919	.005	.0154	.0829
	PEEK-Optima-Inj(100)	-.0513-*	.00986	.003	-.0857-	-.0168-
	PEEK-Optima-Inj(150)	-.0337-	.01002	.060	-.0684-	.0011
	PEEK-Optima-Inj(175)	-.0462-*	.01056	.008	-.0820-	-.0103-
	PEEK-Optima-Inj(200)	-.0270-	.00983	.168	-.0614-	.0074

Based on observed means.

The error term is Mean Square(Error) = .000.

*. The mean difference is significant at the .05 level.

Part (F): Flexural Properties (4-Point Bending)

Between-Subjects Factors

		Value Label	N
Material	1.00	PMMA-HC	10
	2.00	PMMA-Thermopress	10
	3.00	Co-Cr	10
	4.00	PEEK-100C	10
	5.00	PEEK-150C	10
	6.00	PEEK-175C	10
	7.00	PEEK-200C	10
	8.00	PEEK-Juvora	10

Descriptive Statistics

Dependent Variable: YoungModulus

Material	Mean	Std. Deviation	N
PMMA-HC	3631.5727	228.09313	10
PMMA-Thermopress	3784.2561	289.88810	10
Co-Cr	259043.7044	134693.49653	10
PEEK-100C	4772.8640	420.28829	10
PEEK-150C	4839.7180	274.62760	10
PEEK-175C	4685.8389	162.64430	10
PEEK-200C	4935.9787	277.94869	10
PEEK-Juvora	5591.1805	328.67353	10
Total	36410.6392	96112.87010	80

Levene's Test of Equality of Error Variances[a]

Dependent Variable: YoungModulus

F	df1	df2	Sig.
12.644	7	72	.000

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Material

1. Grand Mean

Dependent Variable: YoungModulus

		95% Confidence Interval	
Mean	Std. Error	Lower Bound	Upper Bound
36410.639	5324.316	25796.809	47024.469

2. Material

Dependent Variable: YoungModulus

			95% Confidence Interval	
Material	Mean	Std. Error	Lower Bound	Upper Bound
PMMA-HC	3631.573	15059.440	-26388.872-	33652.017
PMMA-Thermopress	3784.256	15059.440	-26236.188-	33804.700
Co-Cr	259043.704	15059.440	229023.260	289064.149
PEEK-100C	4772.864	15059.440	-25247.580-	34793.308
PEEK-150C	4839.718	15059.440	-25180.726-	34860.162
PEEK-175C	4685.839	15059.440	-25334.605-	34706.283
PEEK-200C	4935.979	15059.440	-25084.466-	34956.423
PEEK-Juvora	5591.181	15059.440	-24429.264-	35611.625

Multiple Comparisons

Dependent Variable: YoungModulus

Games-Howell

(I) Material	(J) Material	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
PMMA-HC	PMMA-Thermopress	-152.6833-	116.64544	.883	-553.2116-	247.8449
	Co-Cr	-255412.1317-*	42593.88458	.003	-419012.8160-	-91811.4474-
	PEEK-100C	-1141.2913-*	151.21796	.000	-1675.6023-	-606.9803-
	PEEK-150C	-1208.1453-*	112.89233	.000	-1594.7946-	-821.4960-
	PEEK-175C	-1054.2662-*	88.58874	.000	-1360.2914-	-748.2410-
	PEEK-200C	-1304.4059-*	113.70222	.000	-1694.0313-	-914.7805-
	PEEK-Juvora	-1959.6078-*	126.51196	.000	-2397.4775-	-1521.7382-
PMMA-Thermopress	PMMA-HC	152.6833	116.64544	.883	-247.8449-	553.2116
	Co-Cr	-255259.4484-*	42593.92215	.003	-418860.1396-	-91658.7571-
	PEEK-100C	-988.6080-*	161.45506	.000	-1547.6696-	-429.5464-
	PEEK-150C	-1055.4620-*	126.27566	.000	-1486.3763-	-624.5477-
	PEEK-175C	-901.5829-*	105.11340	.000	-1271.8740-	-531.2917-
	PEEK-200C	-1151.7226-*	127.00023	.000	-1585.0504-	-718.3948-
	PEEK-Juvora	-1806.9245-*	138.58622	.000	-2280.5588-	-1333.2902-
Co-Cr	PMMA-HC	255412.1317*	42593.88458	.003	91811.4474	419012.8160
	PMMA-Thermopress	255259.4484*	42593.92215	.003	91658.7571	418860.1396
	PEEK-100C	254270.8404*	42594.03086	.003	90670.1292	417871.5516
	PEEK-150C	254203.9864*	42593.91204	.003	90603.2970	417804.6758
	PEEK-175C	254357.8655*	42593.85456	.003	90757.1867	417958.5443
	PEEK-200C	254107.7258*	42593.91419	.003	90507.0360	417708.4155
	PEEK-Juvora	253452.5239*	42593.95031	.003	89851.8275	417053.2203
PEEK-100C	PMMA-HC	1141.2913*	151.21796	.000	606.9803	1675.6023
	PMMA-Thermopress	988.6080*	161.45506	.000	429.5464	1547.6696
	Co-Cr	-254270.8404-*	42594.03086	.003	-417871.5516-	-90670.1292-
	PEEK-150C	-66.8540-	158.76478	1.000	-618.8863-	485.1783
	PEEK-175C	87.0251	142.51155	.998	-431.6616-	605.7118
	PEEK-200C	-163.1146-	159.34168	.963	-716.6261-	390.3969
	PEEK-Juvora	-818.3165-*	168.72123	.003	-1397.8477-	-238.7853-
PEEK-150C	PMMA-HC	1208.1453*	112.89233	.000	821.4960	1594.7946
	PMMA-Thermopress	1055.4620*	126.27566	.000	624.5477	1486.3763
	Co-Cr	-254203.9864-*	42593.91204	.003	-417804.6758-	-90603.2970-
	PEEK-100C	66.8540	158.76478	1.000	-485.1783-	618.8863
	PEEK-175C	153.8791	100.93240	.784	-199.9790-	507.7372
	PEEK-200C	-96.2606-	123.56205	.992	-517.7764-	325.2551
	PEEK-Juvora	-751.4625-*	135.44246	.001	-1215.2293-	-287.6958-
PEEK-175C	PMMA-HC	1054.2662*	88.58874	.000	748.2410	1360.2914
	PMMA-Thermopress	901.5829*	105.11340	.000	531.2917	1271.8740
	Co-Cr	-254357.8655-*	42593.85456	.003	-417958.5443-	-90757.1867-
	PEEK-100C	-87.0251-	142.51155	.998	-605.7118-	431.6616
	PEEK-150C	-153.8791-	100.93240	.784	-507.7372-	199.9790
	PEEK-200C	-250.1397-	101.83744	.286	-607.5482-	107.2687
	PEEK-Juvora	-905.3416-*	115.96528	.000	-1318.5510-	-492.1323-
PEEK-200C	PMMA-HC	1304.4059*	113.70222	.000	914.7805	1694.0313
	PMMA-Thermopress	1151.7226*	127.00023	.000	718.3948	1585.0504
	Co-Cr	-254107.7258-*	42593.91419	.003	-417708.4155-	-90507.0360-
	PEEK-100C	163.1146	159.34168	.963	-390.3969-	716.6261
	PEEK-150C	96.2606	123.56205	.992	-325.2551-	517.7764
	PEEK-175C	250.1397	101.83744	.286	-107.2687-	607.5482
	PEEK-Juvora	-655.2019-*	136.11824	.003	-1121.0614-	-189.3424-
PEEK-Juvora	PMMA-HC	1959.6078*	126.51196	.000	1521.7382	2397.4775
	PMMA-Thermopress	1806.9245*	138.58622	.000	1333.2902	2280.5588
	Co-Cr	-253452.5239-*	42593.95031	.003	-417053.2203-	-89851.8275-
	PEEK-100C	818.3165*	168.72123	.003	238.7853	1397.8477
	PEEK-150C	751.4625*	135.44246	.001	287.6958	1215.2293
	PEEK-175C	905.3416*	115.96528	.000	492.1323	1318.5510
	PEEK-200C	655.2019*	136.11824	.003	189.3424	1121.0614

Based on observed means.

The error term is Mean Square(Error) = 2267867233.167.

*. The mean difference is significant at the .05 level.

Between-Subjects Factors

		Value Label	N
Material	1.00	PMMA-HC	10
	2.00	PMMA-Thermopress	10
	3.00	Co-Cr	10
	4.00	PEEK-100C	10
	5.00	PEEK-150C	10
	6.00	PEEK-175C	10
	7.00	PEEK-200C	10
	8.00	PEEK-Juvora	10

Descriptive Statistics

Dependent Variable: MaximumDeflection

Material	Mean	Std. Deviation	N
PMMA-HC	5.3666	.36603	10
PMMA-Thermopress	5.4662	.34453	10
Co-Cr	.2642	.01616	10
PEEK-100C	3.9639	.29163	10
PEEK-150C	3.9399	.16160	10
PEEK-175C	3.9526	.19579	10
PEEK-200C	3.6759	.10735	10
PEEK-Juvora	3.2237	.21537	10
Total	3.7316	1.53135	80

Levene's Test of Equality of Error Variances[a]

Dependent Variable: MaximumDeflection

F	df1	df2	Sig.
6.527	7	72	.000

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Material

1. Grand Mean

Dependent Variable: MaximumDeflection

		95% Confidence Interval	
Mean	Std. Error	Lower Bound	Upper Bound
3.732	.027	3.678	3.785

2. Material

Dependent Variable: MaximumDeflection

			95% Confidence Interval	
Material	Mean	Std. Error	Lower Bound	Upper Bound
PMMA-HC	5.367	.076	5.215	5.518
PMMA-Thermopress	5.466	.076	5.315	5.617
Co-Cr	.264	.076	.113	.415
PEEK-100C	3.964	.076	3.813	4.115
PEEK-150C	3.940	.076	3.789	4.091
PEEK-175C	3.953	.076	3.801	4.104
PEEK-200C	3.676	.076	3.525	3.827
PEEK-Juvora	3.224	.076	3.073	3.375

