The University Of Sheffield.

Investigating The Potential for the use of Ultrasound for the Measurement of Tooth Wear

A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

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Summary

Tooth wear is one of the major dental problems that patients encounter, and it is a growing condition that is becoming increasingly vital to the long-term health of the oral cavity and the general well-being of those who suffer its effects. Therefore, it is of paramount importance that early diagnosis and a tooth wear monitoring process are established, along with other preventative approaches where necessary. The current techniques used to monitor tooth wear in dental practise are subjective and unreliable. Most laboratory-based monitoring methods are time-consuming and costly. Also, in most cases, tooth wear defects require repair and restoration to restore the function and appearance of the dentition to a healthy state. The success of any dental restoration depends on different factors, most importantly the use of cement to bind the restorative material to the remaining tooth structure. Adding this cement creates an additional interface layer, which affects the structural integrity of the overall restoration. Measuring this interface is considered one of the essential factors in determining the success of repairs. Although different methods are implemented for measuring the interface, destructive methods such as sectioning and replica techniques still produce inaccurate results. Ultrasound is a non-invasive, non-destructive method that is mainly used in the medical field. Its use in dentistry started in the 1950s, but is still limited to laboratory applications. Nevertheless, it has demonstrated possibilities for detecting problems in dentistry that can be further investigated to aid in monitoring tooth wear. Ultrasonic techniques were applied to simple specimens, and teeth and validations were obtained by a digital caliper and a digital microscope, respectively. A fatigue-simulation rig has been introduced to create damage on specimens as well, ultrasonic signals showed variations before and after the damage initiated. An agreement of 74% between ultrasonic measurements of enamel thickness and the digital microscope was highlighted. This study concluded that ultrasound methods were able to evaluate thickness measurements, therefore any loss or changes in size for simple samples, as well as identify changes that occur in materials when cyclic impact loads are applied.

Acknowledgments

I am deeply grateful to many people who have made this dissertation possible and because of whom my graduate experience has been one that I will appreciate forever. Foremost, I would like to express my sincere gratitude to my supervisors, Prof Roger Lewis and Prof Inna Gitman, for their continuous support throughout my Ph.D. study and research and for their patience, motivation, and immense knowledge. Their guidance helped me throughout the years in terms of discussion advice and valuable feedback to finish my thesis. I could not have imagined having well-organized, motivated, and helpful supervisors and mentors for my Ph.D. journey.

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Terminology and Abbreviations

Term	Abbreviation	Definition
The maxilla		The upper jawbone, fixed, forming the upper part of the skull. It contains the sockets where the upper teeth are attached.
The mandible		The lower jawbone, movable, forming the lower part of the skull. It holds the lower teeth and is connected to the skull via the temporomandibular joint.
Temporomandibular joint	**TMJ**	The joint that connects the mandible (lower jaw) to the skull. It allows for movement of the jaw, such as opening and closing the mouth, chewing, and speaking.
Direct restoration		A dental filling procedure performed directly in the dental clinic. The dentist places the filling material directly into the prepared cavity in the tooth during the same appointment.
Indirect restoration		A dental restoration procedure where the tooth preparation is done in the dental clinic, but the actual restoration (e.g., crown, veneer) is fabricated in a dental laboratory. The fabricated restoration is then cemented or bonded to the tooth during a subsequent appointment.
Recurrent caries		Also known as secondary or recurrent decay, refers to tooth decay that occurs beneath or around an existing dental restoration, such as a filling or crown. It often happens when the margin or edges of the restoration become compromised or when oral hygiene is insufficient, allowing bacteria to infiltrate and cause new decay. Regular dental examinations are important to detect and address recurrent caries early.

Caliper device		A measuring tool used to measure distances or dimensions accurately. It typically consists of two hinged legs with a scale or digital display to provide measurements.
Piezo Electric Transducer probe	**PTZ probe**	A sensor or transducer that utilizes the piezoelectric effect to convert electrical energy into mechanical vibrations and vice versa. Commonly used in ultrasonic testing for applications such as flaw detection, thickness measurement, and material characterization.
Poly methyl methacrylate	**PMMA**	A synthetic polymer commonly known as acrylic, widely used in dentistry for applications including denture fabrication, temporary crowns, and dental restorations.
Speed of Sound	**SOS**	Refers to the velocity at which sound waves propagate through a medium. In dentistry, it can be measured to assess the integrity or quality of dental materials or structures.
Time of Flight	**TOF**	A technique used to measure the time it takes for a signal or wave to travel a distance. In dentistry, TOF can be used to measure the time it takes for an ultrasonic wave to travel through a tooth or dental structure, providing information about its properties or conditions.
Tooth Surface Loss	**TSL**	Refers to the loss of dental hard tissue (enamel and dentin) due to various factors such as erosion, abrasion, or attrition. Often used to describe the wear or damage that occurs to teeth over time.

Chapter 1: Introduction

2.1 Background

Human teeth are vulnerable to a variety of defects, including trauma, dental caries, developmental abnormalities, and tooth wear. Of particular concern is tooth surface loss (TSL), a gradual erosion of the enamel surface that not only impacts dental function but also compromises the overall appearance and health of the patient. In many cases, dental repair becomes necessary to address these defects, involving the placement of restorative materials that are cemented into the remaining tooth structure. However, the introduction of dental restorations can lead to alterations in the physical and mechanical properties of the tooth structure itself. This can lead to a mismatch in elasticity, hardness, and thermal expansion between the restoration and the natural tooth, which may cause stress concentrations and potential failure points over time. These changes are due to different factors which mainly the way forces are distributed across a tooth during biting and chewing. As improper design or placement of the restorative material can result in uneven stress distribution, leading to wear, cracks, or fractures in the tooth or the restoration. Also, when removing a portion of the natural tooth structure. This reduction can compromise the tooth's integrity and strength, making it more susceptible to fractures and other forms of damage. The extent of preparation depends on the type and size of the restoration(1). These alterations can have a significant impact on the restored tooth's ability to withstand the forces exerted during chewing, as compared to an unrestored tooth. Consequently, additional stresses and strains may accumulate within the interface layer between the restoration and the tooth structure, potentially leading to failure of the restoration. Therefore, it is crucial to accurately measure and evaluate the interface of restored teeth to identify any issues within the cement and ensure the long-term success of the restoration.

2.2 Rationale

There is a growing interest in the field of dentistry to employ non-destructive clinical tools that can effectively monitor tooth wear and assess the integrity of restored teeth at the interface level. Ultrasound, which has been utilized in dentistry since the 1950s, offers a non-ionizing imaging technique that provides advantages over conventional imaging methods such as X-rays. The non-ionizing feature of ultrasound ensures patient safety and reduces potential health risks associated with repeated exposure to ionizing radiation. Ultrasound has demonstrated its potential in measuring the thickness of teeth, making it particularly valuable in detecting changes in enamel structure, such as those seen in TSL. Furthermore, ultrasound has the capability to detect and identify gaps or discrepancies in the interface geometry of dental restorations, thereby providing valuable insights into the overall quality and longevity of the restoration. By utilizing ultrasound techniques, clinicians and researchers can gain a deeper understanding of tooth wear and its impact on dental restorations, enabling them to make more informed decisions and develop better treatment strategies.

In conclusion, the evaluation of tooth wear using non-destructive ultrasound techniques is a crucial area of research in contemporary dentistry. TSL and its consequences on dental health underscore the importance of accurate measurement and assessment of the interface between dental restorations and tooth structure. Ultrasound imaging presents a promising avenue for addressing these challenges, offering a non-ionizing and effective tool for monitoring tooth wear, detecting changes in enamel structure, and identifying any issues within the interface geometry of dental restorations. By further exploring the potential of ultrasound in dental applications, researchers can contribute to enhanced clinical outcomes, improved patient care, and the advancement of dental practice as a whole.

2.3 Aim and Objectives

The primary aim of this research is to develop and implement an ultrasonic approach for the analysis and detection of (TSL) and interface changes in restored teeth. This study seeks to advance our understanding of tooth wear by utilizing ultrasound techniques in the field of dentistry.

1. Design and develop a specialized sensor package specifically tailored for assessing the interface in restored teeth.
2. Establish a robust and comprehensive test method, encompassing the design and implementation of an impact rig capable of simulating the occlusal forces experienced during chewing.

3. Fabricate simple specimens. Apply the developed ultrasonic tool to these specimens, conducting thorough measurements and analysis of ultrasonic signals to evaluate tooth wear and interface changes accurately.
4. Generate empirical evidence to assess the performance, reliability, and effectiveness of the ultrasonic approach in detecting tooth thickness.
5. Develop a dedicated test methodology specifically tailored for bovine teeth, including the development of a methodology to simulate and impose controlled damage to mimic tooth wear conditions.

By achieving these objectives, this research aims to contribute to the advancement of non-destructive evaluation methods in dentistry, providing valuable insights into tooth wear through the application of innovative ultrasound techniques. This would act as a proof concept of the possibility of developing ultrasonic diagnostic device.

2.4 Approach of the Work

The research conducted in this thesis, "Investigating the Potential for the use of Ultrasound for the Measurement of Tooth Wear," follows a systematic and rigorous approach to achieve the study objectives. This section outlines the general approach and methodology employed throughout the research process.

2.4.1 Literature Review:

The research begins with an extensive review of the current literature pertaining to tooth wear, dental restoration, ultrasound techniques in dentistry, and interface measurement methodologies. This review provides a comprehensive understanding of the existing knowledge and identifies gaps and limitations in previous studies. The review guides the development of the research methodology and ensures that the research is built upon a solid foundation.

2.4.2 Experimental Design:

The research methodology encompasses a combination of in vitro experiments to evaluate tooth wear and restoration integrity using ultrasound techniques. The experimental design is carefully planned to address each objective of the study.

Development of Sensor Package: A specialized sensor package is developed to assess the interface in restored teeth. The sensor package is designed and refined iteratively, considering factors such as sensor placement, geometry, and detection of air gaps within the interface. Prototyping and testing of the sensor pack are conducted to ensure its reliability and effectiveness.

Test Method Development: A comprehensive test method is developed to simulate occlusal forces and evaluate tooth wear and interface changes. This includes the design and implementation of an impact rig capable of replicating chewing forces. Simple specimens, following the full-tooth model with a repair, are manufactured for controlled testing of the ultrasonic tool. The ultrasonic approach is applied to these specimens, and measurements are taken to analyse tooth wear and interface changes. Additionally, a sectioning approach is developed as a validation method to compare the ultrasonic measurements with direct physical observations.

Experimental Testing and Analysis: A series of experiments is designed and executed to evaluate various variables, starting with the simple tooth model and progressing to the fully repaired tooth model. The ultrasonic approach is applied, and data is collected to study tooth wear progression and interface changes. The specimens are subsequently sectioned to generate validation evidence, allowing for the correlation and verification of the ultrasonic measurements.

2.4.3 Testing on Different Specimens:

The research extends to testing on different specimens to enhance the applicability of the findings.

Bovine Teeth: A dedicated test method is developed for bovine teeth, which includes methodologies to simulate and impose controlled damage similar to tooth wear conditions. A specialized sensor probe is designed and fabricated specifically for bovine teeth to enable accurate assessment using the ultrasonic technique. The developed ultrasonic approach is further tested on real human teeth. The results obtained from ultrasonic measurements are linked with the validation evidence obtained through sectioning techniques, providing insights into the accuracy, reliability, and clinical effectiveness of the ultrasonic technique in detecting and assessing tooth wear and interface changes in a real-life clinical setting.

2.4.4 Data Analysis and Interpretation:

The data collected from the experiments are meticulously analysed and interpreted. Statistical analysis and qualitative assessments are employed to extract meaningful insights from the results. The findings are then discussed in the context of the existing literature, addressing the research objectives and contributing to the overall understanding of tooth wear and restoration integrity.

In conclusion, this research adopts a systematic and comprehensive approach to evaluate tooth wear and teeth restoration using ultrasound techniques. The methodology encompasses a literature review, experimental design, sensor package development, test method development, experimental testing and analysis, and testing on different specimens. By adhering to this approach, this study aims to provide valuable insights into the assessment of tooth wear and restoration integrity, contributing to advancements in non-destructive evaluation methods in dentistry.

2.5 Novelty and Impact

The thesis " Investigating the Potential for the use of Ultrasound for the Measurement of Tooth Wear" introduces a novel approach to the assessment of tooth wear and restoration integrity using ultrasound techniques as well as introduction of cyclic damage by the use of fatigue impact rig. This section highlights the unique contributions and potential impact of the research.

2.5.1 Novelty:

- **Ultrasonic Assessment of Tooth Wear:** The novelty of this thesis lies in the application of ultrasound techniques for evaluating tooth wear. While various imaging modalities have been used in dental practice, the utilization of ultrasound, particularly in the context of tooth wear, is relatively novel. The research explores the potential of ultrasound to assess enamel thickness, detect changes in enamel structure associated with tooth wear, and identify gaps or discrepancies within dental restorations. This innovative approach provides a non-destructive and radiation-free method for evaluating tooth wear and restoration integrity.
- **Interface Analysis:** Another novel aspect of this research is the focus on interface analysis in dental restorations. By developing a specialized sensor package and employing ultrasound techniques, the study enables the detection and characterization of air gaps within the interface between the restoration and the tooth structure. This capability contributes to the understanding of the quality and longevity of dental restorations, this was mainly introduced through the use of multiple layers of simple materials rather than a restorative materials of restored tooth geometry, offering insights into potential failure points and guiding

improvements in restoration techniques. As well as introducing the cyclic load applications to the specimen by using an impact fatigue rig.

2.5.2 Impact:

- **Advancement of Non-Destructive Evaluation Methods:** The thesis significantly advances the field of non-destructive evaluation methods in dentistry. By harnessing the potential of ultrasound techniques, the research provides dental practitioners with a valuable tool for assessing tooth wear and monitoring restoration integrity. The non-ionizing nature of ultrasound and its ability to measure enamel thickness and identify interface issues offer distinct advantages over traditional imaging techniques, such as X-rays. This research expands the repertoire of non-destructive evaluation methods available to dentists, enhancing their ability to diagnose and address tooth wear and restoration-related concerns.
- **Improved Clinical Decision-Making:** The findings of this research have the potential to impact clinical decision-making in the field of dentistry. By incorporating ultrasound assessment into routine dental practice, clinicians can obtain more comprehensive information about tooth wear and restoration quality. This, in turn, facilitates informed decision-making regarding treatment planning, restoration placement, and monitoring of restoration longevity. The ability to detect and address interface issues at an early stage can lead to improved patient outcomes, reduced restoration failures, and enhanced patient satisfaction.
- **Enhanced Patient Care:** The research outcomes have implications for patient care and oral health management. Accurate assessment of tooth wear and restoration integrity using ultrasound techniques allows for timely interventions and preventive measures. Early detection of tooth wear and identification of potential restoration issues enable dentists to provide targeted treatments, preserve natural tooth structure, and optimize the longevity of restorations. This contributes to improved patient oral health, reduced treatment costs, and enhanced patient satisfaction.

In conclusion, the thesis on " Investigating the Potential for the use of Ultrasound for the Measurement of Tooth Wear" introduces a novel approach that combines ultrasound assessment and interface analysis for evaluating tooth wear and restoration integrity. The research significantly advances non-destructive evaluation methods in dentistry, provides valuable insights into tooth wear progression, and guides improved clinical decision-making. The impact of this research extends to enhanced patient care, improved treatment outcomes, and the potential for reducing restoration failures. By introducing this innovative approach, the thesis contributes to the advancement of dental practice and the broader field of non-destructive evaluation methods in healthcare.

2.6 The Structure of the Thesis

The structure of the thesis, "Investigating the Potential for the use of Ultrasound for the Measurement of Tooth Wear," is organized into several chapters to provide a comprehensive examination of the research. The following outlines the structure of the thesis:

Chapter 1 Introduction which serves as an introduction to the thesis, presenting an overview of the research topic and outlining its significance. It provides a clear statement of the research problem, objectives, and research questions. Additionally, this chapter offers a brief introduction to the thesis structure, giving readers an overview of the subsequent chapters.

Chapter 2: Literature Review that is dedicated to a thorough literature review. It begins by providing a concise explanation of human tooth structures, specifically focusing on enamel and dentin. The chapter then delves into tooth wear degradation, discussing its definition, various types, and diagnostic techniques. Restoration and repair aspects in dentistry, including reasons for replacement and interface layer geometry, are explored. Furthermore, this chapter critically examines the utilization of ultrasound in dentistry, considering existing models and techniques. The literature review aims to establish a solid understanding of tooth wear, restoration, and the current methods employed to monitor tooth wear and interfaces. It also identifies gaps in the literature, providing a foundation for the research's future progression.

Chapter 3: Ultrasound Theory provides an overview of the fundamental theory and principles of ultrasound relevant to the research. It covers basic concepts, such as ultrasound properties, ultrasonic setups, methods, and transducers. This chapter serves as a theoretical background for understanding the ultrasound measurement techniques employed in the project.

Chapter 4: Ultrasonic Measurement Analysis for Simple Specimen Specifications focuses on the development of the ultrasonic measurement approach, specifically for simple teeth specimens. It describes the design of the specimens and outlines the ultrasonic technique used to test them. The chapter also addresses the selection and usage of ultrasonic sensors for rig specimens. Additionally, it includes ray tracing descriptions of actual teeth and factors influencing the tracing. The transducers utilized for simple specimen and tooth measurement and dental enamel measurements are also discussed in detail.

Chapter 5: Bovine Teeth Wear/Defects Measurement investigates the application of ultrasound to measure tooth wear and defects in bovine teeth. It introduces the necessary methods and techniques for conducting the measurements and provides insights into the sample preparations required. Furthermore, the validation of the results obtained through ultrasound measurements is introduced, involving digital microscope measurements.

Chapter 6: Impact Rig/Fatigue Machine explores the use of a fatigue simulating machine, specifically the impact rig, in the research. It provides a comprehensive description of the impact rig and establishes the test methodology incorporating ultrasonic measurements. This chapter also explains the design of the specimen required for interface and fatigue measurement, ensuring a thorough understanding of the experimental setup.

Chapter 7: General Discussion consists of a comprehensive discussion and conclusion. It provides an overall analysis and discussion of the project's findings, addressing the research objectives and answering the research questions. The chapter also highlights challenges encountered during the research process and offers recommendations for future studies.

Chapter 8: Conclusions summarizes the main findings and their implications, emphasizing the impact and significance of the research. Finally, the chapter concludes the thesis by providing a concise summary of the key findings and their broader implications.

By following this structured approach, the thesis ensures a systematic exploration of tooth wear and restoration assessment using ultrasound techniques, providing a comprehensive analysis of the research topic.

Chapter 2: Literature Review

3.1 Introduction

This chapter undertakes a comprehensive exploration of the prevailing review of the current literature related to the work to be conducted in this research. Commencing with a concise explanation of human tooth structures, including enamel and dentin, and then discusses tooth wear degradation, in terms of its definition, types, and diagnostic techniques. This section also discusses restoration and repair aspects in dentistry, reasons for replacement and interface layer geometry, finally considering ultrasound in dentistry and modelling. Overall, this literature review aims to understand tooth wear, repair, and highlight the current methods and techniques used to monitor tooth wear and interfaces. It further seeks to gather information on methods for future progression of this research, by investigating and comparing current practice in using ultrasound and identifying gaps in the literature concerning such practice.

3.2 Tooth Structure

Teeth are considered one of the most intricate structures within the human anatomy. They consist of three different tissues: dental enamel, underneath dentin and cementum, and are supported by another hard tissue and the bone as shown in Figure 2.1. Humans have two types of teeth during their lifetime; first, the primary, teeth emerge into the mouth from the age of about 6 months; these number 20 in total, 10 in the upper jaw (maxilla) and 10 in the lower (mandible). The second set of teeth are the permanent teeth, they number 32 in total, 16 in the top and 16 in the bottom jaw. Each tooth consists of a crown, containing a pulp chamber and one or more roots, which include the pulp canals. The outer layer of the crown is protected by the enamel, which is the strongest substance in the human body, supported underneath by dentin. In the premolar and molar teeth, the sides of the crown facing the cheeks are referred to as the buccal or facial surfaces Figure 2.1, whereas the surfaces of the incisors and canines facing the lips are called the labial surfaces. The surfaces of upper teeth facing the palate are called palatal surfaces, and surfaces of mandibular teeth facing the tongue are referred to as lingual. Finally, tooth surfaces facing an adjacent tooth in the same arch are referred to as proximal. Regarding these proximal surfaces, mesial is the term used to describe any surface toward midline facing the front part of the mouth, while distal is used to describe those away from the midline, facing the back part of the oral cavity.

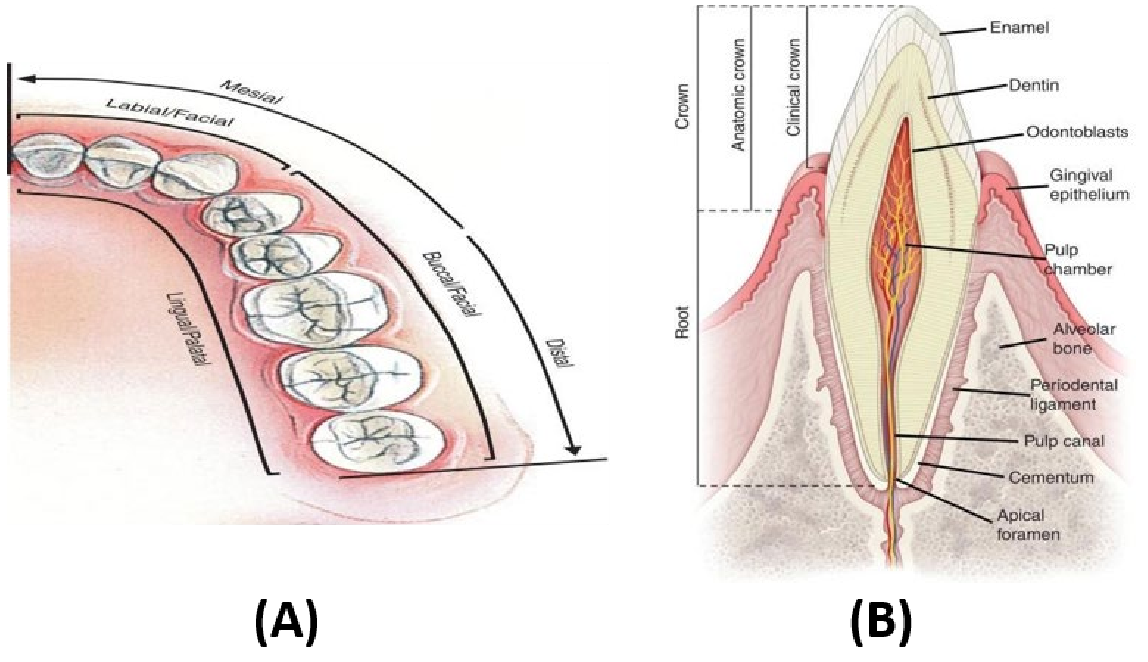

Figure 2.1 Direction of tooth surfaces in the mouth (A) Tooth structures (B) (2)(3)**.**

As mentioned earlier, enamel covers the crown of a tooth. It is highly mineralised hard tissue, generally appearing as white in colour. Although it is considered translucent, its colour is affected by underlying dentin or restorations. Enamel consists of rods or prisms of large, elongated crystals of mineral hydroxyapatite Figure 2.2. These rods spread from the dentin enamel junction (DEJ) toward tooth surface. Within the rods, these crystals are arranged parallel to the prisms. This pattern of enamel rods allows the load to pass within enamel structure toward dentin; hence, any stress distribution would follow the directions of these prisms. This feature of prism orientation is considered when applying ultrasound as the sound waves travel faster in rods that are parallel to each other. In addition, enamel is formed by ameloblast cells, which progress through numerous morphological changes. Once a tooth has erupted, these ameloblasts are lost; hence, if any damage occurs to the dental enamel, including wear, decay or cracks, it cannot regenerate again by itself.

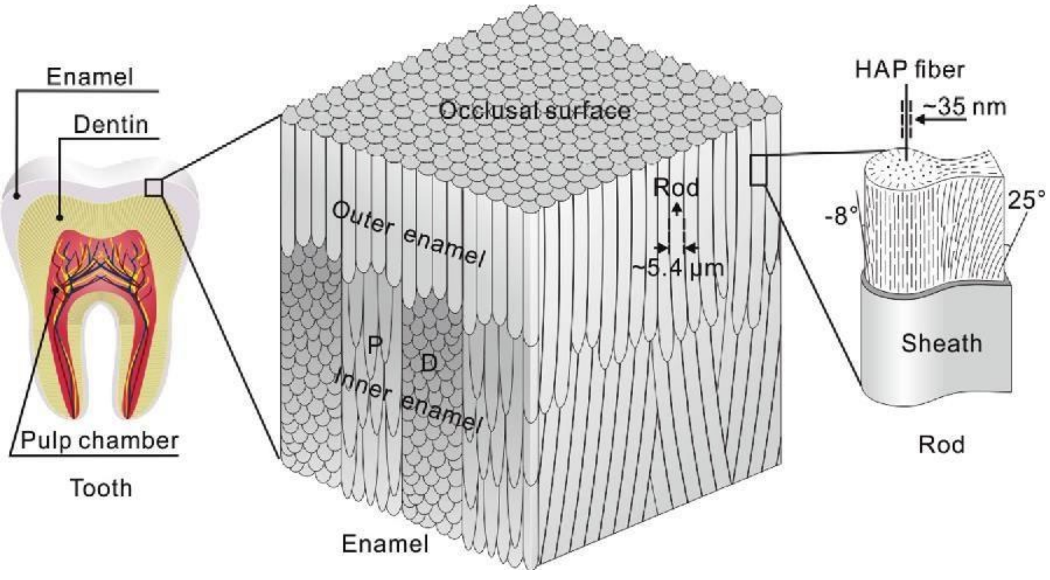

Figure 2.2 Diagram shows enamel rod prism orientation (4).

Dentin is the primary substance of the tooth, and contains a mineralised collagenous matrix produced by odontoblasts. Dentin is a living tissue because it derives from mesenchymal cells capable of repair and regeneration, unlike enamel, which is incapable of recovery or repair because it derives from non-living tissue. The temporomandibular joint (TMJ) also plays an important part in preserving the function of the oral cavity. This joint provides both translational and rotational movement of the mouth and thereby allows opening and closing of the mouth and movement of the mandible during chewing and speech. This joint is affected during dental wear, as the distance between opposing teeth is reduced therefore, oral health is compromise.

3.3 Tooth Wear/ Degradation

The four main conditions causing tooth structure loss are dental caries, trauma, developmental defects and tooth wear (5). Understanding the process of each situation enables clinicians to prevent or diagnose it and provide the necessary treatment and restoration techniques to patients. It is crucial to explain the differences between these conditions and the processes used to diagnose them.

Dental caries are considered the most common conditions affecting teeth (Figure 2.3). The formation process may take place in any tooth surface, including the roots. Its progression starts from bacterial plaque remaining in the oral cavity and becoming attached to tooth surfaces with the presence of nutrients. These nutrients metabolise to produce acid, which decreases the pH to below 5.0 to 5.5, causing demineralisation of enamel crystals and decay formation.

Diagnosis of this decay requires assessing the patient's history, visual examination inside the mouth, vitality tests to determine whether the tooth is still alive or not, and radiographs when needed. It may be necessary to use some or all of these diagnostic tools for each dental caries scenario. However, it is challenging to detect a decays spots on proximal surfaces as adjacent teeth obscure vision. Hence, a diagnostic radiograph cannot show the exact extent of decays, but can aid in estimation of the defect (Figure 2.4).

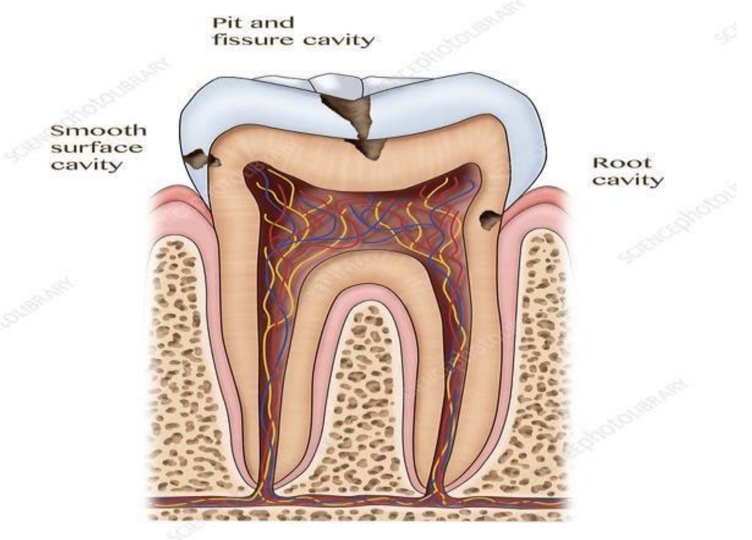

Figure 2.3 Dental caries (1).

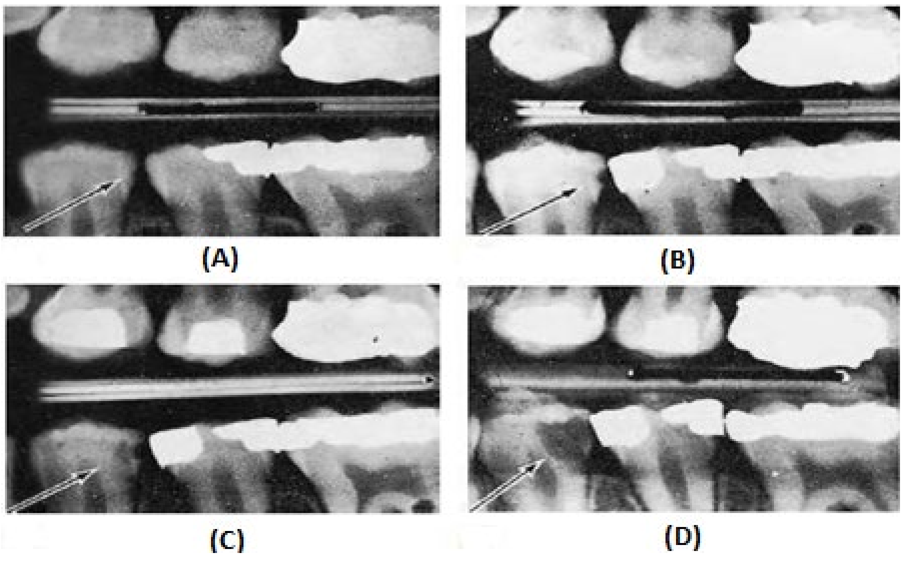

Figure 2.4 Radiographs recording the progress of a proximal decay on the distal part of a patient's. (A) Initial enamel decay (B) after 9 months (C) after a year, extended decay (D) 2 year later large black area of decay (6)***.***

Dental trauma refers to tooth injuries varying from enamel fracture only to the involvement of dentin and pulp, which require immediate treatment. Injuries due to trauma include gum, tongue and lips, and more complicated breaks to surrounding bone. Also, it could lead to a complete displacement of a tooth from its socket. To diagnose a dental injury, thorough knowledge of the patient's dental history, examinations, assessment of the vitality of the teeth, and radiographs are essential.

Developmental defects refer to teeth which do not develop normally, regarding tooth structure or shape. For example, any damage to the ameloblast cells due to infection during childhood may result in enamel hypoplasia. This makes teeth more prone to excessive tooth wear compared to teeth that developed normally. Also, some hereditary conditions causing defects in tooth shape, number, structure and size.

Tooth wear is one of the most common complaints affecting teeth that regularly requires management from clinician. This sort of wear can be just a natural physiological process, which in most patients may not necessitate treatment. Whereas with diseased tooth wear, the severity of damage is apparent and causes trouble to patients who then require dental care. Injuries from tooth wear can vary from slight sensitivity due to an abrasion injury to massive damage to the all teeth. Also, management can vary from a single filling procedure to complete teeth restoration involving dentures or crowns. Tooth wear also defined as "the pathological non-carious loss of tooth tissue"(7). It is difficult to differentiate between normal and pathological wear, although the estimated average vertical damage of enamel from functional wear is thought to be almost 20-38 μm per year (8). Tooth wear is often multifactorial and can be subdivided into: Attrition, Dental Erosion, Dental Abrasion and Abfraction, the boundaries between these categories sometimes being indistinct. In general, these dental subdivisions can be defined in terms of engineering tribology. Table 2.1 shows the dental terms used and their equivalents in engineering tribology.

Table 2.1 Dental terms and their engineering equivalents (9)**.**

Dental term	***Tribology Term***	***Definition***
Attrition	*Adhesion* *Two-body abrasion*	*"*When teeth get into contact with each other without a third medium between them, two body wear, or attrition, is caused*"* (10)
Abrasion	*Three body abrasion Erosion*	*"*Chewing on food items or brushing teeth with a toothbrush and toothpaste results in three-body wear, or abrasive wear*"* (11)
Abfraction	*Fatigue wear*	Fatigue wear occurs when large portions of dental hard tissues or restorative material chip off. If this occurs on the cervical part of the tooth, the term abfraction is used(10)
Erosion	*Chemical wear/corrosion*	*"*The acidic attacks that cause loss of tooth substance are summarized as erosive wear, but the term corrosive wear would be more adequate here*"* (12)

3.3.1 Causes of Tooth Wear

Diagnosis of a tooth wear depends on how the defect appears in the mouth, which is divided into the previous terms mentioned. However, the causes of tooth wear in general are due to different factors working together Figure 2.5 that, reaching the diagnosis is more challenging. Thus, it is essential to acknowledge these factors, as treatment outcomes might otherwise be compromised.