Multiple Comparisons

Dependent Variable: MaximumDeflection
Games-Howell

		Mean Difference			95% Confidence Interval	
(I) Material	(J) Material	(I-J)	Std. Error	Sig.	Lower Bound	Upper Bound
PMMA-HC	PMMA-Thermopress	-.0996-	.15896	.998	-.6421-	.4429
	Co-Cr	5.1023*	.11586	.000	4.6577	5.5469
	PEEK-100C	1.4027*	.14800	.000	.8948	1.9105
	PEEK-150C	1.4267*	.12653	.000	.9712	1.8822
	PEEK-175C	1.4140*	.13127	.000	.9496	1.8784
	PEEK-200C	1.6907*	.12062	.000	1.2432	2.1382
	PEEK-Juvora	2.1428*	.13430	.000	1.6717	2.6139
PMMA-Thermopress	PMMA-HC	.0996	.15896	.998	-.4429-	.6421
	Co-Cr	5.2019*	.10907	.000	4.7834	5.6204
	PEEK-100C	1.5023*	.14274	.000	1.0138	1.9908
	PEEK-150C	1.5263*	.12034	.000	1.0954	1.9572
	PEEK-175C	1.5136*	.12531	.000	1.0726	1.9545
	PEEK-200C	1.7903*	.11412	.000	1.3685	2.2121
	PEEK-Juvora	2.2424*	.12848	.000	1.7941	2.6908
Co-Cr	PMMA-HC	-5.1023-*	.11586	.000	-5.5469-	-4.6577-
	PMMA-Thermopress	-5.2019-*	.10907	.000	-5.6204-	-4.7834-
	PEEK-100C	-3.6996-*	.09236	.000	-4.0539-	-3.3454-
	PEEK-150C	-3.6756-*	.05136	.000	-3.8720-	-3.4793-
	PEEK-175C	-3.6883-*	.06213	.000	-3.9262-	-3.4505-
	PEEK-200C	-3.4116-*	.03433	.000	-3.5421-	-3.2811-
	PEEK-Juvora	-2.9595-*	.06830	.000	-3.2211-	-2.6979-
PEEK-100C	PMMA-HC	-1.4027-*	.14800	.000	-1.9105-	-.8948-
	PMMA-Thermopress	-1.5023-*	.14274	.000	-1.9908-	-1.0138-
	Co-Cr	3.6996*	.09236	.000	3.3454	4.0539
	PEEK-150C	.0240	.10543	1.000	-.3478-	.3958
	PEEK-175C	.0113	.11108	1.000	-.3741-	.3967
	PEEK-200C	.2880	.09827	.154	-.0711-	.6470
	PEEK-Juvora	.7401*	.11464	.000	.3450	1.1353
PEEK-150C	PMMA-HC	-1.4267-*	.12653	.000	-1.8822-	-.9712-
	PMMA-Thermopress	-1.5263-*	.12034	.000	-1.9572-	-1.0954-
	Co-Cr	3.6756*	.05136	.000	3.4793	3.8720
	PEEK-100C	-.0240-	.10543	1.000	-.3958-	.3478
	PEEK-175C	-.0127-	.08028	1.000	-.2877-	.2623
	PEEK-200C	.2640*	.06135	.010	.0509	.4770
	PEEK-Juvora	.7161*	.08515	.000	.4230	1.0093
PEEK-175C	PMMA-HC	-1.4140-*	.13127	.000	-1.8784-	-.9496-
	PMMA-Thermopress	-1.5136-*	.12531	.000	-1.9545-	-1.0726-
	Co-Cr	3.6883*	.06213	.000	3.4505	3.9262
	PEEK-100C	-.0113-	.11108	1.000	-.3967-	.3741
	PEEK-150C	.0127	.08028	1.000	-.2623-	.2877
	PEEK-200C	.2767*	.07061	.025	.0274	.5259
	PEEK-Juvora	.7288*	.09204	.000	.4145	1.0432
PEEK-200C	PMMA-HC	-1.6907-*	.12062	.000	-2.1382-	-1.2432-
	PMMA-Thermopress	-1.7903-*	.11412	.000	-2.2121-	-1.3685-
	Co-Cr	3.4116*	.03433	.000	3.2811	3.5421
	PEEK-100C	-.2880-	.09827	.154	-.6470-	.0711
	PEEK-150C	-.2640-*	.06135	.010	-.4770-	-.0509-
	PEEK-175C	-.2767-*	.07061	.025	-.5259-	-.0274-
	PEEK-Juvora	.4522*	.07610	.001	.1812	.7231
PEEK-Juvora	PMMA-HC	-2.1428-*	.13430	.000	-2.6139-	-1.6717-
	PMMA-Thermopress	-2.2424-*	.12848	.000	-2.6908-	-1.7941-
	Co-Cr	2.9595*	.06830	.000	2.6979	3.2211
	PEEK-100C	-.7401-*	.11464	.000	-1.1353-	-.3450-
	PEEK-150C	-.7161-*	.08515	.000	-1.0093-	-.4230-
	PEEK-175C	-.7288-*	.09204	.000	-1.0432-	-.4145-
	PEEK-200C	-.4522-*	.07610	.001	-.7231-	-.1812-

Based on observed means.
The error term is Mean Square(Error) = .058.
*. The mean difference is significant at the .05 level.

Between-Subjects Factors

		Value Label	N
Material	1.00	PMMA-HC	10
	2.00	PMMA-Thermopress	10
	3.00	Co-Cr	10
	4.00	PEEK-100C	10
	5.00	PEEK-150C	10
	6.00	PEEK-175C	10
	7.00	PEEK-200C	10
	8.00	PEEK-Juvora	10

Descriptive Statistics

Dependent Variable: Resilience

Material	Mean	Std. Deviation	N
PMMA-HC	.0358	.04940	10
PMMA-Thermopress	.0246	.01454	10
Co-Cr	.0010	.00071	10
PEEK-100C	.0398	.01318	10
PEEK-150C	.0336	.01741	10
PEEK-175C	.0336	.01026	10
PEEK-200C	.0360	.02302	10
PEEK-Juvora	.0459	.02876	10
Total	.0313	.02622	80

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Resilience

F	df1	df2	Sig.
2.661	7	72	.017

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Material

1. Grand Mean

Dependent Variable: Resilience

		95% Confidence Interval	
Mean	Std. Error	Lower Bound	Upper Bound
.031	.003	.026	.037

2. Material

Dependent Variable: Resilience

			95% Confidence Interval	
Material	Mean	Std. Error	Lower Bound	Upper Bound
PMMA-HC	.036	.008	.021	.051
PMMA-Thermopress	.025	.008	.010	.040
Co-Cr	.001	.008	-.014-	.016
PEEK-100C	.040	.008	.025	.055
PEEK-150C	.034	.008	.019	.049
PEEK-175C	.034	.008	.018	.049
PEEK-200C	.036	.008	.021	.051
PEEK-Juvora	.046	.008	.031	.061

Multiple Comparisons

Dependent Variable: Resilience

Games-Howell

(I) Material	(J) Material	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
PMMA-HC	PMMA-Thermopress	.0112	.01629	.996	-.0492-	.0716
	Co-Cr	.0348	.01562	.416	-.0252-	.0948
	PEEK-100C	-.0040-	.01617	1.000	-.0643-	.0563
	PEEK-150C	.0022	.01656	1.000	-.0586-	.0629
	PEEK-175C	.0022	.01596	1.000	-.0579-	.0623
	PEEK-200C	-.0002-	.01724	1.000	-.0619-	.0616
	PEEK-Juvora	-.0101-	.01808	.999	-.0735-	.0534
PMMA-Thermopress	PMMA-HC	-.0112-	.01629	.996	-.0716-	.0492
	Co-Cr	.0236*	.00460	.009	.0060	.0413
	PEEK-100C	-.0152-	.00620	.279	-.0364-	.0060
	PEEK-150C	-.0090-	.00717	.903	-.0336-	.0155
	PEEK-175C	-.0090-	.00563	.748	-.0284-	.0105
	PEEK-200C	-.0114-	.00861	.878	-.0414-	.0187
	PEEK-Juvora	-.0212-	.01019	.469	-.0575-	.0150
Co-Cr	PMMA-HC	-.0348-	.01562	.416	-.0948-	.0252
	PMMA-Thermopress	-.0236-*	.00460	.009	-.0413-	-.0060-
	PEEK-100C	-.0388-*	.00417	.000	-.0548-	-.0228-
	PEEK-150C	-.0326-*	.00551	.003	-.0538-	-.0115-
	PEEK-175C	-.0326-*	.00325	.000	-.0450-	-.0201-
	PEEK-200C	-.0350-*	.00728	.014	-.0629-	-.0070-
	PEEK-Juvora	-.0449-*	.00910	.012	-.0798-	-.0099-
PEEK-100C	PMMA-HC	.0040	.01617	1.000	-.0563-	.0643
	PMMA-Thermopress	.0152	.00620	.279	-.0060-	.0364
	Co-Cr	.0388*	.00417	.000	.0228	.0548
	PEEK-150C	.0062	.00690	.983	-.0176-	.0299
	PEEK-175C	.0062	.00528	.928	-.0119-	.0244
	PEEK-200C	.0038	.00839	1.000	-.0257-	.0333
	PEEK-Juvora	-.0061-	.01000	.998	-.0420-	.0298
PEEK-150C	PMMA-HC	-.0022-	.01656	1.000	-.0629-	.0586
	PMMA-Thermopress	.0090	.00717	.903	-.0155-	.0336
	Co-Cr	.0326*	.00551	.003	.0115	.0538
	PEEK-100C	-.0062-	.00690	.983	-.0299-	.0176
	PEEK-175C	.0000	.00639	1.000	-.0224-	.0225
	PEEK-200C	-.0024-	.00913	1.000	-.0338-	.0291
	PEEK-Juvora	-.0122-	.01063	.934	-.0494-	.0250
PEEK-175C	PMMA-HC	-.0022-	.01596	1.000	-.0623-	.0579
	PMMA-Thermopress	.0090	.00563	.748	-.0105-	.0284
	Co-Cr	.0326*	.00325	.000	.0201	.0450
	PEEK-100C	-.0062-	.00528	.928	-.0244-	.0119
	PEEK-150C	.0000	.00639	1.000	-.0225-	.0224
	PEEK-200C	-.0024-	.00797	1.000	-.0311-	.0263
	PEEK-Juvora	-.0123-	.00966	.892	-.0476-	.0231
PEEK-200C	PMMA-HC	.0002	.01724	1.000	-.0616-	.0619
	PMMA-Thermopress	.0114	.00861	.878	-.0187-	.0414
	Co-Cr	.0350*	.00728	.014	.0070	.0629
	PEEK-100C	-.0038-	.00839	1.000	-.0333-	.0257
	PEEK-150C	.0024	.00913	1.000	-.0291-	.0338
	PEEK-175C	.0024	.00797	1.000	-.0263-	.0311
	PEEK-Juvora	-.0099-	.01165	.987	-.0498-	.0301
PEEK-Juvora	PMMA-HC	.0101	.01808	.999	-.0534-	.0735
	PMMA-Thermopress	.0212	.01019	.469	-.0150-	.0575
	Co-Cr	.0449*	.00910	.012	.0099	.0798
	PEEK-100C	.0061	.01000	.998	-.0298-	.0420
	PEEK-150C	.0122	.01063	.934	-.0250-	.0494
	PEEK-175C	.0123	.00966	.892	-.0231-	.0476
	PEEK-200C	.0099	.01165	.987	-.0301-	.0498

Based on observed means.