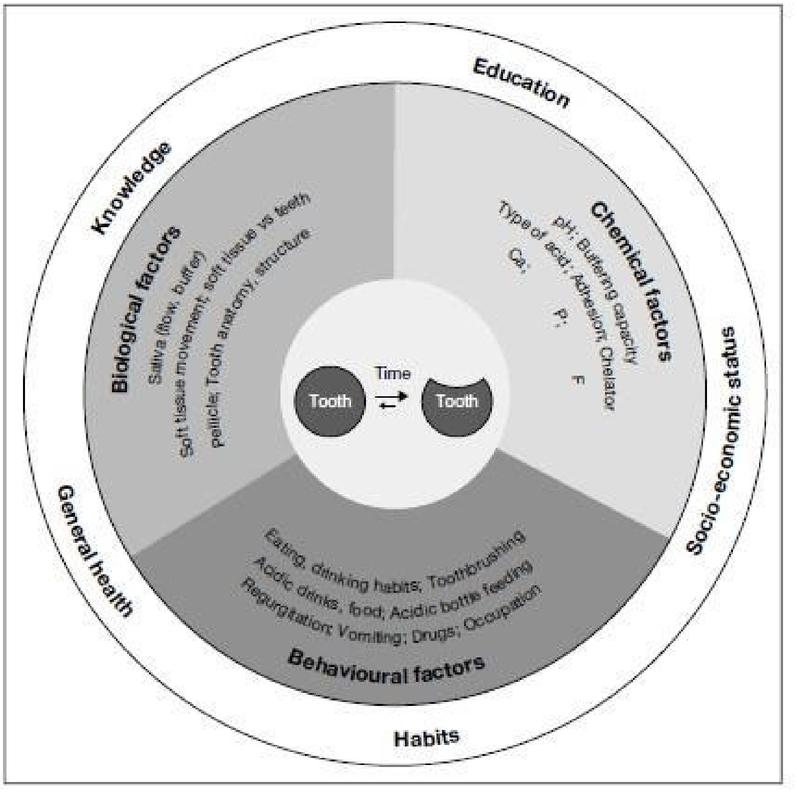

Figure 2.5 Illustration of different factors for erosive tooth wear (13).

Attrition: it has been noted that attrition accounts for half of the total causes of dental wear (14). Frequently, normal tooth wear that increases with age may become pathological once parafunctional habits are involved (15). Patients are most often not aware of these habits, which makes the diagnosis more variable. In addition, It has been reported only 50% of patient who suffer from parafunctional habit such bruxism, are aware of its presence in their mouth (16). Hence, the stated prevalence of bruxism differs between 5% and 96% (17). It is essential to mention that there are two causes of bruxism, the first being stress and the second being premature contacts of teeth on mandibular movement (18)(19).

Erosion: dental erosion occurs because of a decline in pH of the mouth beneath the critical pH, i.e. 5-5.5 (20). Dental erosion, divided into an intrinsic or an extrinsic type, based on the acidity of the causative agent (21). In addition, some diseases and medication used are thought to be a cause of erosion for example, asthmatic inhalers containing steroid, which, lead to a drop in the PH of the mouth, as well as, reduce saliva content in the mouth (22). Extensive use of acidic drinks and food also induces erosion (21). Acid exposure can also be found in the workplace; for example, wine tasting and manufacturing of battery acid can make workers susceptible to erosive tooth wear. On the other hand, intrinsic erosion might result from gastric content entering oral cavity and causing damage to the teeth (23).

Abfraction: Fatigue wear occurs when large portions of dental hard tissues or restorative material chip off. If this occurs on the cervical part of the tooth, the term abfraction is used (10).

Wear of natural or teeth that undergone restorations can result in three primary consequences: (24) aesthetic impacts that affect the appearance of the teeth, in cases of severe wear, irritation of the inner part of the tooth (pulp) can occur, leading to hypersensitivity, infection of the pulp (pulpitis) , or even pulp exposure, and functional effects that alter the relationship between the tooth and its antagonist or adjacent teeth, causing issues such as elongation of opposing teeth, tooth movement, or a reduction in vertical height, which can impact the (TMJ) (25). A clinical study in the UK involving 290 patients referred to a dental clinic for severe tooth wear found that aesthetic concerns were the most common complaint (59%), followed by tooth hypersensitivity (40%). Patients without molar support experienced significantly more severe wear in the premolar and anterior regions, and severe tooth wear was more than twice as prevalent in males compared to females (10). Another study on 1007 individuals in southeast England revealed that the percentage of excessive wear on natural teeth varied between 3% and 9% of all tooth surfaces, depending on age group.

Wear particles from restorative materials can have biological and toxicological effects if swallowed or inhaled. Components like copper, zinc, and mercury can be released from amalgams during chewing (26). However, clinical wear rates indicate that the amounts of dissolved zinc and copper are minimal over time, and mercury release due to abrasion is clinically insignificant, even in patients who have bruxism. Noble gold-based dental alloys and ceramics exhibit low wear and are considered relatively inert, though some particles may still be swallowed. Alloys containing nickel, chromium, and beryllium have higher allergic and mutagenic potential. Resin-based composites raise concerns due to the potential leaching of (co)monomers and the wear of micro- and nano-sized filler particles, which may be ingested or inhaled and accumulate in tissues, potentially causing diseases of the liver, kidney, lung, and intestines. The dust created during the grinding and polishing of resin composite fillings is in the micrometre and sub-micrometre range, with 75% of particles being smaller than 2.5 µm. To minimize inhalation of these particles, efficient suction systems, water spray, and protective masks should be used during these procedures (12). However, ingestion of particles due to wear cannot be completely avoided. Diagnosis of wear in teeth clinically remain crucial, as the appearance varies due to different factors. A recent study (27) compared intraoral photograph of teeth wear and digitally (Figure 2.6) concluded that assessment of tooth wear on digital models showed fair to moderate agreement with in vivo assessments.

Figure 2.6 A comparison of intraoral photograph of teeth wear and digitally (27).

3.4 Evaluation of Tooth Wear

3.4.1 In Vivo Techniques

To diagnose dental wear, finding the cause is essential. Due to the different factors involvement in causing, tooth wear appearance varies. Patients in the early phases of the development of wear often are not aware of their condition. However, if the problems become severe, often patients seek dental treatment complaining of poor teeth aesthetics, as their teeth become shorter. Evaluation of tooth wear in a dental practice starts with an assessment of the TMJ whether a pain exists or any clicking sound should be recorded. A full intraoral examination is also conducted. Furthermore, measuring and monitoring tooth wear in clinical practice is challenging, despite the use of a variety of indices for this purpose, for example, the Basic Erosive Wear Examination (BEWE) (28) and Tooth Wear Index (TWI) (14).

These indices can only provide the clinician with in vivo occurrence of wear at the time of checking, whereas consistent natural reference points are needed for continuousness. Additionally, most of these guides depend on visual monitoring which is subjective from dentist to another. Moreover, the availability of numerous different indices guides leads to different opinion and data comparisons become more challenging (29). The TWI is a broad index where, all surfaces of teeth are recorded based on amount of enamel loss, state of dentine loss and any changes surface shape (14). Meanwhile, the BEWE is a limited scoring indices that only score the highest surface affected in a tooth for each sextant. In addition, replica casts, photographs of the teeth, reviewing personal habits, diet analysis, and tooth brushing techniques are ways done to monitor and treat the progress of wear.

3.4.2 In vitro Techniques

Some techniques reported in the literature as methods for monitoring or measuring the tooth wear are summarised below. However, none of these methods are currently applied in dental practice. Polarised Light Microscopy: is often used to detect crystal deviations in specimen’s cross-sections of erosion, allowing measurement of affected areas in small segments. In worn dentine, PLM can distinguish between initial and full dentin erosion. Non-Contact Confocal Laser Scanning Microscopy (CLSM) has the improvement of recording of surface in high resolution. However, it is mainly used to gather qualitative data. Another tool is called Surface profilometry which, measures any losses of enamel along the surface of untreated areas and has the ability to detect any rough surfaces. However, this measurement is only feasible during the initial stages of wear. In addition, a three-dimensional image can be produced when required. There are two types of profilometry: contact and non-contact. The former can give deep penetration on the surface to be measured, however, this would establish more damage hence, overestimation of the measurements. In contrast, for non-contact profilometry, the laser does not have this issue as there is no direct involvement on the surface. Another diagnostic tool in vitro research called a Scanning Acoustic Microscope(SAM), this can be used for both research and as a diagnostic tool. SAM is non-destructive method for evaluation tooth structure in case of dental wear. Iodide Permeability Test (IPT): the idea behind this method is using potassium iodide as a soaking element where sections of enamel are used in for few minutes, this iodide then measured from enamel by using pre-filter papers disc. An estimation of enamel pores, and initial wear stages can be obtained however, this is only in-vitro research.

3.5 Repairing and Restoring Tooth Integrity

Dental repair is usually required when teeth defects occur, and these defects could be due to developmental issues affecting the teeth, dental decay, wear, or dental trauma. Such repair affects the shape and structure of the remaining tooth structure. In an undamaged tooth, the enamel structure exhibits a perfect bonding to the dentine, but once the tooth is damaged a restoration is required. This causes a slight separation between enamel and dentin compared to an intact tooth, if the tooth is fully restored, and an additional layer of cement is added, this could contribute to the separation of the bond as well. In the case of such a change the tooth restoration becomes subject to a different load during mastication, that of an unrestored tooth, which provides an increase to changes in the pattern of stress distribution among the tooth and the restoration (30). Various factors are essential to consider in maintaining the restoration in its place, including accurate fitting of the restoration material and adaptation to the remaining tooth structure. The most important requirement is to have a uniform layer of cement and tooth structure (31), as unevenness of the cement layer contributes to additional stress and reduces its adherence to the tooth structure (32). Hence, this affects both the surface bonded to the tooth and the structural integrity of the tooth, which is why measuring this interface is necessary in determining the success of the overall restoration.

Different techniques are used in measuring the interface, including tooth sectioning, replica technique, and obtaining 3D images using CT scans. Additionally, ultrasound can be used to distinguish cement mismatch and de-bonding of replacement, more specifically when there is a gap. One study investigated the cement layer in a prepared specimen with 30 MHz transducers by a pulse-echo method in a tank of water. When the crowns had poor cement they were more 'echogenic' than a crown cemented well, this shows more reflection of the sound wave coming from cement that has a gap compared to well-sealed ones. When the adhesive cement used separate, micro-leakage and decay of the beneath tooth structure occur (33).

The above demonstrate the ability of ultrasound in detecting possible changes in the interface. These findings are important as the longevity and the success of any restoration depend strongly on the bond in the interface layer. Also, whenever a pulse of ultrasound is focused at an interface that has a weak bond, a very high amount of echo established from the cement area suggestion the interface is deboning (34). If the interface is well bonded, only small echoes will arise from the cement area because it becomes invisible to be detected. Therefore, it is essential to further evaluate the interface layer by using ultrasound, which is one of the main objectives of this study, by evaluating the combined specimens' reflections and identifying the differences in their signals.

3.5.1 Common Materials used in Restoration of Teeth

In restoration of teeth, a wide variety of materials are used to replace damaged tooth materials. These materials can be either metal only, such as gold, silver, cobalt, and titanium, or different ceramic forms, such as feldspathic, zirconia-based, lithium disilicate. While metallic materials offer strength and less of the tooth structure has to be removed, they give poor aesthetics, which tends to make them less preferable for patients. On the other hand, ceramic is a tooth-coloured restoration material that offers better aesthetics. Whilst improvements have been made in terms of its structure, it is still considered brittle and less ductile compared to metal restorations. It can however be constructed in a lab and then placed on the prepared tooth. Glass ceramic is a commonly used immaterial that can be etched and fixed to the prepared tooth with adhesive cement (35).

These materials exhibit different properties, and when selecting the appropriate material dentists should consider hardness, wear resistance, and fracture toughness for each chosen restoration material, as these properties are considered essential even in thin restorations (36). The fracture resistance of the ceramic, and its adhesion can be affected by the cement layer used and the preparation of tooth structures (37). Additionally, different techniques are used by dentists to restore damaged parts of teeth; for example, damage due to decay or fracture can be restored by direct filling with amalgam (silver filling) or composite resin (white filling). Other restorations may require full coverage using a dental cap on one tooth (crown), or multiple teeth (bridge), or implant replacement.

For each clinical scenario of restoring or replacing damaged teeth/missing teeth, different materials can be used, with various techniques. Some of these materials are attached to a tooth without an intermediate layer, e.g. amalgam; others require additional bonding or use of cement, e.g. ceramic, composite resin. Unlike natural teeth material, dental materials do not have an adaptive structure or self-organisation. The loss of restorations is common in dentistry (38). Therefore, it is essential to evaluate the interface between restoration and tooth, in order to detect any defects which already existing or about to start within the interface.

3.5.2 The Load Distribution on Teeth

Natural teeth are very complex, and enamel, being anisotropic, directs any load towards the dentin, and they both respond differently (39). Also, teeth are composed of various structures with different mechanical properties (40). During normal chewing normal load stress is distributed from the enamel through the dentin to the root and periodontal ligaments; however, once a tooth has been damaged and restored, the new complex restoration system tends to have a different distribution of load from an intact tooth. In this case, the load applied is a mixture of shear, compressive, and tensile stress, and within the interface, rather than just the compression stress on a normal tooth (41). As a result, the distribution of stress within an undamaged tooth structure is not the same as in the tooth which was restored (42).

Moreover, the cement used in the restored system is a significant part in the success of the replacement. Since an uneven thickness of the cement layer can disturb the tooth structural integrity, by altering the stress pattern and increasing shear stress to the extent that the strength of the bonding of the cement layer to the replacement and remaining tooth structure is compromised.

Additionally, once a tooth has been restored, changes in loading and thus stress to the remaining natural teeth occur, which then lead also to variations in the physical and mechanical properties of the repaired tooth. It has, furthermore, been stated that the stress in the enamel distributed toward the dentine because the stress follows the prisms of enamel, while within the isotropic structure of the restoration the load distribution is directed toward the cement and underlying tooth (43). The bonding between enamel and dentin in an undamaged tooth is strong, which is different in the restored tooth, where layer of cement is held between the restoration and dentin, leading to different stress distribution between restored and unrestored teeth (35).

3.5.3 Measuring the Restoration Interface

In dentistry, applying bonded interfaces between resin-based adhesives or composite and enamel/dentin are common procedures. Measurement of the mechanical properties of the resin-dentin interface has become an important research area in terms of determining the success of restorations.

A study conducted using nano-indentation of adult teeth to evaluate the elastic modulus and the hardness, revealed an expected transition from the higher modulus in dentin towards lower modulus, which is the layer called hybrid, then to the cement (44). Hardness had similar result route. Another study, conducted by Ryou, used a nano-dynamic mechanical study to present the hybrid layers are a different modulus because of the variations of properties between cement and dentin in the interface (38).

It has been noted that the main testing methods for the tooth-cement layer are the shear-bond, tensile, and micro-tensile bond methods Figure 2.7. In a micro-tensile test, the composite is bonded to an enamel surface, or dentin or within a prepared tooth hole, and to test in tension a separate stick samples are cut to produce a bonded interface (39). Also, through fatigue load cycling, Dong was able to produce crack propagation across the dentin-enamel junction (40). However, the reported limitations of mechanical testing, including its destructiveness and the variations in tooth forms render it suitable only for in vitro.

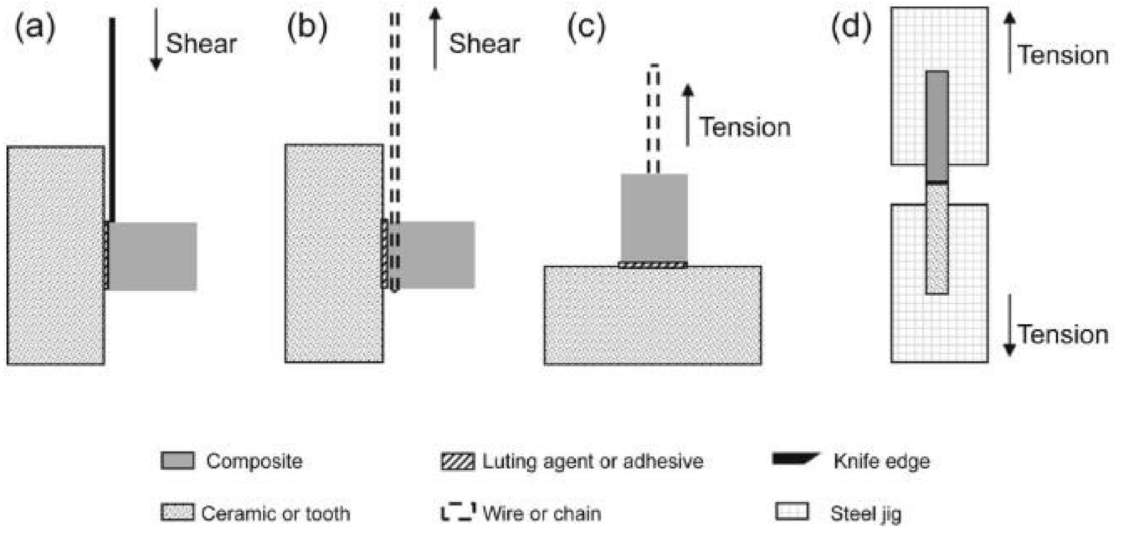

Figure 2.7 Techniques for testing link strength: (a) a shear method knife shape, (b) a wire pulled in tension, (c) the tension test, and (d) the micro-tensile test (41).