The error term is Mean Square(Error) = .001.

*. The mean difference is significant at the .05 level.

Part (G): Tensile Strength

Between-Subjects Factors

		Value Label	N
Materials	1.00	PMMA H-C	10
	2.00	PMMA-Injection	10
	3.00	PEEK 100C	10
	4.00	PEEK 150C	10
	5.00	PEEK 175C	10
	6.00	PEEK 200C	10
	7.00	PEEK-Juvora	10

Descriptive Statistics

Dependent Variable: Tensilestrength

Materials	Mean	Std. Deviation	N
PMMA H-C	65.4345	5.12048	10
PMMA-Injection	67.7980	9.02798	10
PEEK 100C	90.9699	3.26239	10
PEEK 150C	95.9319	2.40245	10
PEEK 175C	92.9450	4.77675	10
PEEK 200C	97.1474	3.67838	10
PEEK-Juvora	117.6433	5.03431	10
Total	89.6957	17.54098	70

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Tensilestrength

F	df1	df2	Sig.
2.633	6	63	.024

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Materials

1. Grand Mean

Dependent Variable: Tensilestrength

		95% Confidence Interval	
Mean	Std. Error	Lower Bound	Upper Bound
89.696	.616	88.465	90.926

2. Materials

Dependent Variable: Tensilestrength

			95% Confidence Interval	
Materials	Mean	Std. Error	Lower Bound	Upper Bound
PMMA H-C	65.435	1.629	62.179	68.690
PMMA-Injection	67.798	1.629	64.542	71.054
PEEK 100C	90.970	1.629	87.714	94.226
PEEK 150C	95.932	1.629	92.676	99.188
PEEK 175C	92.945	1.629	89.689	96.201
PEEK 200C	97.147	1.629	93.891	100.403
PEEK-Juvora	117.643	1.629	114.387	120.899

Multiple Comparisons

Dependent Variable: Tensilestrength

Games-Howell

(I) Materials	(J) Materials	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
PMMA H-C	PMMA-Injection	-2.3635-	3.28213	.989	-13.5419-	8.8149
	PEEK 100C	-25.5354-*	1.91996	.000	-32.0111-	-19.0598-
	PEEK 150C	-30.4974-*	1.78860	.000	-36.6917-	-24.3031-
	PEEK 175C	-27.5105-*	2.21442	.000	-34.8319-	-20.1892-
	PEEK 200C	-31.7129-*	1.99374	.000	-38.3784-	-25.0473-
	PEEK-Juvora	-52.2088-*	2.27076	.000	-59.7126-	-44.7051-
PMMA-Injection	PMMA H-C	2.3635	3.28213	.989	-8.8149-	13.5419
	PEEK 100C	-23.1720-*	3.03558	.000	-33.9087-	-12.4352-
	PEEK 150C	-28.1339-*	2.95425	.000	-38.7801-	-17.4878-
	PEEK 175C	-25.1471-*	3.22989	.000	-36.2149-	-14.0793-
	PEEK 200C	-29.3494-*	3.08277	.000	-40.1532-	-18.5456-
	PEEK-Juvora	-49.8454-*	3.26877	.000	-60.9947-	-38.6960-
PEEK 100C	PMMA H-C	25.5354*	1.91996	.000	19.0598	32.0111
	PMMA-Injection	23.1720*	3.03558	.000	12.4352	33.9087
	PEEK 150C	-4.9620-*	1.28121	.018	-9.2386-	-.6854-
	PEEK 175C	-1.9751-	1.82922	.925	-8.1121-	4.1618
	PEEK 200C	-6.1774-*	1.55479	.013	-11.3235-	-1.0314-
	PEEK-Juvora	-26.6734-*	1.89704	.000	-33.0631-	-20.2837-
PEEK 150C	PMMA H-C	30.4974*	1.78860	.000	24.3031	36.6917
	PMMA-Injection	28.1339*	2.95425	.000	17.4878	38.7801
	PEEK 100C	4.9620*	1.28121	.018	.6854	9.2386
	PEEK 175C	2.9869	1.69083	.589	-2.8332-	8.8069
	PEEK 200C	-1.2155-	1.38933	.971	-5.8922-	3.4613
	PEEK-Juvora	-21.7114-*	1.76397	.000	-27.8114-	-15.6115-
PEEK 175C	PMMA H-C	27.5105*	2.21442	.000	20.1892	34.8319
	PMMA-Injection	25.1471*	3.22989	.000	14.0793	36.2149
	PEEK 100C	1.9751	1.82922	.925	-4.1618-	8.1121
	PEEK 150C	-2.9869-	1.69083	.589	-8.8069-	2.8332
	PEEK 200C	-4.2023-	1.90651	.343	-10.5495-	2.1449
	PEEK-Juvora	-24.6983-*	2.19457	.000	-31.9523-	-17.4443-
PEEK 200C	PMMA H-C	31.7129*	1.99374	.000	25.0473	38.3784
	PMMA-Injection	29.3494*	3.08277	.000	18.5456	40.1532
	PEEK 100C	6.1774*	1.55479	.013	1.0314	11.3235
	PEEK 150C	1.2155	1.38933	.971	-3.4613-	5.8922
	PEEK 175C	4.2023	1.90651	.343	-2.1449-	10.5495
	PEEK-Juvora	-20.4960-*	1.97167	.000	-27.0805-	-13.9114-
PEEK-Juvora	PMMA H-C	52.2088*	2.27076	.000	44.7051	59.7126
	PMMA-Injection	49.8454*	3.26877	.000	38.6960	60.9947
	PEEK 100C	26.6734*	1.89704	.000	20.2837	33.0631
	PEEK 150C	21.7114*	1.76397	.000	15.6115	27.8114
	PEEK 175C	24.6983*	2.19457	.000	17.4443	31.9523
	PEEK 200C	20.4960*	1.97167	.000	13.9114	27.0805

Based on observed means.

The error term is Mean Square(Error) = 26.547.

*. The mean difference is significant at the .05 level.

Between-Subjects Factors

		Value Label	N
Materials	1.00	PMMA H-C	10
	2.00	PMMA-Injection	10
	3.00	PEEK 100C	10
	4.00	PEEK 150C	10
	5.00	PEEK 175C	10
	6.00	PEEK 200C	10
	7.00	PEEK-Juvora	10

Descriptive Statistics

Dependent Variable: DeflectionatBreak

Materials	Mean	Std. Deviation	N
PMMA H-C	4.3617	.58879	10
PMMA-Injection	4.7492	1.18914	10
PEEK 100C	14.7154	3.51712	10
PEEK 150C	15.4956	3.12689	10
PEEK 175C	10.7871	2.42073	10
PEEK 200C	11.5495	3.74461	10
PEEK-Juvora	7.0366	.37746	10
Total	9.8136	4.85882	70

Levene's Test of Equality of Error Variances[a]

Dependent Variable: DeflectionatBreak

F	df1	df2	Sig.
3.824	6	63	.003

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Materials

1. Grand Mean

Dependent Variable: DeflectionatBreak

		95% Confidence Interval	
Mean	Std. Error	Lower Bound	Upper Bound
9.814	.299	9.215	10.412

2. Materials

Dependent Variable: DeflectionatBreak

			95% Confidence Interval	
Materials	Mean	Std. Error	Lower Bound	Upper Bound
PMMA H-C	4.362	.792	2.779	5.945
PMMA-Injection	4.749	.792	3.166	6.332
PEEK 100C	14.715	.792	13.132	16.299
PEEK 150C	15.496	.792	13.912	17.079
PEEK 175C	10.787	.792	9.204	12.370
PEEK 200C	11.550	.792	9.966	13.133
PEEK-Juvora	7.037	.792	5.453	8.620