In dental practice, dentists use a dental probe and mirror to check the adaptation of a restoration. This is a basic method that does not necessarily provide an accurate interpretation of the interface layer. Dental radiographs (Figure 2.8) are also used in practice to assess any caries between restoration and tooth (45). However, this method is thought to provide insufficient information to assess the interface area which is between the dental restoration and remaining of tooth structure or underlying the restorations (42).

Figure 2.8 Recurrent decay seen by x-ray. The black arrow indicates dark area of decay below filling (42).

In evaluating the layer within the restoration tooth system, several methods have been introduced, including sectioning, which is a destructive method (43). Replica techniques are considered non-invasive and more reliable, but the measurements obtained differ when different planes are used. Finite element analysis has been helpful in assessing stress distribution in restorations, offering the possibility to study the distortion of the different part of the restoration instantaneously, and using FE in conjunction with micro CT scans leads to the production of 3D replica with high accuracy to the real model.

3.5.4 Dental Composite Resin

The use of dental composite in dentistry is very popular among dentists and has increased in the last few decades due to patients' aesthetic preferences (44). Its composition depends on the clinical application, but generally it is composed of: 1) a matrix (Bis-GMA, and dimethacylate) with suitable levels of viscosity (45); 2) a coupling agent, to provide an adequate link between different components of the dental composite; 3) other chemical substances to help in the process of polymerization reaction; 4) fillers to enhance strength and reduce perishability.

3.5.5 Bonding to Enamel and Dentin

Dental enamel is considered a highly mineralised material, composed of almost 96% hydroxyapatite. By using acid etching to the surface of enamel, bonding with resin becomes possible. Enamel acid etching as a method to hold a filling to a tooth structure was first reported back in the 1970s (46). For clinical uses such as bonding between enamel and resin it is thought to be successful and reliable. Due to the composition of the enamel demonstrating a relatively consistent response to acid etching and ability to infiltrate resin. On the other hand, damage to teeth is not confined to the outer layer enamel, but may penetrate to include the dentin, which differs from enamel in its composition, consisting of 50% inorganic, 30% organic medium and 20% water. The structure of this organic is influenced by the dentin location, the presence or absence of defects, and the age of the dentin (46). The presence of tubules is considered one of the main aspects of the dentin's structure. These tubules are derived during the process of dentin formation and directed from the (DEJ) to the underlying pulp. Their density and position differ within a tooth. These tubules are in line with intratubular dentin which consists of a layer of largely mineralised material composed of crystals. The mentioned tubules play an essential part in the success of a dentin/resin interface link (48). In order for the resin cement to bond to the dentin, current theory suggests, firstly, removing the dentin's mineral contents without affecting the collagen; secondly, occupy any voids left from minerals by the cement. As a result, what is known as a hybrid layer is formed, see Figure 2.9.

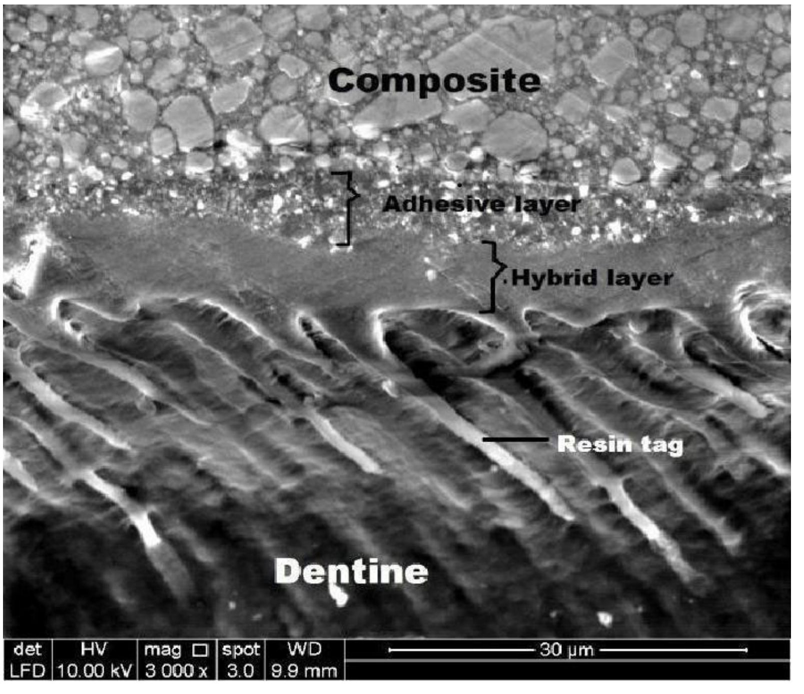

Figure 2.9 Hybrid layer (48).

Theoretically this hybrid layer would be a 3D resin-collagen structure linked together which should provide a stable and continuous bond between the dentin and the resin (47) However, this ideal link is not always achievable, and this interface has been suggested as the weakest bond in the cement/dentin link (50).

3.5.6 Factors Influencing Resin/Tooth Interface Failure

Composite resin is considered the most alternative filling material used to amalgam. However, research reports that such a replacement exhibits a high rate of failure, increased cases of replacement, and the presence of recurrent caries (48). Although many factors might be responsible for resin composite restoration failure, including patient selection, preparation of the tooth, and the technique used, it has been reported that the interface between resin and tooth remains the main primary reason(49). These difficulties are not seen where the enamel is linked to resin, but mainly where composite resin is attached to dentin. Various improvements have been introduced to the composition of dental composites to overcome such restoration failures and shortcomings; however, stress is still an issue in any area of high mastication.

Inadequate sealing of composites or presence of recurrent caries suggests weakness of the bond in a resin/tooth interface to withstand any chemical, physical, and mechanical stresses within the mouth. It has been suggested that deboning at this interface was mainly related to the failure of resin to produce a secure closure with the underlying dentin (50). Such a failure of bonding allows pores to open within the interface, which enable fluid and bacteria to penetrate. Some studies reported that when the interface of resin/dentin is uncovered inside the mouth, loss of retention as well as discolouration occurs (51). The success and failure of dental restorations is influenced by multiple factors, including the type of restorative materials used, the clinician's experience(52), the tooth type and its position in the dental arch, the restoration design, its size, the number of restored surfaces, and the patient's age. Failure occurs when a restoration degrades to the point where it no longer performs properly, either aesthetically or functionally, or fails to prevent new disease (53). This is a significant concern in dental practice, with the replacement of failed restorations accounting for about 50 percent of all operative work (54). Survival and failure rates are important measures of clinical performance, and understanding the reasons for failure can highlight specific weaknesses in the restoration-tooth system.

3.5.7 Ultrasound in Dentistry

The use of ultrasound in medical fields has been noticed for many years. Its use in the dental field has been widely explored recently due to numerous benefits that ultrasound provides as a diagnostic tool. It is a non-destructive and cheap technique, and, unlike X-rays, it contains no ionising radiation. “Ultrasound” describes any waves with frequencies above 20 KHz, which is above the audible limit to humans (55). A (amplitude) and B (brightness) modes are the most commonly used display modes in dental field (56). The use of ultrasound in the dental field includes dental scanning to detect cracks. 2-D image scanning of the real teeth and their DEJ using frequencies in the round of 10-MHz (57). However, some errors were encountered because of irregular tooth anatomy when the beam hit the surface, leading to the image being inaccurate upon transmission and reflection. To overcome and understand these issues, a 3-D finite element simulation was produced by Sun et al. in a study on propagation of ultrasound in a tooth (58). The research showed significant findings from the simulation compared to the vitro tests. The enamel was also assessed with the use of a high frequency ultrasonic probe for its thickness (59). The difference in thickness of the enamel compared to corresponding values obtained using an acoustic microscope was found to be 10%.

Furthermore, enamel thickness has been measured by using a probe with frequency of 15 MHz. In this method a Fractional Fourier Transform (FrFT) were used to distinguish any echoes that were overlapped, this overlapping was a result of the reflection between dentin and enamel layers. The main reason for using a FrFT was to separate the overlapping signals in frequency and time domains with the help of matched layer techniques. As validation techniques a micro-computed tomography was introduced. The study concluded this method can be considered as a diagnostic tool in dental practice in terms of finding cracks, or measuring thickness of enamel and assessing any failure of restorations (60). Similar conclusions were reported by using a 11MHz probe to evaluate enamel thickness (49). Another study compared three methods to measure enamel thickness, using contact, immersion transducers and a layer of resonance and concluded that these methods could be used to determine the thickness of enamel (61)

3.5.8 Detecting Caries

Early diagnosis of caries is essential to prevent further damage to the tooth structure. Among different methods, ultrasound has been developed to assist in detecting dental caries (62). Ghorayeb et al. (63)analysed the teeth structure using both A and B mode scans. Four teeth scenarios were tested: 1) normal intact; 2) filling with amalgam and a natural hole; 3) drilled hole of 1mm to represent decay; and 4) calcified tooth. The results with use of FEA showed that ultrasound is a promising method for teeth assessment. However, due to the complexity of the tooth structure and heterogeneous components, it was not possible to highlight strong conclusions about the probability of the outcomes (63). In another study, a traditional radiograph was compared with ultrasound for proximal decay diagnosis (64). For this study, teeth were used and seen by different dentists and repeated after a week, results were validated against microscope images and showing that ultrasound was able to detect decay areas in the proximal region.

3.5.9 Dental Fracture

Dental fracture can also be detected by ultrasound. Culjat et al (65) used a phantom with similar properties to those of real teeth. A crack was simulated at the DEJ. This study was effective in differentiating areas that had simulated cracks and the one without simulated cracks (66). Additionally, Sing et al(66). conducted research to detect cracks in porcelain, gold and amalgam fillings. In this study, a 19 MHz probe was used, and measurement of the returned echo was conducted. The measurements were taken in extracted human teeth. The study concluded that cracks under amalgam and porcelain molars were noticed; however, cracks beneath gold were not. The reason could be that gold restorations have the property of large acoustic impedance and therefore transmit minimal acoustic energy (67) .

3.5.10 Soft Tissue Lesions

The clinical application of ultrasound in soft tissue lesions, measurement of tongue cancer thickness, and diagnosis in the cervical lymph nodes were demonstrated by (68). Doppler ultrasound images were taken in B-mode scans, with a 7.5-10 MHz linear array transducer. The Doppler mode in ultrasound was reported to be a beneficial modality in the differential diagnosis between normal and metastatic lymph nodes in patients with oral cancer of the tongue. The authors highlighted the importance of additional research in this area, using standardised methods.

3.5.11 Measuring Thickness of Enamel

The use of ultrasound in determining the thickness of enamel is still not fully established, and research into the topic is still limited to small studies. One of the main reasons could be due to losses of the large signal because of impedance dissimilar (enamel, dentine and pulp) and the angle dependency caused by the teeth shape (69). Several studies have compared ultrasound measurements of enamel thickness with histology, the gold standard in the field, but with mixed results (70) These variations between studies may be due to the speed of sound (SOS) assumed for enamel, which is the value used to derive the enamel thickness. Table 2.2 shows the different SOS values obtained in literature studies. Furthermore, Huysmans and Thijssen (71) demonstrated that ultrasound could be used to measure enamel thickness in a sample of nine extracted human incisors. On the other hand, different factors may influence the reliability of the measurement, including the difference in enamel rod prism orientation with regard to the ultrasound beam (72); the more parallel the enamel rods to the ultrasound beam the faster it travels. The orientation of the ultrasound transducer with respect to the enamel surface can be an additional factor. Ideally, the measurements would be done at normal incidence. Dwyer-Joyce et al, investigated the incidence angle after which no echo was seen from the ADJ and found that in human molar teeth this angle was 10º. Another in vivo study (73), assessing the reproducibility of enamel thickness measurement of premolar teeth Figure 2.10, concluded that ultrasound is a reproducible and reliable technique for monitoring enamel thickness in vivo, with a reproducibility of 0.05 mm.

Figure 2.10 Ultrasonic transducer position on teeth when taking measurements (74).

Table 2.2 Speed of Sound (SOS) in enamel as reported in different literature (70).

Study	***SOS (±SD) (m/s)***	***Teeth***
(75) Blodgett	6250	Human incisors
(76) Lees and Barber	6000 ±190	Human molars
(71) Huysmans and Thijssen	6500	Human incisors
(77) Barber	6250 ±410	Human incisors
(78) Kossoff and Sharpe	4500 ±410	Human incisors and molars
(64) Bozkurt et al.	6132	Human premolars

Anticipating the thickness of enamel is considered a practical way to evaluate the wear in teeth, for example, one study discussed the effectiveness of ultrasound on measuring the thickness of enamel in abrasion, and concluded that ultrasound method was reliable in measuring enamel thickness (64).

In addition, another study described an ultrasonic pulse-echo measurements were made using a Perspex delay line transducer (15 MHz) and glycerine coupling medium.

Ultrasonic measurements were validated by measuring the thickness of the enamel layer at the marked side of the tooth slices with a light stereomicroscope and concluded that this method was feasible in measuring the thickness of enamel (79).

One of the uses of ultrasound is to determine a presence of cracks in engineering, in dental field a study utilized ultrasound to detect a 25 μm thick crack in the crown of a tooth phantom(66). They successfully received a reflection from the crack, demonstrating the potential utility of ultrasound in such scenarios. However, further research on natural teeth is necessary to determine if the same results can be achieved in vivo.

Most of the thickness measurements were directly aimed on teeth without exploring different samples or validating the technique. Therefore, to fulfil this gap, this study aims to explore the process of measurement using ultrasounds, by first testing samples that have similar acoustic properties to teeth such as Glass, and PMMA materials, establishing the signals of these materials would help in understanding the ultrasonic methods in signals analysis, which, eventually, facilitate the understanding of signals reflections when measuring teeth samples. Having a systematic approach from simple materials testing to teeth, as this approach helps in understanding signal behaviour for each material and how they differ compared to teeth signals in the same study, previous research did not highlight this aspect of ultrasound measurements.

3.6 Non dental applications of ultrasound

The application of ultrasound has significantly increased, and its effectiveness, especially in industrial settings, has been extensively studied by researchers over the past twenty years. Ultrasound energy input is known to greatly enhance both the yield and quality of products, while also aiding in the recovery and purification processes across various industries and in tissue engineering (80). This technology is widely utilized in the processing, chilling, and preservation of food products due to its cleanliness and efficiency(81). Additionally, ultrasound is employed to predict the useful lifespan of industrial processes and machine components, as well as in the treatment of waste from industries such as textiles, agriculture, and tanneries (82). This review article outlines the methods for generating power ultrasound and discusses advancements in its application in various industrial procedures (83). As a diagnostic medical tool ultrasound is commonly used for monitoring fetal development, assessing fetal health, and guiding certain prenatal procedures. This non-invasive nature of ultrasound can provide real-time monitoring and detailed imaging without exposing patients to ionizing radiation. This emphasizes the importance of patient safety and comfort in diagnostic procedures. Also, echocardiograms use ultrasound to visualise the heart's structure and function, helping diagnose conditions such as heart valve issues, cardiac tumours, and congenital heart defects (84).Ultrasound helps in diagnosing injuries and conditions related to muscles, tendons, ligaments, and joints (85). Ultrasound has also a Therapeutic application, for example ultrasound is used to promote tissue healing, reduce pain, and improve blood flow in injured areas. Industrial Applications Ultrasound is used to detect flaws in materials, measure thickness, and evaluate structural integrity in industries like aerospace, construction, and manufacturing. helps monitor the flow of liquids and gases in pipelines, detect leaks, and ensure proper functioning of industrial processes. As in medical diagnostics, ultrasound can offer non-invasive, real-time imaging for dental applications, potentially improving diagnostics and patient outcomes. The capability of ultrasound to provide detailed and dynamic images can enhance the assessment of dental structures, such as detecting periodontal issues or evaluating the condition of soft tissues. Exploring therapeutic ultrasound in dentistry could aid in pain management, tissue healing, and post-surgical recovery, leveraging the technology’s proven benefits in physiotherapy and oncology. Like its use in industrial NDT, ultrasound could be used in dental laboratories for non-destructive testing of dental materials and prosthetics, ensuring higher quality and durability. By understanding and integrating these insights, dental professionals can potentially enhance diagnostic accuracy, treatment efficacy, and overall patient care using ultrasound technology.

3.7 Testing Teeth for Wear Measurement

3.7.1 Bovine Teeth in Research

Although specimens generated from human teeth are ideal for in vitro and in vivo dental research because they allow for representation of vivo teeth, the use of human teeth presents certain limitations and disadvantages. As most of these teeth are extracted due to extensive caries lesions or other defects, they tend to have insufficient tooth structure to obtain adequate quality required for testing (86). Moreover, the relatively small and curved surface area of human teeth may also be a limitation for specific tests requiring flat surfaces of uniform thickness. Finally, awareness of the infection hazard and ethical issues has increased. Therefore, alternative substrates have been proposed and used in teeth related research, such as bovine teeth. Bovine teeth have been widely used in dental study, as they are easier to obtain in large quantities, and in relatively better condition than extracted human teeth. Also, compared to human teeth which have small and curved surfaces, they have relatively large flat surfaces and are considered free of any caries lesions or other defects that might affect the outcomes(79). Moreover, mechanical tests of such as shear bond strength, fracture resistance, and other microbiological properties have used bovine teeth as an alternative to human teeth with successful results (87).

3.8 Summary

From the previous literature, it can be concluded that human teeth that have undergone various injuries to their structure, in most cases, require repair and restoration with suitable materials. Monitoring these conditions and restoring them requires thorough evaluation using non-invasive techniques. Up to now, there is no specific tool that can be used to determine the current status of teeth in vivo, including monitoring tooth wear and helping dentists to diagnose problems or to evaluate the interface layer in a restoration. The use of ultrasound shows promising results for measuring wear in teeth, and it has the advantages over X-ray of being a non-ionising non-destructive method, and able to detect differences in layers. The aim of this research is to further explore the potential of ultrasound in these areas.

Future research should concentrate on developing techniques to measure very small changes in the tooth surface so that the preventive regimes can be scientifically and quantitatively assessed.

Chapter 3: Ultrasound Theory

This chapter investigates the use of ultrasound for the non-invasive measurement of tooth structures, specifically enamel and dentin. The primary aim is to assess the viability and accuracy of ultrasonic techniques in capturing dental morphology and detecting changes such as enamel thickness, dentin thickness, and (TSL). Detailed methods and materials are outlined, from the calibration of ultrasound instrumentation to application on bovine teeth specimens, aiming to pioneer a novel diagnostic tool in dental practice. Before that theoretical aspect of ultrasound is described below in the following sections.

Sound is a type of mechanical energy. In order to produce a sound, a source in the form of a vibrating object is essential. The vibrations occur per unit time, referred to as frequency, which is expressed in units of Hertz (Hz). Each 1 Hz equal 1 vibration per second. Based on the ability of human to hear sound, it is divided into three parts, audible sound which can be perceived by humans, infrasound which is below human ear perception and ultrasound.

Ultrasound is the name given to sound waves of a frequency higher than those audible by the human ear. This varies from one individual to another, but the audible range is understood to be higher than20 kHz (88). Ultrasound cannot travel in an empty space; therefore, it requires a material host to propagate. Ultrasonic propagation can be created by using mechanical equipment as a source, contacting with an object initiating vibrations, and by monitoring these vibrations with the use of sensors, detailed information about the status of the object can be obtained. Analysing the behaviour of the introduced ultrasonic wave, particularly the changes experienced by the wave as it propagates through the material is of great interest. Variations in material properties may result in reflections of the sound wave. The study of these reflections and transmissions, a process known as ultrasonic reflectometry, reveals sub-surface details. The most prevalent application of ultrasonic reflectometry is found in medical sonography, where it is employed to generate images of foetuses within the womb (89)

Being non-destructive in nature, ultrasonic testing allows for in-situ inspection without causing permanent alterations to the object under investigation. Therefore, it constitutes a valuable technique in non-destructive examination, yielding significant savings in both time and financial resources in the realms of product evaluation, troubleshooting, and research (90)

4.1 Wave Propagation

When waves traverse a material, they induce vibrations in the constituent particles, leading to small deviation from their average position within the medium. These minute vibrations then influence adjacent particles, resulting in small movement and deviation as energy is transferred from one particle to another (88). Mechanical movements are associated with the acceleration motion of piston which operates in a restricted space. As a result, alternating regions transmit with expansion and compression throughout the medium. There are two traditional types of waves: longitudinal waves and shear waves (91)

4.1.1 Longitudinal Waves

The waves are categorized as “longitudinal” once the displacement of the medium particles and the oscillation are on the same plane level of the ultrasound source. This kind of occurrence is detected when energy travels through a series of compression and rarefaction movements, which happens in fluids and large solids, as shown in Figure 3.1.

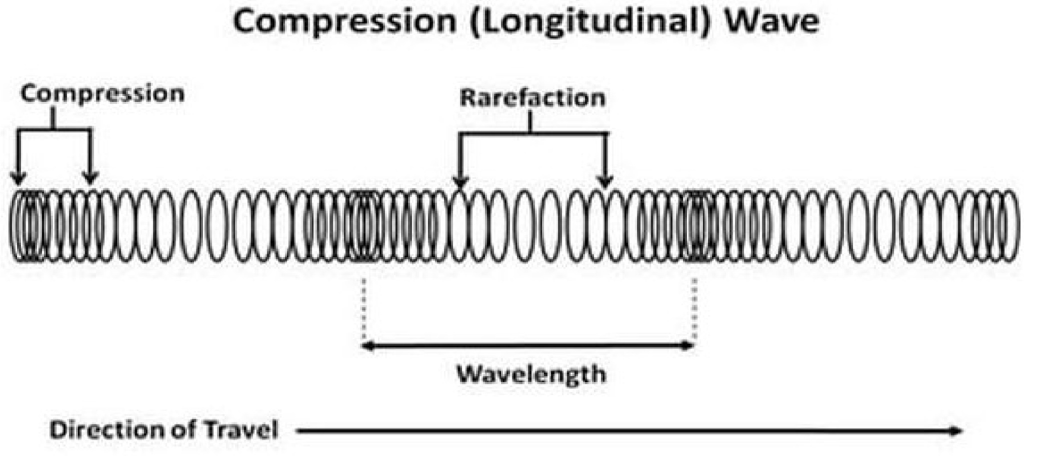

Figure 3.1 Propagation of ultrasonic longitudinal wave(92).

When this type of longitudinal wave is propagating through the body, it presents an image which captures a snapshot of that body section. It presents areas of compression and tension of the body section with the wavelength λ indicating the distance between cycles. Those waves travel towards the right with equal intervals at a constant velocity. This description presents a longitudinal wave, which is also called the pressure of compression waves.

4.1.2 Shear Waves

When the particles oscillate perpendicular to the direction of propagation, transverse waves, which referred to as shared waves occurred Figure 3.2. Utilizing ultrasonic shear would directly create shear waves

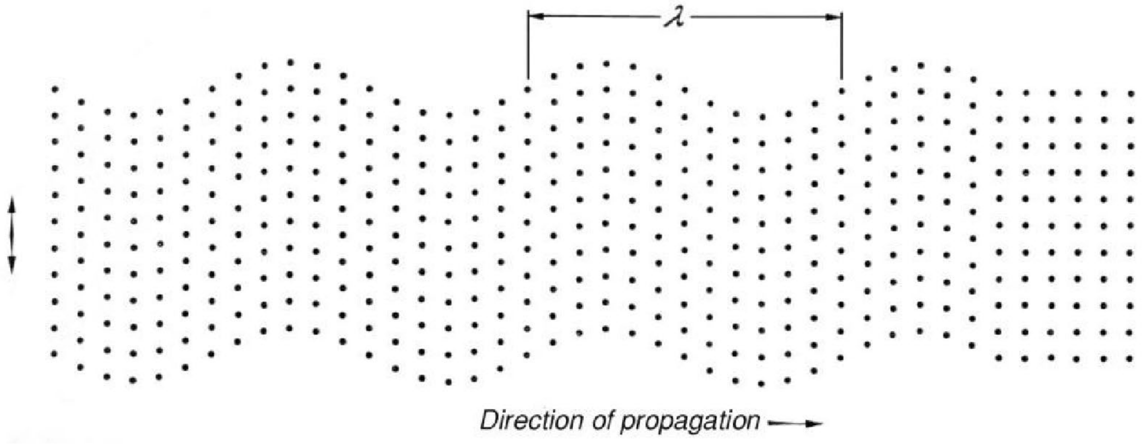

Figure 3.2 Propagation of shear type of wave (92).

4.2 The Speed of Sound

The rate of ultrasound travel through a medium is referred as the wave velocity. The wave velocity may not be constant for all materials as it varies based on the elastic properties of the host medium. The two fundamental properties of the medium that impact the wave speed are its density and compressibility. Also, the wave type plays an important role in determining the wave velocity.

These differences in the speed of sound (SOS) enable the use of readily available SOS reference tables for standards materials. This is seen clearly when using diamniotic ultrasound for medical reasons, as the velocities in various soft tissues are quite similar. However, this is not the case in dental structures where variations of SOS in teeth components are quite distinct from one tooth to another and between different individuals. Equation 3.1 explains how to find the wave velocity, c by using a direct time-of-flight measurement. This technique based on measuring the time required for a sonic pressure wave to propagate through a specific distance. To calculate the thickness of the material, the relationship between speed, distance, and time, utilizing an ultrasonic pulse.

$$d = \frac{ct}{2} \qquad 3.1$$

where d is the distance (thickness of the material); c is the speed of sound and T is time T= time

The following relationship, Equation 3.2, connect the wave velocity, c, frequency, f¸ and acoustic wavelength, λ .

$$C = f\lambda \qquad 3.2$$

4.3 Acoustic Impedance

The acoustic pressure which is generated by the oscillatory movement of the particles within the host medium is measured by the acoustic impedance. The measurement of the acoustic impedance, z, is determined by multiplying the density, p, and the sound velocity, c, as seen in Equation 3.3.

$$z = pc \qquad 3.3$$

The acoustic impedance measurement unit is referred to as Rayls per square meter which expressed as pressure per velocity per area.

The reflection coefficient, R, is another term used to describe the proportion of the wave reflected at an interface (this could be the interface between two different materials in a composite structure (for a tooth, enamel-to-dentine; or enamel-to-tooth restoration) or the edge of a component (so material/air interface). The following equation represent an atomically perfect interface between two different materials, R is defined as:

$$R = \frac{z1 - z2}{z1 + z2} \qquad 3.4$$

Both z1 and z2 represent the acoustic impedances for the two materials. This equation shows the maximum potential proportion of sound that can be transmitted between two materials at an interface.

Equation 3.4 explains that as sound travels from solid, such as steel, to gas, such as air, the reflection of the energy occurs at the interface. Ultrasonic crack detection technique is based on this principle. This principle can be utilized in dental restoration to assess the integrity of the interface during repair. The ultrasound signal will show increased echogenicity in case of a gap exists in restoration compared to a restoration that is accurately fitted.

4.4 Attenuation of Ultrasound

Whenever an object interacts with an ultrasound beam and diminishes its intensity as it passes through the host, it means this object attenuates or reduces the ultrasonic wave. The ultrasound wave reduces when an object interacts with an ultrasound beam which decreases its intensity as its basses through the host. This is referred to as the sound wave magnitude reduction as it propagates via the host medium. Attenuation occurs in both tissues and solids, and it is essential to thoroughly consider its impact on the final outcomes. Attenuation and absorption are two different terms. Absorption is defined as the alteration of ultrasonic energy into thermal energy within a material. Whereas attenuation describes the total propagation losses that result in reduction of the beam intensity.

Attenuation includes several factors such as reflection, scattering, refraction, and absorption that contribute to the overall loss of ultrasonic energy. The reduction occurs in the magnitude of sound pressure reflected at an interface in an ideal material due to the spreading of the sound wave and subsequent reflections at the boundaries because of a variance in acoustic impedance. The factors that impact the magnitude of this affect are the grain size, the wavelength, and the degree of anisotropy (88) Scattering basically refers to this effect, along with reflections caused by micro-cracks in the material. Equation 3.2 shows that there's a positive correlation as the frequency increases, the wavelength decreases. Attenuation increases proportionally to the frequency squared. Thus, high frequency signals cannot be transmitted over long distance through materials that have significantly high extenuative (93). Figure 3.3 is an A-Scan which is the time domain waveform plot. It shows the reduction of magnitude of consecutive ultrasonic reflections over time after the first reflection.

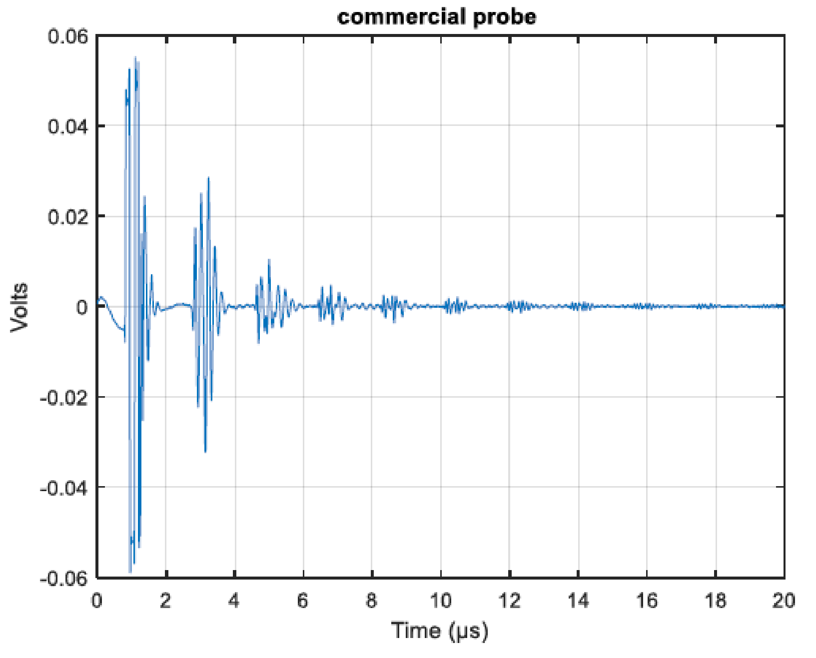

Figure 3.3 The magnitude of consecutive ultrasonic reflections declining over time.

4.5 Snell's Law

There is a similarity in the behaviour of ultrasonic waves and light waves in terms of reflection and refraction. In case an oblique wave interacts with different materials, it experiences both reflection and transmission. The wave velocity changes as it enters the material which causes its path to bend.

Snell's Law states that the ratio of sound velocities in material 1 and material 2 (c1 and c2) is equal to the ratio of sine the angles (θ 1) and (θ 2) of the incident wave and the refracted wave as described in Equation 3.5

$$\frac{c1}{c2} = \frac{sin\theta 1}{sin\theta 2} \qquad 3.5$$

This relationship becomes significantly important when applying immersion transducers. Another important point is that the mode conversion process occurs when a wave hits an interface with a specific angle, the particles start to move in the transverse plane due to the energy of the wave which results in a shear wave generation.

Acoustoelastic Effect

The process by which stress affects the travel of a sound wave through solid media is known as the Acoustoelastic Effect. The velocity of sound wave travel is determined by material's elasticity, which is influenced by the presence of stress When the materials is under compression, the wave propagates faster, but if the material is under tension, the sound propagates slower, as should by (94)and (95)

4.6 Ultrasonic Thickness Measurement

Using ultrasound can aid in determining the thickness of a material, the Time of flight (TOF) measurement is commonly used in ultrasonic thickness gauging.

4.6.1 Time-of-Flight Measurement

The Equation 3.1 is used to find the distance, d, the sound wave travels if the speed, c, the sound travels along a host medium and the time, t, it takes both are known. Since the sound wave travels back and forth through the material, the distance, d, is twice the thickness of the material. Thus, since the time-of-flight refers to the path of material that the ultrasound travels, then it is determined to be twice the thickness of the material the sound has travelled. Figure 3.4 shows that to measure the (TOF), the distance between the zero crossing points of two consecutive echoes is utilized (96).

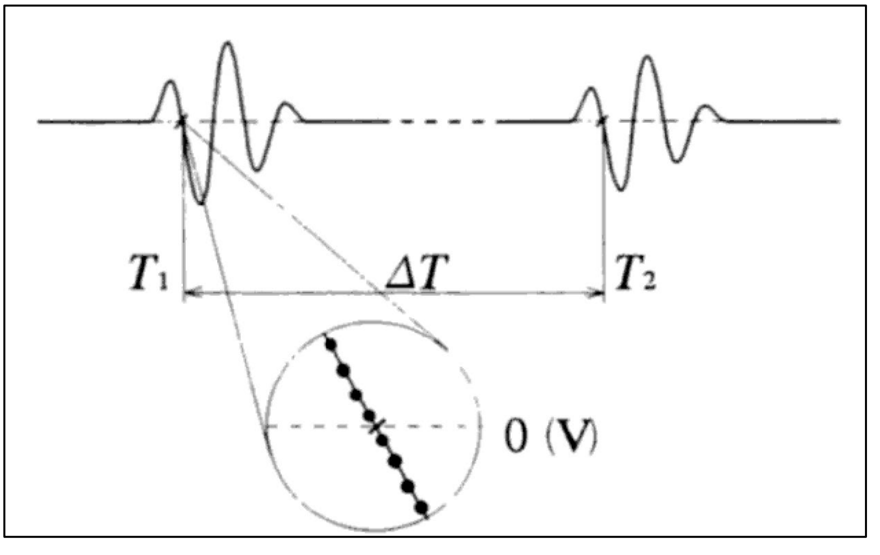

Figure 3.4 Zero crossing illustration to obtain time of flight (92)

To use this method of measurement it is crucial to capture a minimum of two consecutive reflections and use the distance between them to calculate the time-of-flight. It is also important that each reflection uses the same zero crossing point. Using the excitation pulse of 'initial bang' is not appropriate as the waveform does not have a similar shape. In many ultrasonic applications, the mode pulse-echo is used where the same transducer is used for both generating the sound wave and receiving the signal after it reflects from the interface.