Multiple Comparisons

Dependent Variable: DeflectionatBreak

Games-Howell

(I) Materials	(J) Materials	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
PMMA H-C	PMMA-Injection	-.3875-	.41961	.962	-1.8339-	1.0588
	PEEK 100C	-10.3537-*	1.12769	.000	-14.4844-	-6.2230-
	PEEK 150C	-11.1339-*	1.00619	.000	-14.8083-	-7.4594-
	PEEK 175C	-6.4254-*	.78782	.000	-9.2764-	-3.5745-
	PEEK 200C	-7.1878-*	1.19870	.002	-11.5847-	-2.7909-
	PEEK-Juvora	-2.6749-*	.22117	.000	-3.4204-	-1.9293-
PMMA-Injection	PMMA H-C	.3875	.41961	.962	-1.0588-	1.8339
	PEEK 100C	-9.9662-*	1.17406	.000	-14.1382-	-5.7941-
	PEEK 150C	-10.7464-*	1.05790	.000	-14.4739-	-7.0188-
	PEEK 175C	-6.0379-*	.85288	.000	-8.9797-	-3.0961-
	PEEK 200C	-6.8003-*	1.24242	.003	-11.2333-	-2.3672-
	PEEK-Juvora	-2.2873-*	.39453	.002	-3.6951-	-.8796-
PEEK 100C	PMMA H-C	10.3537*	1.12769	.000	6.2230	14.4844
	PMMA-Injection	9.9662*	1.17406	.000	5.7941	14.1382
	PEEK 150C	-.7802-	1.48820	.998	-5.7056-	4.1452
	PEEK 175C	3.9282	1.35019	.112	-.5991-	8.4555
	PEEK 200C	3.1659	1.62457	.477	-2.2048-	8.5365
	PEEK-Juvora	7.6788*	1.11860	.001	3.5523	11.8053
PEEK 150C	PMMA H-C	11.1339*	1.00619	.000	7.4594	14.8083
	PMMA-Injection	10.7464*	1.05790	.000	7.0188	14.4739
	PEEK 100C	.7802	1.48820	.998	-4.1452-	5.7056
	PEEK 175C	4.7085*	1.25049	.021	.5465	8.8704
	PEEK 200C	3.9461	1.54271	.198	-1.1703-	9.0624
	PEEK-Juvora	8.4590*	.99599	.000	4.7898	12.1283
PEEK 175C	PMMA H-C	6.4254*	.78782	.000	3.5745	9.2764
	PMMA-Injection	6.0379*	.85288	.000	3.0961	8.9797
	PEEK 100C	-3.9282-	1.35019	.112	-8.4555-	.5991
	PEEK 150C	-4.7085-*	1.25049	.021	-8.8704-	-.5465-
	PEEK 200C	-.7624-	1.41004	.998	-5.5127-	3.9879
	PEEK-Juvora	3.7506*	.77475	.010	.9083	6.5929
PEEK 200C	PMMA H-C	7.1878*	1.19870	.002	2.7909	11.5847
	PMMA-Injection	6.8003*	1.24242	.003	2.3672	11.2333
	PEEK 100C	-3.1659-	1.62457	.477	-8.5365-	2.2048
	PEEK 150C	-3.9461-	1.54271	.198	-9.0624-	1.1703
	PEEK 175C	.7624	1.41004	.998	-3.9879-	5.5127
	PEEK-Juvora	4.5130*	1.19015	.043	.1198	8.9061
PEEK-Juvora	PMMA H-C	2.6749*	.22117	.000	1.9293	3.4204
	PMMA-Injection	2.2873*	.39453	.002	.8796	3.6951
	PEEK 100C	-7.6788-*	1.11860	.001	-11.8053-	-3.5523-
	PEEK 150C	-8.4590-*	.99599	.000	-12.1283-	-4.7898-
	PEEK 175C	-3.7506-*	.77475	.010	-6.5929-	-.9083-
	PEEK 200C	-4.5130-*	1.19015	.043	-8.9061-	-.1198-

Based on observed means.

The error term is Mean Square(Error) = 6.276.

*. The mean difference is significant at the .05 level.

Between-Subjects Factors

		Value Label	N
Materials	1.00	PMMA H-C	10
	2.00	PMMA-Injection	10
	3.00	PEEK 100C	10
	4.00	PEEK 150C	10
	5.00	PEEK 175C	10
	6.00	PEEK 200C	10
	7.00	PEEK-Juvora	10

Descriptive Statistics

Dependent Variable: LoadatBreak

Materials	Mean	Std. Deviation	N
PMMA H-C	439.2156	37.69651	10
PMMA-Injection	424.1139	62.97367	10
PEEK 100C	547.2318	33.80823	10
PEEK 150C	576.5476	26.12898	10
PEEK 175C	528.3978	36.51455	10
PEEK 200C	561.7741	43.07699	10
PEEK-Juvora	584.9689	22.01053	10
Total	523.1785	71.64987	70

Levene's Test of Equality of Error Variances[a]

Dependent Variable: LoadatBreak

F	df1	df2	Sig.
2.128	6	63	.062

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Materials

1. Grand Mean

Dependent Variable: LoadatBreak

		95% Confidence Interval	
Mean	Std. Error	Lower Bound	Upper Bound
523.179	4.713	513.760	532.597

2. Materials

Dependent Variable: LoadatBreak

			95% Confidence Interval	
Materials	Mean	Std. Error	Lower Bound	Upper Bound
PMMA H-C	439.216	12.470	414.295	464.136
PMMA-Injection	424.114	12.470	399.194	449.034
PEEK 100C	547.232	12.470	522.312	572.152
PEEK 150C	576.548	12.470	551.627	601.468
PEEK 175C	528.398	12.470	503.478	553.318
PEEK 200C	561.774	12.470	536.854	586.694
PEEK-Juvora	584.969	12.470	560.049	609.889

Multiple Comparisons

Dependent Variable: LoadatBreak

Tukey HSD

(I) Materials	(J) Materials	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
PMMA H-C	PMMA-Injection	15.1017	17.63587	.978	-38.6101-	68.8136
	PEEK 100C	-108.0162-*	17.63587	.000	-161.7281-	-54.3043-
	PEEK 150C	-137.3320-*	17.63587	.000	-191.0439-	-83.6201-
	PEEK 175C	-89.1821-*	17.63587	.000	-142.8940-	-35.4703-
	PEEK 200C	-122.5585-*	17.63587	.000	-176.2704-	-68.8466-
	PEEK-Juvora	-145.7533-*	17.63587	.000	-199.4652-	-92.0414-
PMMA-Injection	PMMA H-C	-15.1017-	17.63587	.978	-68.8136-	38.6101
	PEEK 100C	-123.1179-*	17.63587	.000	-176.8298-	-69.4060-
	PEEK 150C	-152.4337-*	17.63587	.000	-206.1456-	-98.7218-
	PEEK 175C	-104.2839-*	17.63587	.000	-157.9958-	-50.5720-
	PEEK 200C	-137.6602-*	17.63587	.000	-191.3721-	-83.9483-
	PEEK-Juvora	-160.8551-*	17.63587	.000	-214.5670-	-107.1432-
PEEK 100C	PMMA H-C	108.0162*	17.63587	.000	54.3043	161.7281
	PMMA-Injection	123.1179*	17.63587	.000	69.4060	176.8298
	PEEK 150C	-29.3158-	17.63587	.643	-83.0277-	24.3961
	PEEK 175C	18.8340	17.63587	.935	-34.8779-	72.5459
	PEEK 200C	-14.5423-	17.63587	.981	-68.2542-	39.1696
	PEEK-Juvora	-37.7372-	17.63587	.343	-91.4491-	15.9747
PEEK 150C	PMMA H-C	137.3320*	17.63587	.000	83.6201	191.0439
	PMMA-Injection	152.4337*	17.63587	.000	98.7218	206.1456
	PEEK 100C	29.3158	17.63587	.643	-24.3961-	83.0277
	PEEK 175C	48.1498	17.63587	.108	-5.5620-	101.8617
	PEEK 200C	14.7735	17.63587	.980	-38.9384-	68.4854
	PEEK-Juvora	-8.4213-	17.63587	.999	-62.1332-	45.2905
PEEK 175C	PMMA H-C	89.1821*	17.63587	.000	35.4703	142.8940
	PMMA-Injection	104.2839*	17.63587	.000	50.5720	157.9958
	PEEK 100C	-18.8340-	17.63587	.935	-72.5459-	34.8779
	PEEK 150C	-48.1498-	17.63587	.108	-101.8617-	5.5620
	PEEK 200C	-33.3763-	17.63587	.493	-87.0882-	20.3356
	PEEK-Juvora	-56.5712-*	17.63587	.033	-110.2831-	-2.8593-
PEEK 200C	PMMA H-C	122.5585*	17.63587	.000	68.8466	176.2704
	PMMA-Injection	137.6602*	17.63587	.000	83.9483	191.3721
	PEEK 100C	14.5423	17.63587	.981	-39.1696-	68.2542
	PEEK 150C	-14.7735-	17.63587	.980	-68.4854-	38.9384
	PEEK 175C	33.3763	17.63587	.493	-20.3356-	87.0882
	PEEK-Juvora	-23.1949-	17.63587	.842	-76.9067-	30.5170
PEEK-Juvora	PMMA H-C	145.7533*	17.63587	.000	92.0414	199.4652
	PMMA-Injection	160.8551*	17.63587	.000	107.1432	214.5670
	PEEK 100C	37.7372	17.63587	.343	-15.9747-	91.4491
	PEEK 150C	8.4213	17.63587	.999	-45.2905-	62.1332
	PEEK 175C	56.5712*	17.63587	.033	2.8593	110.2831
	PEEK 200C	23.1949	17.63587	.842	-30.5170-	76.9067

Based on observed means.

The error term is Mean Square(Error) = 1555.119.

*. The mean difference is significant at the .05 level.

Part (H): Clasp Retentive Force

Statistics for clasp retentive test over 3 years at specific materials- Clasp

JUVORA 0.25mm

Between-Subjects Factors

		Value Label	N
Measurements	.00	Initial	10
	1.00	1st Year	10
	2.00	2nd Year	10
	3.00	3rd Year	10

Descriptive Statistics

Dependent Variable: JUVORA0.25

Measurements	Mean	Std. Deviation	N
Initial	32.2434	1.82743	10
1st Year	31.6184	1.84850	10
2nd Year	30.5283	1.71131	10
3rd Year	28.8257	1.63943	10
Total	30.8040	2.14000	40

Levene's Test of Equality of Error Variances[a]

Dependent Variable: JUVORA0.25

F	df1	df2	Sig.
.255	3	36	.857

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Measurements

1. Grand Mean

Dependent Variable: JUVORA0.25

		95% Confidence Interval	
Mean	Std. Error	Lower Bound	Upper Bound
30.804	.278	30.240	31.368

2. Measurements

Dependent Variable: JUVORA0.25

			95% Confidence Interval	
Measurements	Mean	Std. Error	Lower Bound	Upper Bound
Initial	32.243	.556	31.115	33.371
1st Year	31.618	.556	30.490	32.746
2nd Year	30.528	.556	29.400	31.656
3rd Year	28.826	.556	27.698	29.954

Multiple Comparisons

Dependent Variable: JUVORA0.25

Tukey HSD

(I) Measurements	(J) Measurements	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Initial	1st Year	.6250	.78654	.856	-1.4933-	2.7433
	2nd Year	1.7151	.78654	.148	-.4032-	3.8334
	3rd Year	3.4177*	.78654	.001	1.2994	5.5360
1st Year	Initial	-.6250-	.78654	.856	-2.7433-	1.4933
	2nd Year	1.0901	.78654	.516	-1.0282-	3.2084
	3rd Year	2.7927*	.78654	.006	.6744	4.9110
2nd Year	Initial	-1.7151-	.78654	.148	-3.8334-	.4032
	1st Year	-1.0901-	.78654	.516	-3.2084-	1.0282
	3rd Year	1.7026	.78654	.153	-.4157-	3.8209
3rd Year	Initial	-3.4177-*	.78654	.001	-5.5360-	-1.2994-
	1st Year	-2.7927-*	.78654	.006	-4.9110-	-.6744-
	2nd Year	-1.7026-	.78654	.153	-3.8209-	.4157

Based on observed means.

The error term is Mean Square(Error) = 3.093.

*. The mean difference is significant at the .05 level.

JUVORA 0.50mm

Between-Subjects Factors

		Value Label	N
Measurements	.00	Initial	10
	1.00	1st Year	10
	2.00	2nd Year	10
	3.00	3rd Year	10

Descriptive Statistics

Dependent Variable: JUVORA0.50

Measurements	Mean	Std. Deviation	N
Initial	35.6842	.88419	10
1st Year	33.5945	.65779	10
2nd Year	32.2416	.96073	10
3rd Year	30.4999	.85180	10
Total	33.0051	2.08538	40

Levene's Test of Equality of Error Variances[a]

Dependent Variable: JUVORA0.50

F	df1	df2	Sig.
.616	3	36	.609

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Measurements

1. Grand Mean

Dependent Variable: JUVORA0.50

Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
33.005	.134	32.734	33.276

2. Measurements

Dependent Variable: JUVORA0.50

Measurements	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Initial	35.684	.268	35.142	36.227
1st Year	33.595	.268	33.052	34.137
2nd Year	32.242	.268	31.699	32.784
3rd Year	30.500	.268	29.957	31.043

Multiple Comparisons

Dependent Variable: JUVORA0.50

Tukey HSD

(I) Measurements	(J) Measurements	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Initial	1st Year	2.0897*	.37836	.000	1.0707	3.1086
	2nd Year	3.4426*	.37836	.000	2.4236	4.4616
	3rd Year	5.1842*	.37836	.000	4.1652	6.2032
1st Year	Initial	-2.0897-*	.37836	.000	-3.1086-	-1.0707-
	2nd Year	1.3529*	.37836	.005	.3339	2.3719
	3rd Year	3.0946*	.37836	.000	2.0756	4.1136
2nd Year	Initial	-3.4426-*	.37836	.000	-4.4616-	-2.4236-
	1st Year	-1.3529-*	.37836	.005	-2.3719-	-.3339-
	3rd Year	1.7416*	.37836	.000	.7226	2.7606
3rd Year	Initial	-5.1842-*	.37836	.000	-6.2032-	-4.1652-
	1st Year	-3.0946-*	.37836	.000	-4.1136-	-2.0756-
	2nd Year	-1.7416-*	.37836	.000	-2.7606-	-.7226-

Based on observed means.

The error term is Mean Square(Error) = .716.

*. The mean difference is significant at the .05 level.

JUVORA 0.75mm

Between-Subjects Factors

		Value Label	N
Measurements	.00	Initial	10
	1.00	1st Year	10
	2.00	2nd Year	10
	3.00	3rd Year	10

Descriptive Statistics

Dependent Variable: JUVORA0.75

Measurements	Mean	Std. Deviation	N
Initial	45.2828	2.12484	10
1st Year	42.6269	1.63633	10
2nd Year	40.4198	1.72400	10
3rd Year	37.8098	2.10185	10
Total	41.5348	3.33910	40

Levene's Test of Equality of Error Variances[a]

Dependent Variable: JUVORA0.75

F	df1	df2	Sig.
.568	3	36	.640

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Measurements

Multiple Comparisons

Dependent Variable: JUVORA0.75

Tukey HSD

(I) Measurements	(J) Measurements	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Initial	1st Year	2.6559*	.85389	.018	.3561	4.9556
	2nd Year	4.8630*	.85389	.000	2.5633	7.1628
	3rd Year	7.4730*	.85389	.000	5.1733	9.7727
1st Year	Initial	-2.6559-*	.85389	.018	-4.9556-	-.3561-
	2nd Year	2.2072	.85389	.064	-.0925-	4.5069
	3rd Year	4.8171*	.85389	.000	2.5174	7.1168
2nd Year	Initial	-4.8630-*	.85389	.000	-7.1628-	-2.5633-
	1st Year	-2.2072-	.85389	.064	-4.5069-	.0925
	3rd Year	2.6099*	.85389	.021	.3102	4.9096
3rd Year	Initial	-7.4730-*	.85389	.000	-9.7727-	-5.1733-
	1st Year	-4.8171-*	.85389	.000	-7.1168-	-2.5174-
	2nd Year	-2.6099-*	.85389	.021	-4.9096-	-.3102-

Based on observed means.

The error term is Mean Square(Error) = 3.646.

*. The mean difference is significant at the .05 level.

OPTIMA 0.25mm

Between-Subjects Factors

		Value Label	N
Measurements	.00	Initial	10
	1.00	1st Year	10
	2.00	2nd Year	10
	3.00	3rd Year	10

Descriptive Statistics

Dependent Variable: OPTIMA0.25

Measurements	Mean	Std. Deviation	N
Initial	22.5432	1.21384	10
1st Year	21.8662	1.28223	10
2nd Year	20.6702	1.69681	10
3rd Year	19.2891	1.42883	10
Total	21.0922	1.85141	40

Levene's Test of Equality of Error Variances[a]

Dependent Variable: OPTIMA0.25

F	df1	df2	Sig.
.629	3	36	.601

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Measurements

1. Grand Mean

Dependent Variable: OPTIMA0.25

Mean	Std. Error	95% Confidence Interval	
		Lower Bound	Upper Bound
21.092	.224	20.638	21.547

2. Measurements

Dependent Variable: OPTIMA0.25

Measurements	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Initial	22.543	.448	21.634	23.452
1st Year	21.866	.448	20.957	22.775
2nd Year	20.670	.448	19.761	21.579
3rd Year	19.289	.448	18.380	20.198

Multiple Comparisons

Dependent Variable: OPTIMA0.25

Tukey HSD

(I) Measurements	(J) Measurements	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Initial	1st Year	.6769	.63396	.711	-1.0305-	2.3843
	2nd Year	1.8730*	.63396	.027	.1655	3.5804
	3rd Year	3.2541*	.63396	.000	1.5467	4.9615
1st Year	Initial	-.6769-	.63396	.711	-2.3843-	1.0305
	2nd Year	1.1960	.63396	.252	-.5114-	2.9034
	3rd Year	2.5771*	.63396	.001	.8697	4.2845
2nd Year	Initial	-1.8730-*	.63396	.027	-3.5804-	-.1655-
	1st Year	-1.1960-	.63396	.252	-2.9034-	.5114
	3rd Year	1.3811	.63396	.149	-.3263-	3.0885
3rd Year	Initial	-3.2541-*	.63396	.000	-4.9615-	-1.5467-
	1st Year	-2.5771-*	.63396	.001	-4.2845-	-.8697-
	2nd Year	-1.3811-	.63396	.149	-3.0885-	.3263

Based on observed means.

The error term is Mean Square(Error) = 2.010.

*. The mean difference is significant at the .05 level.

OPTIMA 0.50mm

Between-Subjects Factors

		Value Label	N
Measurements	.00	Initial	10
	1.00	1st Year	10
	2.00	2nd Year	10
	3.00	3rd Year	10

Descriptive Statistics

Dependent Variable: OPTIMA0.50

Measurements	Mean	Std. Deviation	N
Initial	30.1880	1.46752	10
1st Year	28.8941	1.50874	10
2nd Year	26.8410	.84475	10
3rd Year	24.8248	.92335	10
Total	27.6870	2.37595	40

Levene's Test of Equality of Error Variances[a]

Dependent Variable: OPTIMA0.50

F	df1	df2	Sig.
4.600	3	36	.008

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Measurements

1. Grand Mean

Dependent Variable: OPTIMA0.50

Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
27.687	.194	27.294	28.080

2. Measurements

Dependent Variable: OPTIMA0.50

Measurements	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Initial	30.188	.387	29.403	30.973
1st Year	28.894	.387	28.109	29.679
2nd Year	26.841	.387	26.056	27.626
3rd Year	24.825	.387	24.040	25.610

Multiple Comparisons

Dependent Variable: OPTIMA0.50

Games-Howell

(I) Measurements	(J) Measurements	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Initial	1st Year	1.2939	.66558	.245	-.5873-	3.1752
	2nd Year	3.3470*	.53546	.000	1.7957	4.8982
	3rd Year	5.3632*	.54829	.000	3.7849	6.9414
1st Year	Initial	-1.2939-	.66558	.245	-3.1752-	.5873
	2nd Year	2.0530*	.54680	.010	.4657	3.6404
	3rd Year	4.0692*	.55936	.000	2.4559	5.6825
2nd Year	Initial	-3.3470-*	.53546	.000	-4.8982-	-1.7957-
	1st Year	-2.0530-*	.54680	.010	-3.6404-	-.4657-
	3rd Year	2.0162*	.39575	.000	.8968	3.1356
3rd Year	Initial	-5.3632-*	.54829	.000	-6.9414-	-3.7849-
	1st Year	-4.0692-*	.55936	.000	-5.6825-	-2.4559-
	2nd Year	-2.0162-*	.39575	.000	-3.1356-	-.8968-

Based on observed means.

The error term is Mean Square(Error) = 1.499.

*. The mean difference is significant at the .05 level.