For measurement accuracy, multiple zero-crossing measurements can possibly be extracted from each reflection and compare the results. The results should give consistent outcomes. However, in some cases, the process can result in significant system noise which may impact the results.

4.6.2 Resonant Dip Technique

This method mainly used to calculate TOF during the examination of thin substances, proximity between two pulse echoes may induce overlap. Such an instance complicates the segregation of individual reflections within the time domain, thus obstructing the execution of zero-crossing measurements, as discerning each reflection becomes a substantial challenge.

4.7 Ultrasonic Apparatus

Due to the raising demand of high-quality products in research and industrial applications, ultrasonic equipment availability is increasing specifically of commercially accessibility. Since no one device fits all applications, it is crucial that the hardware used is optimized for the measurement applications for all exploratory work. The hardware requirements and settings cover a broad range of factors that need to be considered such as transducer selection, portability, and excitation pulse rise time and filters.

There are five crucial elements that are necessary for any ultrasonic measurement: a pulse generator, a transducer, an amplifier, a digitizer, and signal processing equipment, typically a PC. Also, the interconnecting cables play a vital role in the setup. Usually, the pulser and the amplifier are combined into a single device called the ultrasonic pulser/receiver of UPR (PICOSCOPE). This device is in charge of transmitting the signal to the transducer and receiving the response from it. The setup usually integrates piezoelectric transducers, which are widely used for their ability of converting mechanical vibrations into electrical signals. This digitizer plays a crucial role in serving as an analogue-to-digital converter to facilitate the analogue signals transformation into digital format.

4.7.1 Pulser/Receiver

The ultrasonic pulser/receiver (UPR) is an important component of ultrasonic systems, as well as choosing the right hardware. The market is full pulser/receivers which offers different features that match several applications and budget. Generating the excitation pulse and amplifying the received signal is the primary purpose of the UPR. These devices are capable of both pulsing and receiving signals from the same transducer, enabling pulse-echo techniques.

4.8 Excitation Pulses

The vibrational response of the transducer, which affects the shape of the resulting sound wave, is heavily influenced by the form of the excitation pulse. The optimal excitation pulse shape will depend on the parameters of the transducer. Always verify the recommended voltage using the manufacturer's instructions. Due to the high amount of coupling that may be produced when ultrasonic elements are directly bonded to the material, the necessary voltage is lowered. The voltage and pulse width dictate the amount of energy transferred to the transducer and must be adjusted so the transducer vibrates at its natural frequency. Attention must be paid to the applied voltage and duty cycle to ensure that the transducer does not overheat as a result of receiving excessive power.

4.9 Pulse Repetition Frequency

The pulse repetition frequency or PRF (pulses/sec) determines the frequency of measurement and can be subject to different limitations. Modern and advanced ultrasonic hardware allows for pulsing and receiving at a rate of 10’s of thousands of pulses per second to higher rate of 100,000 pulses per second. The thickness of the host medium impacts and sets a limit on the pulse rate. When the pulse repetition rate exceeds a certain limit, the second pulse will interfere with the subsequent reflections of the first pulse.

4.10 Signal Amplification

Before digitization, the low voltage output. The low voltage (around1 mV) from the transducer requires amplification. This amplification process consists of two steps; an initial low noise amplifier raises the voltage to around 1 V and after that a variable gain amplifier is used to increase the voltage to a level determined by the user (93).

Performing this amplification process is crucial to fully utilize the digitizer’s vertical resolution. In pulse-echo mode, where the same cable is used for transmission and reception, the UPR must have switching circuitry to guide the received signal through the low noise amplifier after the generation of the excitation pulse. Pitch-catch mode involves simpler circuitry which permits the use of external preamplifier.

4.11 Band Pass Filters

Filtering can be applied to the returned signal to reduce the bandwidth of the FR signal. To improve the signal-to-noise ration and in cases where the full receiver bandwidth is not necessary, low pass filters can be utilized. On the other hand, to eliminate unwanted low frequency energy from the signal, higher filters can be used and can be implemented before and after amplification (94).

4.12 Digitisers

The digitizer, also known as an analogue-to-digital converter (ADC), converts an analogue voltage into a digital representation of its magnitude. After the signal has been digitized, the signal becomes impervious to typical forms of radio frequency (RF) attenuation and noise that are frequently encountered in ultrasonic hardware. This ensures the signal is well-preserved and suitable for real-time processing for future analysis if stored. While digitized signals may still be vulnerable to noise, the impact is typically minimal compared to analogue signals. The impact of noise is primarily influenced by the transfer bus.

Oscilloscopes are the type of devices that store and analyze signals digitally, enabling the user to view the signals in real-time on a screen. There are several key factors that need to be taken into account when choosing an ADC, including sampling rate, number of channels, amplitude resolution, bandwidth, on-board memory, noise, over sampling, data transfer rate and communication bus.

4.12.1 Sample Rate

The sample rate is known as the frequency at which the analogue signal is converted into digital samples per second. This is usually known as the “clock speed” its measured by the unit of Hz

4.12.2 Vertical Resolution the Amplitude

The AScan amplitude resolution responsibility is defining the level of detail in voltage steps by which the signal is divided. Its significance becomes apparent especially when analyzing small magnitude variations in waveforms.

4.12.3 The Bandwidth

It is a critical digitiser characteristic that helps determine the frequency range the hardware can accommodate.

4.12.4 Ultrasonic Transducers

A transducer is a device that converts energy from one form to another (95). In the field of ultrasound, transducers play a vital role in converting electrical energy into mechanical energy in the form of sound waves. They are considered one of the main essential components of ultrasound system.

4.13 Piezoelectric Materials

When piezoelectric crystals are pressed or extended, an electrical charge appears on their surfaces. The transformation of mechanical energy into electrical energy. This phenomenon is referred to as the piezoelectric effect. This acceptable criterion for transducers includes being homogeneous throughout, chemically and physically stable, and exhibiting little changes in its properties as a function of temperature. Notably, the thickness of the piezoelectric element determines its resonance frequency.

4.14 Contact Transducers

As the names suggest, it is primarily employed when there is direct touch with the object being evaluated. This type is utilised for non-destructive fracture detection and medical diagnostics, as well as detection of delamination, material speed of sound, and thickness gauging in a wide variety of materials. These are preferable when it comes to application in dental clinical environments.

4.15 Immersion Transducers

These are the containers designed to be filled with liquid. They can scan many dimensions with any liquid media.

4.16 Summary

Different sectors can benefit from the usage of ultrasound, which has a variety of uses and requires a diverse array of equipment, transducers, and procedures. It is gaining popularity since it is non-destructive, non-ionizing, and inexpensive. It is ideally suited for dental imaging due to its capacity to penetrate tooth structures and replacement materials. Due to the intricacy of teeth, however, specific ultrasonic transducers and angle accuracy positioning for measuring teeth must be developed.

Chapter 4:Ultrasonic Measurement Analysis for Simple Specimen Specifications

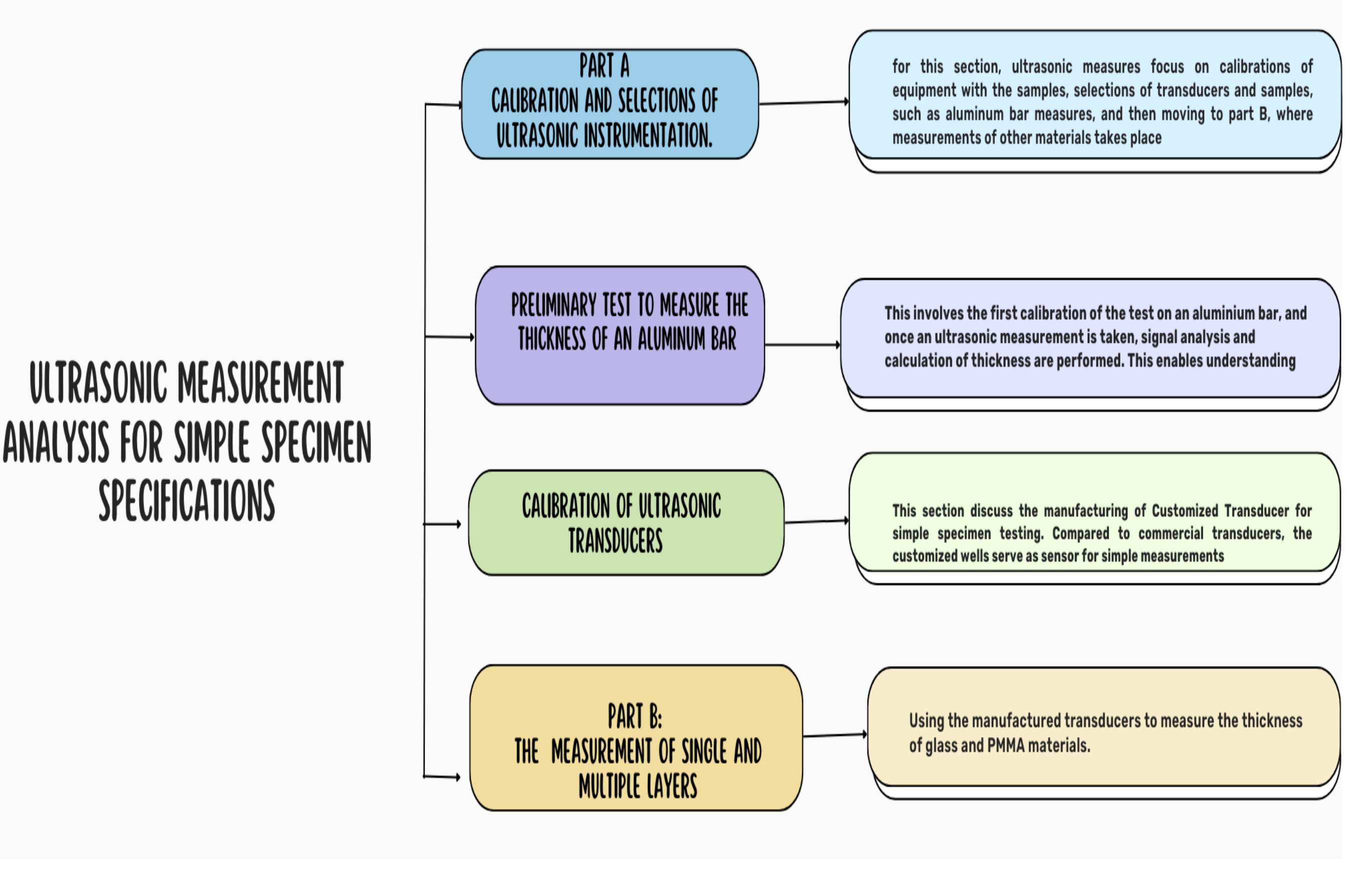

Figure 4.1 Flowchart showing the experimental method in this chapter.

5.1 Introduction

A-mode ultrasonography emerges as a preferred technique, which facilitates point measurements on the labial or buccal surface of teeth, diverging from total bulk measurements seen in practices such as 3D laser scanning and image registration. With erosive agents making even contact with the labial tooth surface, a collection of such spot measurements suffices to monitor erosive (TSL).

In pursuit of enamel thickness measurements that are non-destructive, the utilisation of a pulse-echo ultrasound technique becomes of significant value. However, many in vitro measurements of enamel thickness resort to destructive methods, as noted by (96). Contradictory findings emerged when researchers compared these measurements to the gold standard of histology (with the use of a microscope).

One plausible explanation for these disparate findings lies in the estimated SOS in enamel. Researchers tend to lean on an average value derived from literature; however, variations in SOS within the enamel are widely recognised, attributed to the differing orientation of enamel rods. Consequently, SOS is known to be faster through enamel rods parallel to the sound beam and slower in the opposite arrangement (72). However, the latter is not feasible to be identified in clinical environment, it would only appear practical to visualize the direction of enamel rods is under the microscope.

A key objective for this chapter, therefore, was to scrutinise the correlation between A-mode ultrasonic scans with simple specimens, and then ultrasonic use with enamel thickness measurements and histology measurements, employing tooth-specific SOS values. A more detailed exposition of the latter findings is deferred to Chapter 5. In the interim, it becomes crucial to underscore the instruments and tissue replacement materials deployed for the study, which mimic tooth material for the purpose of testing ultrasonic procedures (Chapter 6).

The inherent properties of ultrasound, such as penetration of dense tissues and metallic restorations, ability to deliver depth information, substantial range resolution, and lack of ionising radiation, render it a strong device for dental monitoring and diagnostics. However, the advancement of dental ultrasonography is fraught with challenges, particularly relating to the measurement of tooth structure.

Several factors conspire to complicate the employment of ultrasonography in dental diagnostics. One key hurdle pertains to high acoustic impedances and surface losses in dental tissues, which curtail the use of common medical transducers and acoustic scanning gels, as they are not acoustically optimised for dental applications.

Further, the intricate microstructure and uneven macrostructure of teeth augment signal reflection and overlap, leading to acoustic scattering. Thus, the utilisation of delay line transducers is advocated. The high compressional velocities inherent in tooth enamel call for brief acoustic pulses and constrained acoustic radiation patterns.

Adding to these complexities is the small size of teeth and limited interdental space, which require precise transducer placement and make imaging near proximal surfaces an arduous task. Finally, the (SOS) variations within enamel, linked to the orientation of enamel rods relative to the incident ultrasound beam (72), suggests that enamel rods parallel to the incident ultrasound beam propagate sound more rapidly, while the inverse holds for perpendicular enamel rods.

The reliability of ultrasound-based measurements is significantly influenced by the orientation of the ultrasonic transducer vis-à-vis the enamel surface. Under ideal circumstances, these measurements should be executed at normal incidence (97). The intricacy of conducting enamel thickness measurements on molar teeth, which lack a planar form as compared to incisors, is an acknowledged issue.

A transducer positioned at normal incidence to the enamel surface ensures that the beam consistently aligns with respect to enamel rods during the measurement. These challenges essentially rule out the deployment of off-the-shelf ultrasonic transducers, inclusive of those designed for medical applications in dental clinical applications. The forward movement of dental ultrasonography towards clinical application necessitates the creation of specially designed ultrasound transducers and systems tailored for dental requirements.

A pivotal step in the progression of clinical ultrasound systems is the successful development of effective tooth analogues. Such analogues facilitate the testing and calibration of ultrasonic systems on targets with well-defined acoustic characteristics, dimensions, surface geometries, and interior features. Consequently, the performance of dental imaging-related systems, as well as system limitations and physical constraints, can be experimentally explored.

The substitute tooth-like material should emulate the acoustic properties of genuine enamel and dentin. Among these properties, density, compressional wave velocity, acoustic impedance, and signal loss are of paramount importance.

5.2 Objectives of This Chapter

The methodology of "Simple Specimen Specifications Ultrasonic Measurement Analysis" has been designed with a meticulous and multifaceted approach, defined by the following objectives.

A critical analysis of the waveforms produced by applying 5MHz and 10MHz frequencies to identical samples serves as a primary target. In order to validate the measurements using a digital caliper, the pulse-echo technique is utilised to establish the thickness of different materials, including glass, PMMA, and dental composite.

A comprehensive exploration of frequency ranges between 10-15MHz is to be performed across all samples. In parallel, the analysis focuses on thoroughly scrutinising the waveform data derived from both materials, observing any alterations, ascertaining patterns and repeatability, and computing the speed of sound.

In the quest for nuanced insights, sample sizes of 1mm, 2mm, and 4mm in both flat and curved shapes are to be fabricated for glass and PMMA. Concurrently, an in-depth evaluation of the diverse results obtained from the identical technique, but applied at different frequencies, forms an integral part of the methodology.

The research strategy further includes synthesising bilayer and tri-layer simulated structures using glass and PMMA and utilising the ultrasound technique to assess the interface of both materials. The objective is to understand and differentiate the wave-signal characteristics resulting from various material interfaces.

The research aims to verify if ultrasound can accurately determine the thickness of a monolayer through direct contact ultrasonic measurement using a 10MHz frequency. Finally, the experimental methodology incorporates the use of different oscilloscopes and sensors to enhance measurement precision and accuracy. Each of these objectives fortifies the integrity of the methodology and steers the research towards yielding accurate, dependable, and insightful results.

5.3 Materials and Methods

Samples comprising 4mm flat glass, 1mm flat glass, 1mm sandblasted glass, and 1mm curved glass were prepared to simulate enamel (70). To simulate dentin, 4mm flat PMMA, 2mm flat PMMA, 1mm flat PMMA, and 2mm curved PMMA were utilised (70). An aluminium plate served the purpose of calibration for the preliminary test, which aimed to confirm the feasibility of ultrasound implementation for the research.

An initial approach involved the use of a 5MHz transducer to capture the waveform signals emanating from the specimen. Subsequently, a 10MHz un-focused contact transducer was employed to generate the waveform, whereby sound is propelled through a gel coupling layer into each specimen. The recording of (TOF) and pulse-echo data was accomplished via the virtual instrument. Glass thickness at each investigated point is calculated using a SOS of 5600m/s for glass. For the PMMA, an SOS of 2657m/s is applied. Validation was achieved through the use of a digital calliper, with different surface shapes employed, see Figure 4.2.

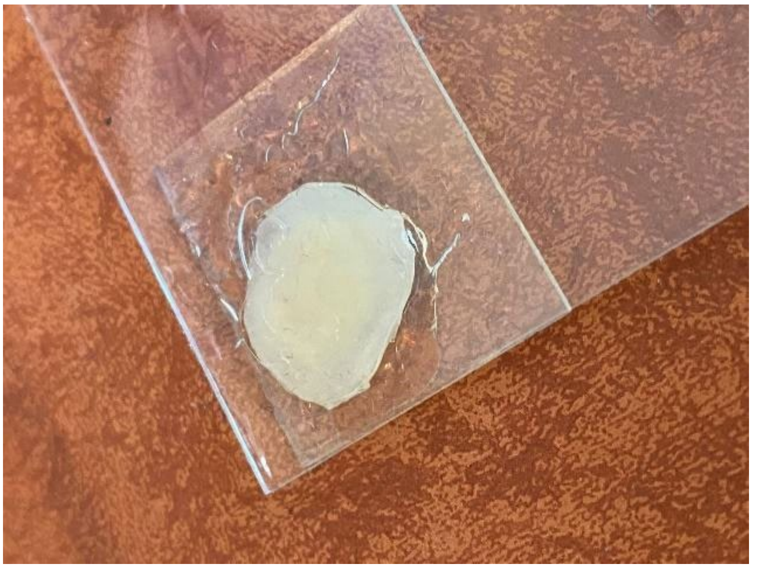

Figure 4.2 Example of some irregularities of dental composite materials, not fine layers.

5.4 Part A Calibration and Selections of Ultrasonic Instrumentation.

5.4.1 Preliminary Test to Measure the Thickness of an Aluminium Bar

One of the main applications of ultrasound is detecting layers and depth. Therefore, a test is done to measure the thickness of an aluminium bar. The aim of this test is to evaluate the feasibility of ultrasound measurement of thickness of an aluminium bar using two different transducers and to validate the result with a caliper measurement. This work will be an initial step before starting to measure changes on simple specimen materials and teeth and their interfaces. Teeth are complex structures, and this research will require additional preparations to be made in terms of transducer and experimental set up selection, that will be considered in the following chapters.

5.4.2 Ultrasonic Set-Up

The Picoscope (5442B), a measuring instrument that connects to the USB port of a computer, is a high-speed portable oscilloscope, with a function generator. It carries pulses into the piezo-electronic element in the transducer to create a signal that fluctuates and then an ultrasonic wave is produced (Figure 4.3). Once the wave is transmitted into the aluminium bar, signals are generated.

The transducer was used as follows:

A direct contact pulse-echo technique was applied using a 10MHz commercial transducer (Figure 4.4) on the aluminium bar. The transducer tip was placed perpendicular to the plate, and another 10MHz ptz transducer was used on the same aluminium bar (Figure 4.5). The transducer was excited with a pulser- receiver unit and the waveform displayed on a LabVIEW.

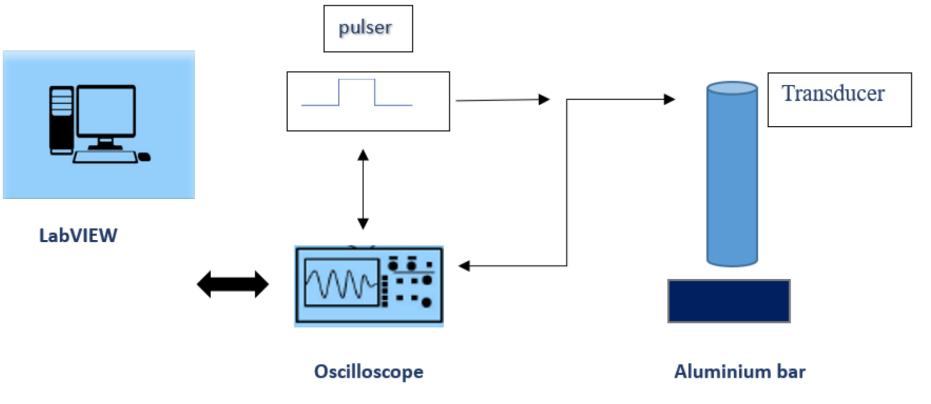

Figure 4.3 Schematic instrumentation used in ultrasonic measurement.

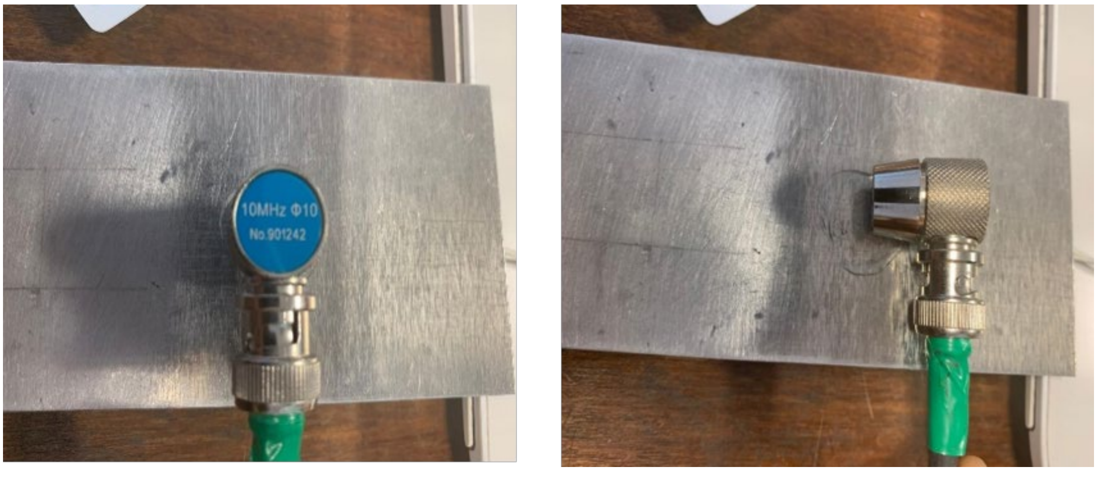

Figure 4.4 10 MHz commercial transducers on aluminium bar.

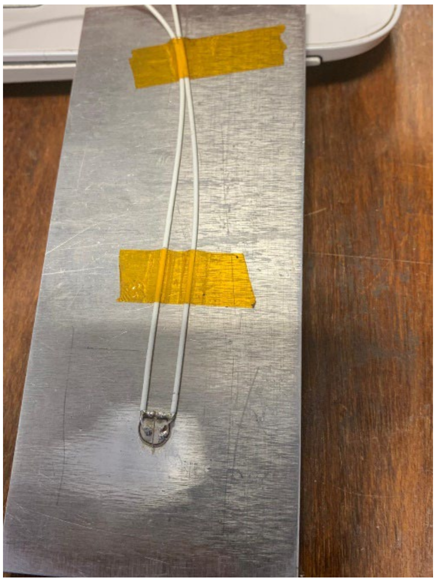

Figure 4.5 10 MHz transducer glued on aluminium bar.

5.4.3 Signal Processing

To ascertain the thickness of an aluminium bar, the application of TOF measurement is necessary, whereby the complete waveform is documented (refer to Eq 1). TOF constitutes a technique for discerning the distance between a sensor and an object. This technique relies on the temporal disparity between the transmission of a signal and its subsequent return to the sensor following reflection by an object. The TOF of the ultrasonic wave under normal incidence within the test sample is determined using the following equation: T2 signifies the TOF of the signal reflected from the sample's rear surface, while T1 is the TOF of the signal reflected from the front surface, as depicted in (Figure 4.6). The same signal processing method will be consistently applied in the experimental studies unless an alternative approach is explicitly stated. Measuring the thickness of materials using ultrasound signals involves a process called ultrasonic thickness gauging. The device that sends and receives ultrasound waves, require a gel or liquid to facilitate the transmission of ultrasound waves between the transducer and the material being tested, in this study a gel-based coupling medium was used. Transducer will act as a device that emits and receives ultrasound waves and selecting the appropriate sound velocity/speed for the material being measured, as different materials have different sound velocities is essential. Once calculations are required, the process involves the following: The sensor will send a burst of ultrasound waves through the material. The waves travel through the sample, reflect off the back surface, and return to the transducer. The oscilloscope through signals measures the time taken for the echo to return. To obtain the thickness of a material, the SOS must be known for the material, and the round-trip time divided by 2. On the other hand, when a thickness is available of a material for example by using a calliper or digital microscope at one point, a SOS of this material can be calculated and obtained with the same method with the known thickness.

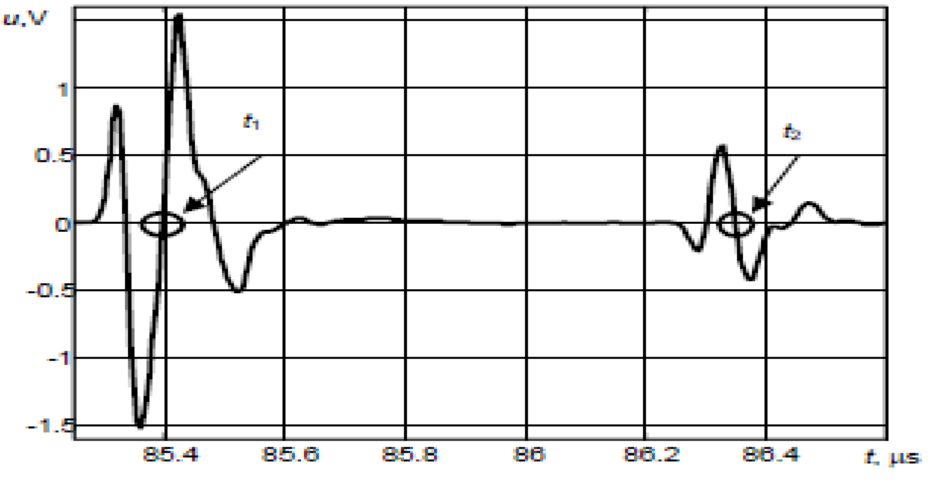

Figure 4.6 The waveform of the Reflected Signals (92).

Utilising Equation 2, the thickness (T) of a material can be calculated. Equation 2 is predicated on the round trip Time of Flight (t) through the material, in conjunction with the velocity or speed of sound (c) within the material under examination.

5.4.4 Results and Discussion

Figure 4.6 shows the waveforms of signal processing from a commercial probe when used on an aluminium bar. The object under consideration is a one-layer aluminium material. Then, Figure 4.7 shows waveforms generated by the Pzt probe when applied to the same aluminium bar. A short electrical impulse excites a piezoelectric element within the transducer in order to generate a burst of ultrasonic waves. Sound waves are connected into the aluminium bar and pass through it until they encounter a rear wall or other barriers. The reflections then return to the transducer, where the sound energy is converted back into electrical energy.

Verification of these results with a caliper measurement of the same aluminium bar is shown in Figure 4.8. The value represents the mean of three thickness measurements obtained at various locations along the edge of the aluminium bar: 5.72, 5.73 and 5.74mm. An average of 5.73mm was taken.

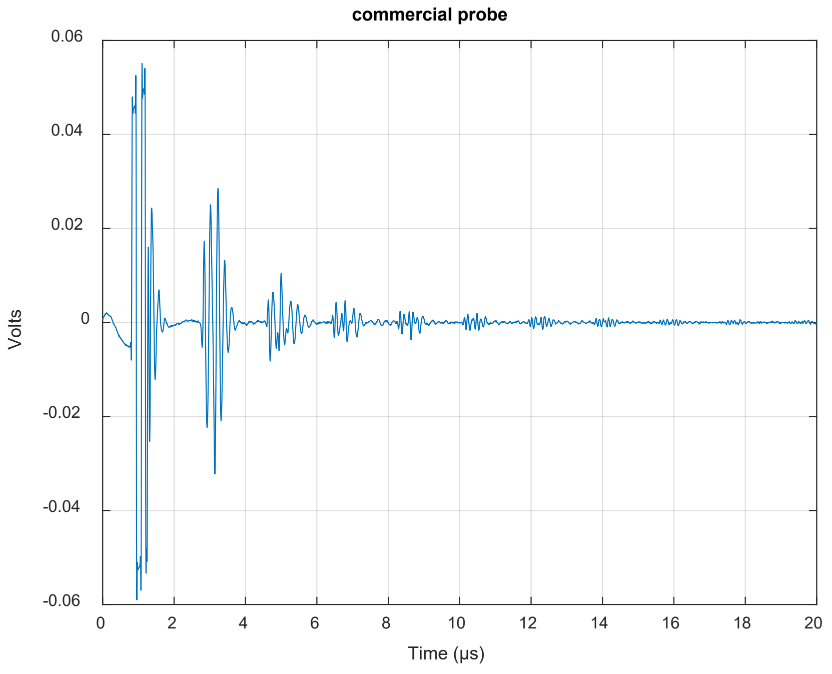

Figure 4.7 Signal waveforms produced using a 10MHz commercial transducer.

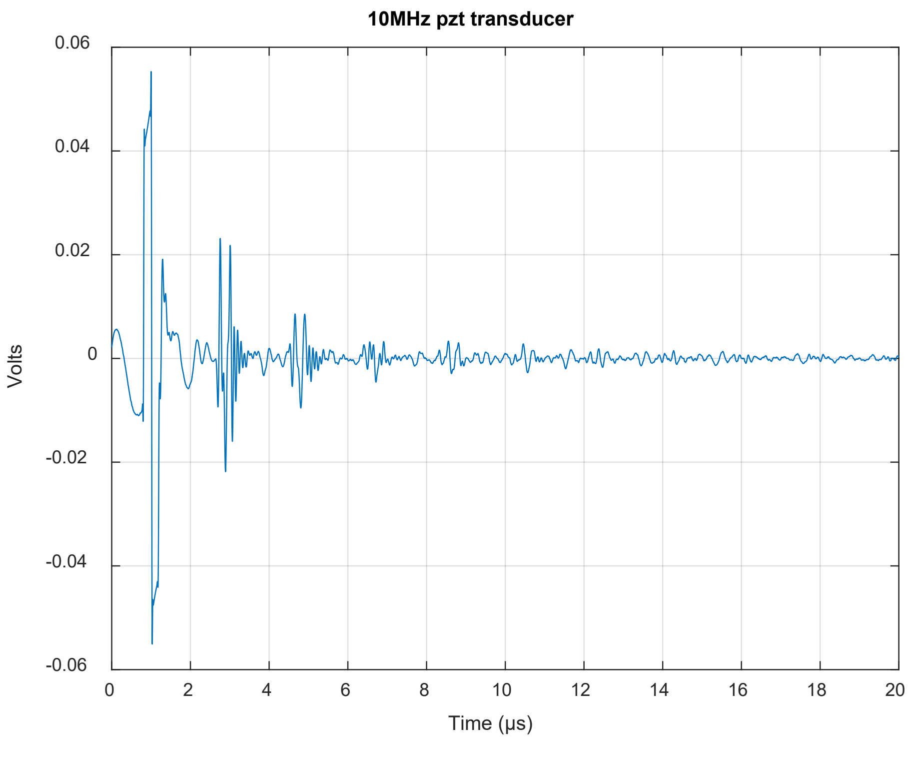

Figure 4.8 Signal waveforms of 10MHz pzt probe.

These above figures mentioned represent the waveform, with slight intensity of signal from Figure 4.6 compared to Figure 4.7.

Figure 4.9 Caliper used for measuring thickness of aluminium bar.

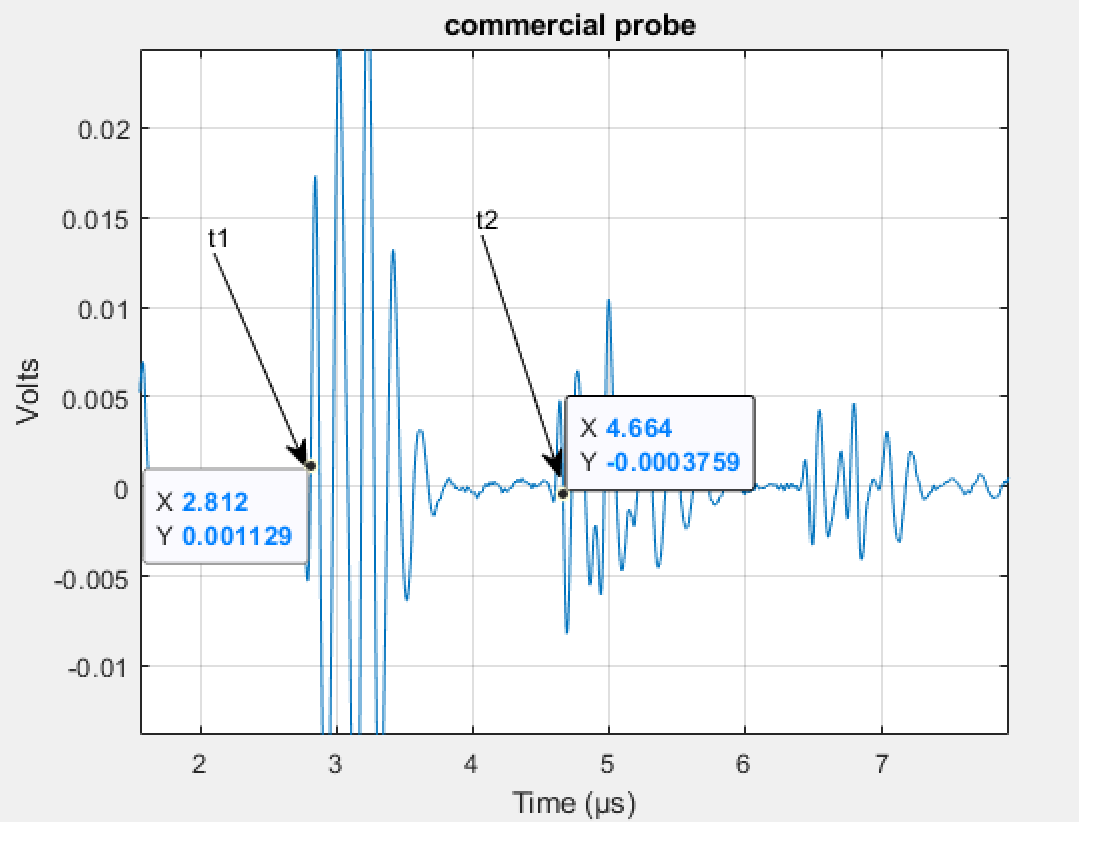

Figure 4.10 Time of flight measurement using commercial probe.