OPTIMA 0.75mm

Between-Subjects Factors

		Value Label	N
Measurements	.00	Initial	10
	1.00	1st Year	10
	2.00	2nd Year	10
	3.00	3rd Year	10

Descriptive Statistics

Dependent Variable: OPTIMA0.75

Measurements	Mean	Std. Deviation	N
Initial	34.9931	1.51347	10
1st Year	33.3189	1.62436	10
2nd Year	31.0034	1.75139	10
3rd Year	28.3049	1.96375	10
Total	31.9051	3.03724	40

Levene's Test of Equality of Error Variances[a]

Dependent Variable: OPTIMA0.75

F	df1	df2	Sig.
.098	3	36	.961

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Measurements

1. Grand Mean

Dependent Variable: OPTIMA0.75

Mean	Std. Error	95% Confidence Interval	
		Lower Bound	Upper Bound
31.905	.272	31.353	32.457

2. Measurements

Dependent Variable: OPTIMA0.75

Measurements	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Initial	34.993	.544	33.889	36.097
1st Year	33.319	.544	32.215	34.423
2nd Year	31.003	.544	29.899	32.107
3rd Year	28.305	.544	27.201	29.409

Multiple Comparisons

Dependent Variable: OPTIMA0.75

Tukey HSD

(I) Measurements	(J) Measurements	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Initial	1st Year	1.6741	.76983	.150	-.3992-	3.7475
	2nd Year	3.9897*	.76983	.000	1.9164	6.0630
	3rd Year	6.6882*	.76983	.000	4.6149	8.7616
1st Year	Initial	-1.6741-	.76983	.150	-3.7475-	.3992
	2nd Year	2.3156*	.76983	.024	.2422	4.3889
	3rd Year	5.0141*	.76983	.000	2.9407	7.0874
2nd Year	Initial	-3.9897-*	.76983	.000	-6.0630-	-1.9164-
	1st Year	-2.3156-*	.76983	.024	-4.3889-	-.2422-
	3rd Year	2.6985*	.76983	.007	.6252	4.7718
3rd Year	Initial	-6.6882-*	.76983	.000	-8.7616-	-4.6149-
	1st Year	-5.0141-*	.76983	.000	-7.0874-	-2.9407-
	2nd Year	-2.6985-*	.76983	.007	-4.7718-	-.6252-

Based on observed means.

The error term is Mean Square(Error) = 2.963.

*. The mean difference is significant at the .05 level.

Co-Cr 0.25mm

Between-Subjects Factors

		Value Label	N
Measurements	.00	Initial	10
	1.00	1st Year	10
	2.00	2nd Year	8
	3.00	3rd Year	7

Descriptive Statistics

Dependent Variable: COCR0.25

Measurements	Mean	Std. Deviation	N
Initial	23.6870	.53713	10
1st Year	22.4024	.89994	10
2nd Year	20.8167	.69579	8
3rd Year	18.1654	.31780	7
Total	21.5596	2.10952	35

Levene's Test of Equality of Error Variances[a]

Dependent Variable: COCR0.25

F	df1	df2	Sig.
1.801	3	31	.167

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Measurements

1. Grand Mean

Dependent Variable: COCR0.25

		95% Confidence Interval	
Mean	Std. Error	Lower Bound	Upper Bound
21.268	.114	21.035	21.501

2. Measurements

Dependent Variable: COCR0.25

			95% Confidence Interval	
Measurements	Mean	Std. Error	Lower Bound	Upper Bound
Initial	23.687	.212	23.255	24.119
1st Year	22.402	.212	21.971	22.834
2nd Year	20.817	.237	20.334	21.299
3rd Year	18.165	.253	17.650	18.681

Multiple Comparisons

Dependent Variable: COCR0.25

Gabriel

(I) Measurements	(J) Measurements	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Initial	1st Year	1.2847*	.29925	.001	.4471	2.1223
	2nd Year	2.8703*	.31740	.000	1.9833	3.7573
	3rd Year	5.5217*	.32976	.000	4.6023	6.4410
1st Year	Initial	-1.2847-*	.29925	.001	-2.1223-	-.4471-
	2nd Year	1.5856*	.31740	.000	.6986	2.4727
	3rd Year	4.2370*	.32976	.000	3.3176	5.1564
2nd Year	Initial	-2.8703-*	.31740	.000	-3.7573-	-1.9833-
	1st Year	-1.5856-*	.31740	.000	-2.4727-	-.6986-
	3rd Year	2.6514*	.34631	.000	1.6826	3.6202
3rd Year	Initial	-5.5217-*	.32976	.000	-6.4410-	-4.6023-
	1st Year	-4.2370-*	.32976	.000	-5.1564-	-3.3176-
	2nd Year	-2.6514-*	.34631	.000	-3.6202-	-1.6826-

Based on observed means.

The error term is Mean Square(Error) = .448.

*. The mean difference is significant at the .05 level.

Co-Cr 0.50mm

Between-Subjects Factors

		Value Label	N
Measurements	.00	Initial	10
	1.00	1st Year	10
	2.00	2nd Year	8
	3.00	3rd Year	5

Descriptive Statistics

Dependent Variable: COCR0.50

Measurements	Mean	Std. Deviation	N
Initial	27.9847	.54038	10
1st Year	26.0767	.44236	10
2nd Year	22.3728	1.09344	8
3rd Year	17.3719	.38485	5
Total	24.4380	3.74903	33

Levene's Test of Equality of Error Variances[a]

Dependent Variable: COCR0.50

F	df1	df2	Sig.
1.640	3	29	.202

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Measurements

1. Grand Mean

Dependent Variable: COCR0.50

Mean	Std. Error	95% Confidence Interval	
		Lower Bound	Upper Bound
23.451	.123	23.200	23.703

2. Measurements

Dependent Variable: COCR0.50

Measurements	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Initial	27.985	.215	27.546	28.424
1st Year	26.077	.215	25.638	26.515
2nd Year	22.373	.240	21.882	22.863
3rd Year	17.372	.303	16.751	17.992

Multiple Comparisons

Dependent Variable: COCR0.50

Hochberg

(I) Measurements	(J) Measurements	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Initial	1st Year	1.9080*	.30344	.000	1.0550	2.7610
	2nd Year	5.6119*	.32185	.000	4.7072	6.5167
	3rd Year	10.6128*	.37164	.000	9.5681	11.6576
1st Year	Initial	-1.9080-*	.30344	.000	-2.7610-	-1.0550-
	2nd Year	3.7039*	.32185	.000	2.7991	4.6086
	3rd Year	8.7048*	.37164	.000	7.6601	9.7495
2nd Year	Initial	-5.6119-*	.32185	.000	-6.5167-	-4.7072-
	1st Year	-3.7039-*	.32185	.000	-4.6086-	-2.7991-
	3rd Year	5.0009*	.38681	.000	3.9135	6.0883
3rd Year	Initial	-10.6128-*	.37164	.000	-11.6576-	-9.5681-
	1st Year	-8.7048-*	.37164	.000	-9.7495-	-7.6601-
	2nd Year	-5.0009-*	.38681	.000	-6.0883-	-3.9135-

Based on observed means.

The error term is Mean Square(Error) = .460.

*. The mean difference is significant at the .05 level.

Co-Cr 0.75mm

Between-Subjects Factors

		Value Label	N
Measurements	.00	Initial	10
	1.00	1st Year	10
	2.00	2nd Year	5
	3.00	3rd Year	3

Descriptive Statistics

Dependent Variable: COCR0.75

Measurements	Mean	Std. Deviation	N
Initial	34.1857	.83828	10
1st Year	30.8031	.93348	10
2nd Year	26.0094	.99379	5
3rd Year	20.4224	1.27066	3
Total	30.0429	4.54509	28

Levene's Test of Equality of Error Variances[a]

Dependent Variable: COCR0.75

F	df1	df2	Sig.
.303	3	24	.823

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Measurements

1. Grand Mean

Dependent Variable: COCR0.75

Mean	Std. Error	95% Confidence Interval	
		Lower Bound	Upper Bound
27.855	.202	27.438	28.272

2. Measurements

Dependent Variable: COCR0.75

Measurements	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Initial	34.186	.298	33.570	34.801
1st Year	30.803	.298	30.188	31.419
2nd Year	26.009	.422	25.139	26.880
3rd Year	20.422	.544	19.299	21.546

Multiple Comparisons

Dependent Variable: COCR0.75

Hochberg

(I) Measurements	(J) Measurements	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Initial	1st Year	3.3826*	.42177	.000	2.1802	4.5849
	2nd Year	8.1763*	.51656	.000	6.7037	9.6488
	3rd Year	13.7633*	.62082	.000	11.9935	15.5331
1st Year	Initial	-3.3826-*	.42177	.000	-4.5849-	-2.1802-
	2nd Year	4.7937*	.51656	.000	3.3212	6.2662
	3rd Year	10.3808*	.62082	.000	8.6110	12.1505
2nd Year	Initial	-8.1763-*	.51656	.000	-9.6488-	-6.7037-
	1st Year	-4.7937-*	.51656	.000	-6.2662-	-3.3212-
	3rd Year	5.5871*	.68874	.000	3.6237	7.5504
3rd Year	Initial	-13.7633-*	.62082	.000	-15.5331-	-11.9935-
	1st Year	-10.3808-*	.62082	.000	-12.1505-	-8.6110-
	2nd Year	-5.5871-*	.68874	.000	-7.5504-	-3.6237-

Based on observed means.

The error term is Mean Square(Error) = .889.

*. The mean difference is significant at the .05 level.

Statistics for clasp retentive test at specific term and undercut and between tested materials

At 0.25mm

Initial 0.25mm

Between-Subjects Factors

		Value Label	N
Materials	1.00	JUVORA	10
	2.00	Optima	10
	3.00	Co-Cr	10

Descriptive Statistics

Dependent Variable: Initial0.25

Materials	Mean	Std. Deviation	N
JUVORA	32.2434	1.82743	10
Optima	22.5432	1.21383	10
Co-Cr	23.6870	.53713	10
Total	26.1579	4.57866	30

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Initial0.25

F	df1	df2	Sig.
5.790	2	27	.008

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Materials

1. Grand Mean

Dependent Variable: Initial0.25

		95% Confidence Interval	
Mean	Std. Error	Lower Bound	Upper Bound
26.158	.238	25.669	26.646

2. Materials

Dependent Variable: Initial0.25

			95% Confidence Interval	
Materials	Mean	Std. Error	Lower Bound	Upper Bound
JUVORA	32.243	.412	31.397	33.090
Optima	22.543	.412	21.697	23.389
Co-Cr	23.687	.412	22.841	24.533

Multiple Comparisons

Dependent Variable: Initial0.25

Games-Howell

					95% Confidence Interval	
(I) Materials	(J) Materials	Mean Difference (I-J)	Std. Error	Sig.	Lower Bound	Upper Bound
JUVORA	Optima	9.7002*	.69375	.000	7.9061	11.4943
	Co-Cr	8.5564*	.60233	.000	6.9191	10.1936
Optima	JUVORA	-9.7002-*	.69375	.000	-11.4943-	-7.9061-
	Co-Cr	-1.1439-*	.41975	.044	-2.2589-	-.0288-
Co-Cr	JUVORA	-8.5564-*	.60233	.000	-10.1936-	-6.9191-
	Optima	1.1439*	.41975	.044	.0288	2.2589

Based on observed means.

The error term is Mean Square(Error) = 1.700.

*. The mean difference is significant at the .05 level.

1st year 0.25mm

Between-Subjects Factors

		Value Label	N
Materials	1.00	JUVORA	10
	2.00	Optima	10
	3.00	Co-Cr	10

Descriptive Statistics

Dependent Variable: FirstY0.25

Materials	Mean	Std. Deviation	N
JUVORA	31.6184	1.84850	10
Optima	21.8662	1.28223	10
Co-Cr	22.4024	.89994	10
Total	25.2957	4.74862	30

Levene's Test of Equality of Error Variances[a]

Dependent Variable: FirstY0.25

F	df1	df2	Sig.
3.160	2	27	.058

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Materials

1. Grand Mean

Dependent Variable: FirstY0.25

Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
25.296	.255	24.772	25.820

2. Materials

Dependent Variable: FirstY0.25

Materials	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
JUVORA	31.618	.442	30.711	32.526
Optima	21.866	.442	20.959	22.774
Co-Cr	22.402	.442	21.495	23.310

Multiple Comparisons

Dependent Variable: FirstY0.25

Bonferroni

(I) Materials	(J) Materials	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
JUVORA	Optima	9.7522*	.62562	.000	8.1553	11.3490
	Co-Cr	9.2161*	.62562	.000	7.6192	10.8129
Optima	JUVORA	-9.7522-*	.62562	.000	-11.3490-	-8.1553-
	Co-Cr	-.5361-	.62562	1.000	-2.1330-	1.0607
Co-Cr	JUVORA	-9.2161-*	.62562	.000	-10.8129-	-7.6192-
	Optima	.5361	.62562	1.000	-1.0607-	2.1330

Based on observed means.

The error term is Mean Square(Error) = 1.957.

*. The mean difference is significant at the .05 level.

2nd Year 0.25mm

Between-Subjects Factors

		Value Label	N
Materials	1.00	JUVORA	10
	2.00	Optima	10
	3.00	Co-Cr	8

Descriptive Statistics

Dependent Variable: SecondY0.25

Materials	Mean	Std. Deviation	N
JUVORA	30.5283	1.71131	10
Optima	20.6702	1.69681	10
Co-Cr	20.8167	.69579	8
Total	24.2328	4.98987	28

Levene's Test of Equality of Error Variances[a]

Dependent Variable: SecondY0.25

F	df1	df2	Sig.
2.820	2	25	.079

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Materials

1. Grand Mean

Dependent Variable: SecondY0.25

		95% Confidence Interval	
Mean	Std. Error	Lower Bound	Upper Bound
24.005	.284	23.421	24.589

2. Materials

Dependent Variable: SecondY0.25

			95% Confidence Interval	
Materials	Mean	Std. Error	Lower Bound	Upper Bound
JUVORA	30.528	.472	29.557	31.500
Optima	20.670	.472	19.698	21.642
Co-Cr	20.817	.528	19.730	21.903

Multiple Comparisons

Dependent Variable: SecondY0.25

Gabriel

					95% Confidence Interval	
(I) Materials	(J) Materials	Mean Difference (I-J)	Std. Error	Sig.	Lower Bound	Upper Bound
JUVORA	Optima	9.8581*	.66728	.000	8.1561	11.5601
	Co-Cr	9.7116*	.70776	.000	7.9091	11.5140
Optima	JUVORA	-9.8581-*	.66728	.000	-11.5601-	-8.1561-
	Co-Cr	-.1465-	.70776	.995	-1.9490-	1.6560
Co-Cr	JUVORA	-9.7116-*	.70776	.000	-11.5140-	-7.9091-
	Optima	.1465	.70776	.995	-1.6560-	1.9490

Based on observed means.

The error term is Mean Square(Error) = 2.226.

*. The mean difference is significant at the .05 level.

3rd Year 0.25mm

Between-Subjects Factors

		Value Label	N
Materials	1.00	JUVORA	10
	2.00	Optima	10
	3.00	Co-Cr	7

Descriptive Statistics

Dependent Variable: ThirdY0.25

Materials	Mean	Std. Deviation	N
JUVORA	28.8257	1.63943	10
Optima	19.2891	1.42885	10
Co-Cr	18.1654	.31783	7
Total	22.5298	5.10622	27

Levene's Test of Equality of Error Variances^a

Dependent Variable: ThirdY0.25

F	df1	df2	Sig.
3.311	2	24	.054

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Materials

1. Grand Mean

Dependent Variable: ThirdY0.25

		95% Confidence Interval	
Mean	Std. Error	Lower Bound	Upper Bound
22.093	.262	21.553	22.634

2. Materials

Dependent Variable: ThirdY0.25

			95% Confidence Interval	
Materials	Mean	Std. Error	Lower Bound	Upper Bound
JUVORA	28.826	.424	27.950	29.701
Optima	19.289	.424	18.414	20.164
Co-Cr	18.165	.507	17.119	19.212

Multiple Comparisons

Dependent Variable: ThirdY0.25

Gabriel

					95% Confidence Interval	
(I) Materials	(J) Materials	Mean Difference (I-J)	Std. Error	Sig.	Lower Bound	Upper Bound
JUVORA	Optima	9.5366*	.59979	.000	8.0024	11.0708
	Co-Cr	10.6603*	.66094	.000	8.9764	12.3442
Optima	JUVORA	-9.5366-*	.59979	.000	-11.0708-	-8.0024-
	Co-Cr	1.1237	.66094	.266	-.5603-	2.8076
Co-Cr	JUVORA	-10.6603-*	.66094	.000	-12.3442-	-8.9764-
	Optima	-1.1237-	.66094	.266	-2.8076-	.5603

Based on observed means.

The error term is Mean Square(Error) = 1.799.

*. The mean difference is significant at the .05 level.

At 0.50mm

Initial 0.50mm

Between-Subjects Factors

		Value Label	N
Materials	1.00	JUVORA	10
	2.00	Optima	10
	3.00	Co-Cr	10

Descriptive Statistics

Dependent Variable: Initial0.50

Materials	Mean	Std. Deviation	N
JUVORA	35.6841	.88418	10
Optima	30.1880	1.46750	10
Co-Cr	27.9847	.54038	10
Total	31.2856	3.44174	30

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Initial0.50

F	df1	df2	Sig.
7.659	2	27	.002

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Materials

1. Grand Mean

Dependent Variable: Initial0.50

		95% Confidence Interval	
Mean	Std. Error	Lower Bound	Upper Bound
31.286	.189	30.897	31.674

2. Materials

Dependent Variable: Initial0.50

			95% Confidence Interval	
Materials	Mean	Std. Error	Lower Bound	Upper Bound
JUVORA	35.684	.328	35.011	36.357
Optima	30.188	.328	29.515	30.861
Co-Cr	27.985	.328	27.312	28.658

Multiple Comparisons

Dependent Variable: Initial0.50

Games-Howell

					95% Confidence Interval	
(I) Materials	(J) Materials	Mean Difference (I-J)	Std. Error	Sig.	Lower Bound	Upper Bound
JUVORA	Optima	5.4961*	.54179	.000	4.0865	6.9057
	Co-Cr	7.6994*	.32769	.000	6.8477	8.5512
Optima	JUVORA	-5.4961-*	.54179	.000	-6.9057-	-4.0865-
	Co-Cr	2.2033*	.49453	.002	.8745	3.5321
Co-Cr	JUVORA	-7.6994-*	.32769	.000	-8.5512-	-6.8477-
	Optima	-2.2033-*	.49453	.002	-3.5321-	-.8745-

Based on observed means.

The error term is Mean Square(Error) = 1.076.

*. The mean difference is significant at the .05 level.

1st Year 0.50mm

Between-Subjects Factors

		Value Label	N
Materials	1.00	JUVORA	10
	2.00	Optima	10
	3.00	Co-Cr	10

Descriptive Statistics

Dependent Variable: FirstY0.50

Materials	Mean	Std. Deviation	N
JUVORA	33.5945	.65779	10
Optima	28.8941	1.50874	10
Co-Cr	26.0767	.44236	10
Total	29.5218	3.29390	30

Levene's Test of Equality of Error Variances[a]

Dependent Variable: FirstY0.50

F	df1	df2	Sig.
21.626	2	27	.000

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Materials

1. Grand Mean

Dependent Variable: FirstY0.50

Mean	Std. Error	95% Confidence Interval	
		Lower Bound	Upper Bound
29.522	.180	29.153	29.890

2. Materials

Dependent Variable: FirstY0.50

Materials	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
JUVORA	33.595	.311	32.956	34.233
Optima	28.894	.311	28.256	29.533
Co-Cr	26.077	.311	25.438	26.715

Multiple Comparisons

Dependent Variable: FirstY0.50

Games-Howell

(I) Materials	(J) Materials	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
JUVORA	Optima	4.7004*	.52048	.000	3.3165	6.0844
	Co-Cr	7.5179*	.25067	.000	6.8701	8.1657
Optima	JUVORA	-4.7004-*	.52048	.000	-6.0844-	-3.3165-
	Co-Cr	2.8174*	.49719	.000	1.4658	4.1691
Co-Cr	JUVORA	-7.5179-*	.25067	.000	-8.1657-	-6.8701-
	Optima	-2.8174-*	.49719	.000	-4.1691-	-1.4658-

Based on observed means.

The error term is Mean Square(Error) = .968.

*. The mean difference is significant at the .05 level.

2nd Year 0.50mm

Between-Subjects Factors

		Value Label	N
Materials	1.00	JUVORA	10
	2.00	Optima	10
	3.00	Co-Cr	8

Descriptive Statistics

Dependent Variable: SecondY0.50

Materials	Mean	Std. Deviation	N
JUVORA	32.2416	.96073	10
Optima	26.8410	.84475	10
Co-Cr	22.3728	1.09344	8
Total	27.4932	4.13913	28

Levene's Test of Equality of Error Variances[a]

Dependent Variable: SecondY0.50

F	df1	df2	Sig.
.020	2	25	.980

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Materials

1. Grand Mean

Dependent Variable: SecondY0.50

		95% Confidence Interval	
Mean	Std. Error	Lower Bound	Upper Bound
27.152	.183	26.776	27.528

2. Materials

Dependent Variable: SecondY0.50

			95% Confidence Interval	
Materials	Mean	Std. Error	Lower Bound	Upper Bound
JUVORA	32.242	.304	31.616	32.868
Optima	26.841	.304	26.215	27.467
Co-Cr	22.373	.340	21.673	23.073

Multiple Comparisons

Dependent Variable: SecondY0.50

Gabriel

					95% Confidence Interval	
(I) Materials	(J) Materials	Mean Difference (I-J)	Std. Error	Sig.	Lower Bound	Upper Bound
JUVORA	Optima	5.4006*	.42987	.000	4.3041	6.4970
	Co-Cr	9.8688*	.45595	.000	8.7076	11.0300
Optima	JUVORA	-5.4006-*	.42987	.000	-6.4970-	-4.3041-
	Co-Cr	4.4683*	.45595	.000	3.3071	5.6295
Co-Cr	JUVORA	-9.8688-*	.45595	.000	-11.0300-	-8.7076-
	Optima	-4.4683-*	.45595	.000	-5.6295-	-3.3071-

Based on observed means.

The error term is Mean Square(Error) = .924.

*. The mean difference is significant at the .05 level.

3rd Year 0.50mm

Between-Subjects Factors

		Value Label	N
Materials	1.00	JUVORA	10
	2.00	Optima	10
	3.00	Co-Cr	5

Descriptive Statistics

Dependent Variable: ThirdY0.50

Materials	Mean	Std. Deviation	N
JUVORA	30.5000	.85176	10
Optima	24.8249	.92336	10
Co-Cr	17.3719	.38485	5
Total	25.6043	4.99755	25

Levene's Test of Equality of Error Variances[a]

Dependent Variable: ThirdY0.50

F	df1	df2	Sig.
1.499	2	22	.245

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Materials

1. Grand Mean

Dependent Variable: ThirdY0.50

Mean	Std. Error	95% Confidence Interval	
		Lower Bound	Upper Bound
24.232	.173	23.874	24.591

2. Materials

Dependent Variable: ThirdY0.50

Materials	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
JUVORA	30.500	.259	29.962	31.038
Optima	24.825	.259	24.287	25.363
Co-Cr	17.372	.367	16.611	18.132

Multiple Comparisons

Dependent Variable: ThirdY0.50

Hochberg

(I) Materials	(J) Materials	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
JUVORA	Optima	5.6751*	.36675	.000	4.7310	6.6192
	Co-Cr	13.1281*	.44917	.000	11.9718	14.2844
Optima	JUVORA	-5.6751-*	.36675	.000	-6.6192-	-4.7310-
	Co-Cr	7.4530*	.44917	.000	6.2968	8.6093
Co-Cr	JUVORA	-13.1281-*	.44917	.000	-14.2844-	-11.9718-
	Optima	-7.4530-*	.44917	.000	-8.6093-	-6.2968-

Based on observed means.

The error term is Mean Square(Error) = .673.

*. The mean difference is significant at the .05 level.

At 0.75mm

Initial 0.75mm

Between-Subjects Factors

		Value Label	N
Materials	1.00	JUVORA	10
	2.00	Optima	10
	3.00	Co-Cr	10

Descriptive Statistics

Dependent Variable: Initial0.75

Materials	Mean	Std. Deviation	N
JUVORA	45.2828	2.12484	10
Optima	34.9931	1.51347	10
Co-Cr	34.1857	.83828	10
Total	38.1538	5.36001	30

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Initial0.75

F	df1	df2	Sig.
3.777	2	27	.036

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Materials

1. Grand Mean

Dependent Variable: Initial0.75

Mean	Std. Error	95% Confidence Interval	
		Lower Bound	Upper Bound
38.154	.289	37.561	38.746

2. Materials

Dependent Variable: Initial0.75

Materials	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
JUVORA	45.283	.500	44.256	46.309
Optima	34.993	.500	33.967	36.020
Co-Cr	34.186	.500	33.159	35.212

Multiple Comparisons

Dependent Variable: Initial0.75

Games-Howell

(I) Materials	(J) Materials	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
JUVORA	Optima	10.2897*	.82496	.000	8.1645	12.4150
	Co-Cr	11.0971*	.72233	.000	9.1642	13.0301
Optima	JUVORA	-10.2897-*	.82496	.000	-12.4150-	-8.1645-
	Co-Cr	.8074	.54711	.332	-.6240-	2.2388
Co-Cr	JUVORA	-11.0971-*	.72233	.000	-13.0301-	-9.1642-
	Optima	-.8074-	.54711	.332	-2.2388-	.6240

Based on observed means.

The error term is Mean Square(Error) = 2.503.

*. The mean difference is significant at the .05 level.

1st Year 0.75mm

Between-Subjects Factors

		Value Label	N
Materials	1.00	JUVORA	10
	2.00	Optima	10
	3.00	Co-Cr	10

Descriptive Statistics

Dependent Variable: FirstY0.75

Materials	Mean	Std. Deviation	N
JUVORA	42.6269	1.63633	10
Optima	33.3189	1.62436	10
Co-Cr	30.8031	.93348	10
Total	35.5830	5.35495	30

Levene's Test of Equality of Error Variances[a]

Dependent Variable: FirstY0.75

F	df1	df2	Sig.
2.138	2	27	.137

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Materials

1. Grand Mean

Dependent Variable: FirstY0.75

		95% Confidence Interval	
Mean	Std. Error	Lower Bound	Upper Bound
35.583	.262	35.045	36.121

2. Materials

Dependent Variable: FirstY0.75

			95% Confidence Interval	
Materials	Mean	Std. Error	Lower Bound	Upper Bound
JUVORA	42.627	.454	41.695	43.559
Optima	33.319	.454	32.387	34.251
Co-Cr	30.803	.454	29.871	31.735

Multiple Comparisons

Dependent Variable: FirstY0.75

Bonferroni

		Mean Difference			95% Confidence Interval	
(I) Materials	(J) Materials	(I-J)	Std. Error	Sig.	Lower Bound	Upper Bound
JUVORA	Optima	9.3080*	.64226	.000	7.6687	10.9474
	Co-Cr	11.8238*	.64226	.000	10.1845	13.4632
Optima	JUVORA	-9.3080-*	.64226	.000	-10.9474-	-7.6687-
	Co-Cr	2.5158*	.64226	.002	.8765	4.1552
Co-Cr	JUVORA	-11.8238-*	.64226	.000	-13.4632-	-10.1845-
	Optima	-2.5158-*	.64226	.002	-4.1552-	-.8765-

Based on observed means.

The error term is Mean Square(Error) = 2.063.

*. The mean difference is significant at the .05 level.

2nd Year 0.75mm

Between-Subjects Factors

		Value Label	N
Materials	1.00	JUVORA	10
	2.00	Optima	10
	3.00	Co-Cr	5

Descriptive Statistics

Dependent Variable: SecondY0.75

Materials	Mean	Std. Deviation	N
JUVORA	40.4198	1.72400	10
Optima	31.0034	1.75139	10
Co-Cr	26.0094	.99379	5
Total	33.7711	6.04901	25

Levene's Test of Equality of Error Variances[a]

Dependent Variable: SecondY0.75

F	df1	df2	Sig.
.720	2	22	.498

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Materials

1. Grand Mean

Dependent Variable: SecondY0.75

		95% Confidence Interval	
Mean	Std. Error	Lower Bound	Upper Bound
32.478	.343	31.766	33.189

2. Materials

Dependent Variable: SecondY0.75

			95% Confidence Interval	
Materials	Mean	Std. Error	Lower Bound	Upper Bound
JUVORA	40.420	.515	39.352	41.487
Optima	31.003	.515	29.936	32.071
Co-Cr	26.009	.728	24.500	27.519

Multiple Comparisons

Dependent Variable: SecondY0.75

Hochberg

					95% Confidence Interval	
(I) Materials	(J) Materials	Mean Difference (I-J)	Std. Error	Sig.	Lower Bound	Upper Bound
JUVORA	Optima	9.4164*	.72805	.000	7.5422	11.2906
	Co-Cr	14.4103*	.89168	.000	12.1149	16.7057
Optima	JUVORA	-9.4164-*	.72805	.000	-11.2906-	-7.5422-
	Co-Cr	4.9939*	.89168	.000	2.6985	7.2893
Co-Cr	JUVORA	-14.4103-*	.89168	.000	-16.7057-	-12.1149-
	Optima	-4.9939-*	.89168	.000	-7.2893-	-2.6985-

Based on observed means.

The error term is Mean Square(Error) = 2.650.

*. The mean difference is significant at the .05 level.

3rd Year 0.75mm

Between-Subjects Factors

		Value Label	N
Materials	1.00	JUVORA	10
	2.00	Optima	10
	3.00	Co-Cr	3

Descriptive Statistics

Dependent Variable: ThirdY0.75

Materials	Mean	Std. Deviation	N
JUVORA	37.8098	2.10180	10
Optima	28.3048	1.96383	10
Co-Cr	20.4223	1.27062	3
Total	31.4093	6.55701	23

Levene's Test of Equality of Error Variances[a]

Dependent Variable: ThirdY0.75

F	df1	df2	Sig.
.769	2	20	.477

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Materials

1. Grand Mean

Dependent Variable: ThirdY0.75

Mean	Std. Error	95% Confidence Interval	
		Lower Bound	Upper Bound
28.846	.480	27.845	29.847

2. Materials

Dependent Variable: ThirdY0.75

Materials	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
JUVORA	37.810	.623	36.510	39.110
Optima	28.305	.623	27.005	29.605
Co-Cr	20.422	1.138	18.049	22.796

Multiple Comparisons

Dependent Variable: ThirdY0.75

Hochberg

(I) Materials	(J) Materials	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
JUVORA	Optima	9.5050*	.88146	.000	7.2184	11.7916
	Co-Cr	17.3874*	1.29747	.000	14.0216	20.7533
Optima	JUVORA	-9.5050-*	.88146	.000	-11.7916-	-7.2184-
	Co-Cr	7.8825*	1.29747	.000	4.5167	11.2483
Co-Cr	JUVORA	-17.3874-*	1.29747	.000	-20.7533-	-14.0216-
	Optima	-7.8825-*	1.29747	.000	-11.2483-	-4.5167-

Based on observed means.

The error term is Mean Square(Error) = 3.885.

*. The mean difference is significant at the .05 level.