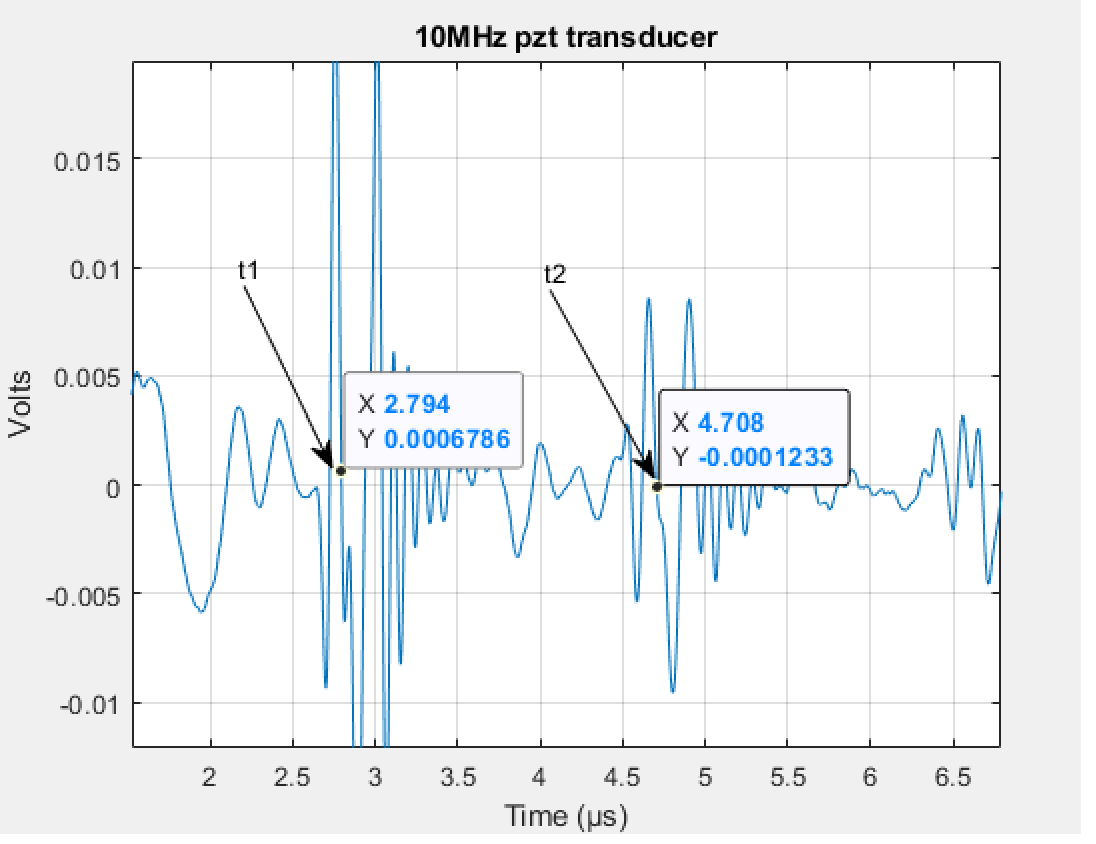

Figure 4.1 Time of flight measurement using pzt probe.

According to Equation 1, the TOF (Figures 4.9, 4.10) obtained when using the commercial probe is 1.852 seconds and for the ptz probe it is 1.914 seconds. Therefore, the thickness of the aluminium bar using the commercial probe and based on Equation 2 is 5.85mm, and using the ptz probe it is 6.04mm. Table 4.1 and Figure 4.11 provides a comparison of these results.

Table 4.1 Comparison of the aluminium thickness results obtained using commercial and ptz probes with the 5.73mm result obtained by a caliper.

Method of measurement of aluminium plate	***Thickness (mm)***	***Difference compared to caliper***
Commercial probe	*5.85*	*2.1%*
Ptz probe	*6.04*	*5.4%*

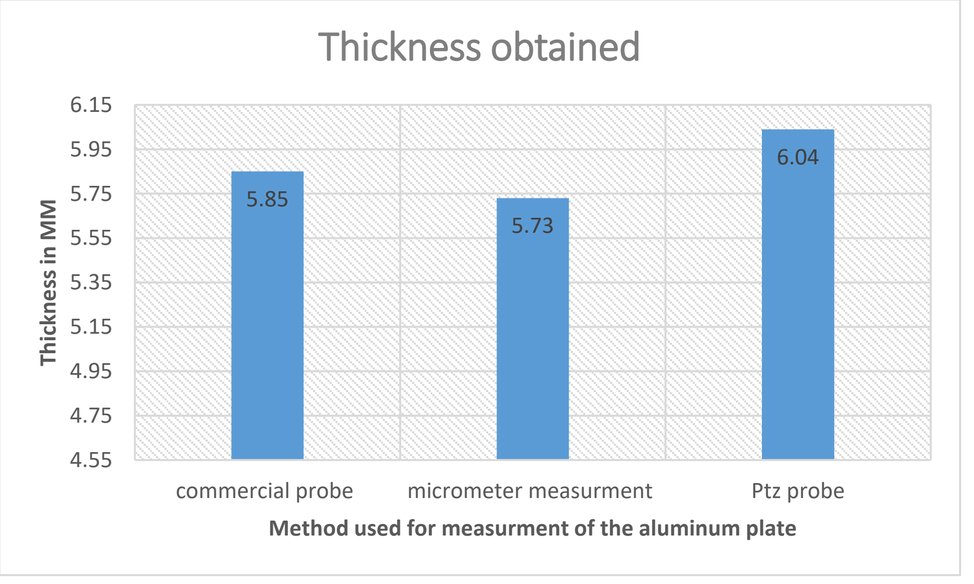

Figure 4.2 Bar chart represents the difference in thickness of using two transducers in comparison with the caliper measurement.

The results reveal a variance of 2.1% between the caliper and commercial probe measurements, and 5.4% discrepancy between the caliper and ptz transducer. These variations could be explained as different sites being measured by the two probes within the same plate; additionally, these discrepancies relate to the high uncertainty associated with use of the caliper. In human teeth, when ultrasound is used to measure thickness, the gold standard would be use of microscopic measurement as a validating method. The simplest pulse-echo technique was used to measure the aluminium bar's thickness. Aluminium has SOS of 6320m/s, whereas the mean SOS value reported in the literature for enamel is 6000m/s.

5.4.5 Conclusions

Aluminium bar thickness may be determined relatively fast and accurately utilising direct application and simple signal processing techniques of 2.1% and 5.4% (while accounting for discrepancies in caliper thickness measurement). This method requires no a priori knowledge of the aluminium thickness, and access to only one side of the bar. Although this methodology can be used in measuring the thickness of layers in teeth and interface gaps, serious errors can occur for thinner and multiple layers, as is the case with teeth. Hence, the transducers used in this particular method could only provide an estimation.

In terms of applying a similar method to measure the interfaces of restored teeth or evaluate the thickness of the enamel structure in tooth wear, sensors should be manufactured that are appropriate to the specimens that will be used in the research. This test primarily focused on to appraise the practicability of ultrasonic measurement of aluminium bar thickness using two diverse transducers and validate the findings against caliper measurement. Marking a preliminary stride prior to starting measurements on basic specimen materials and teeth, along with their interfaces, despite being achievable result, the calibration of the preliminary test is not an indication of the usefulness of ultrasonic measurement still. The research will demand extra preparatory steps concerning transducer selection and experimental setup, aspects which will receive attention in subsequent chapters. Given the intricate structure of teeth, this research necessitates meticulous planning and application of appropriate ultrasound techniques.

5.5 Calibration of Ultrasonic Transducers

An initial approach involved the use of a 5MHz transducer to capture the waveform signals emanating from the specimen. Subsequently, a 10MHz un-focused contact transducer was employed to generate the waveform, whereby sound is propelled through a gel coupling layer into each specimen. The recording of TOF and pulse-echo data was accomplished via the virtual instrument. A waveform obtained after applying transducers of frequencies 5MHz and 10MHz to evaluate their ability to perform for the samples, and to consider which sensors that required, and whether a constructed transducer was necessary for the rest of experiments.

With a similar ultrasonic set-up to that mentioned above, the transducers projected through glass material of 4mm thickness and 2mm of PMMA sample, to just highlight the signal waveform intensity and its display.

5.5.1 Results and Discussion.

To evaluate the amplitude of 5MHz and 10MHz frequency transducers for the chosen samples, waveforms were generated, sparking considerations about the specific sensors required and the potential necessity of tailor-made transducers for subsequent experiments. Under a uniform ultrasonic configuration, these transducers were projected through 4mm thickness glass and 2mm PMMA sample. The primary focus was on accentuating the intensity of the signal waveform and the character of its display, contributing to a deeper understanding of the equipment's functioning.

The ensuing illustrations delineate the waveforms acquired from a 4mm glass sample. Sequentially, they demonstrate a 5MHz waveform and a 10MHz waveform. Evidently, the 10MHz transducer presents distinct, slowly deteriorating reflected signals, superior to those of the 5MHz transducer (see Figure 4.12). Establishing waveform characteristics forms a critical component of justifying the selection of appropriate equipment.

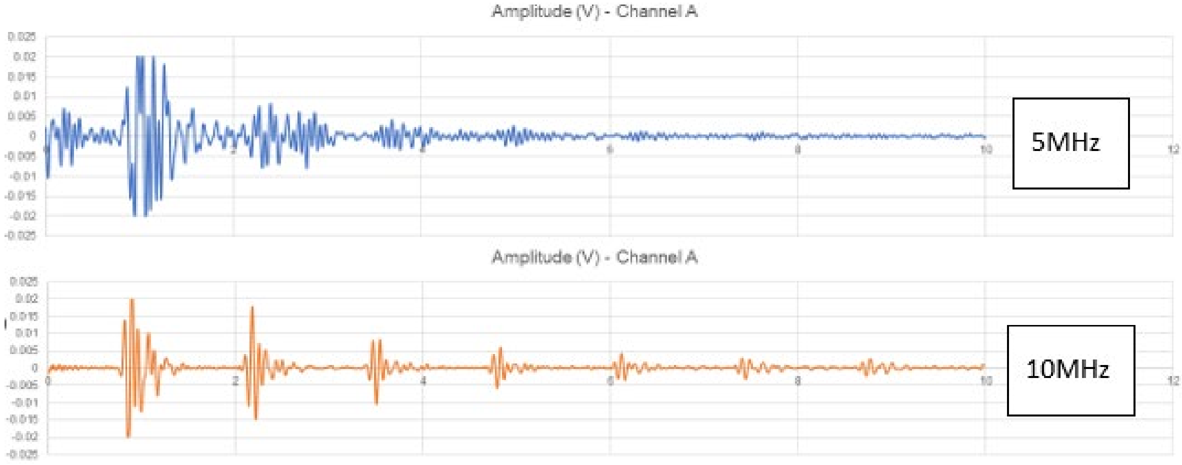

Figure 4.3 Comparison between 5MHz transducers signal waveform and 10MHz on 4mm glass.

Figure 4.13 show reflections for 2mm PMMA top waveform 5MHz and bottom 10MHz. It can be seen 10MHz gives a more distinguishable set of signals than 5MHz

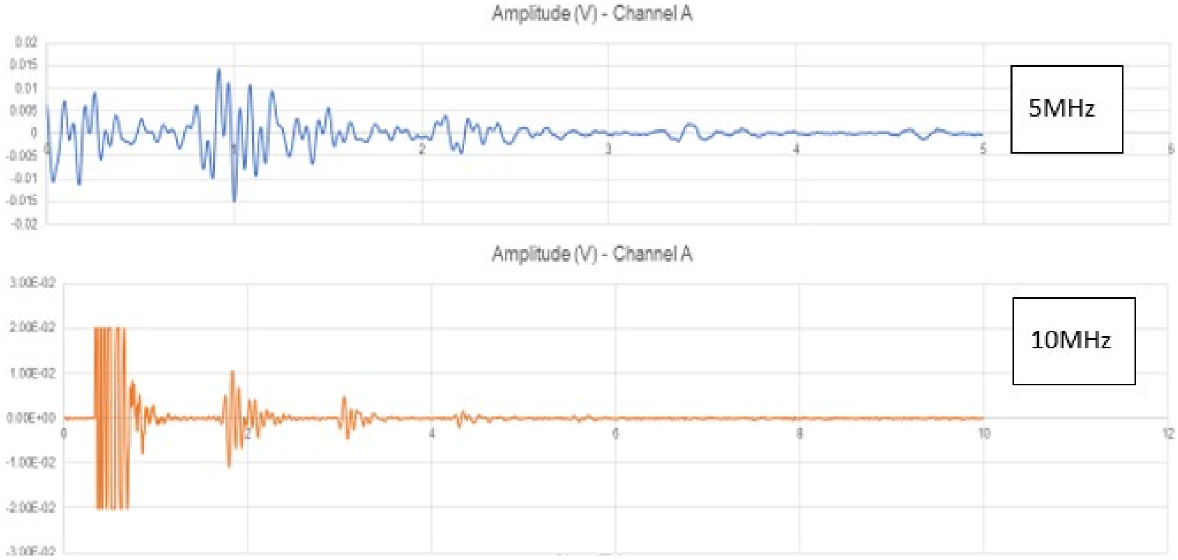

Figure 4.4 Comparison of 5MHz transducer signal waveform and a signal waveform 10MHz PMMA.

5.5.2 Conclusions

Commercial transducers, readily available for purchase and immediate use, present certain advantages, but might not be the optimal choice for all specific experimental settings. Consideration of a myriad of factors, including the type of material under inspection, thickness range, geometric precision requirements, and temperature, is critical when selecting the most appropriate transducer. When the object of measurement is a tooth, one must account for the fact that ultrasound waves will interact with a multi-layered structure comprised of enamel and dentin-enamel junctions. In such cases, the preferred instrument is a delay line transducer, which employs a cylinder of plastic, epoxy, or fused silica as a delay line situated between the active element and the test subject.

The advantage of utilizing a delay line in examining thinner materials, akin to dental structures, stems from its ability to clearly separate recovery of the excitation pulse from back wall echoes. The definition of the initial enamel border hinges heavily on the existence of a delay line. Without it, the echo from the proximal enamel surface arrives amidst the transducer excitation period, causing significant loss. Delay lines consequently establish a temporal gap between the transducer excitation and the arrival of the first echo. Furthermore, it is recommended to construct a piezoelectric transducer operating at 10MHz, suited for measurements on simple specimens, and to procure a delay-line transducer for dental measurements. The ensuing sections shed light on the construction of ultrasonic sensors and delve into measurements conducted on simple tooth-like substitute materials in Part B.

5.5.3 Manufacturing of Customized Transducer for the Simple Specimen Testing

The journey toward manufacturing a customized transducer that serves the requirements of simple specimen testing commenced with an outline of the transducer's core features. Under consideration as test samples were 4mm or 8mm glass, and the discernible features presented when using either a 5MHz or 10MHz were investigated. Predominantly, the requirement for measuring enamel thickness, which stands at a maximum of approximately 2.5mm, formed the basis of the discussion.

Further, an exploration into equipment selection alongside waveform software processing was conducted. As the measurement process begins, the calculation of the TOF points indicating zero crossing are crucial. It is also necessary to verify whether the amplitude undergoes changes while the transducer is positioned on the specimen, fluctuating between 20mv and 50mv. The creation of the sensor, specifically tailored for these methods, necessitated a comprehensive exposition of the steps involved in its construction. This report captures the step-by-step process through detailed descriptions and photographic documentation.

The choice of Piezoelectric Transducer (PZT) is paramount, with two main types available differing in terms of wire connection. The PZT used in this instrumentation operates at around 10 MHz, a frequency tied to its thickness. The process involves performing a clean cut on the glass mirror and cleaning it with Isopropanol before placing transducers on it. The bottom surface of the PZT material is gently wiped with a fibreglass pencil to eliminate the oxide layer. Using a Stanley blade, the PZT is cut into small pieces (5mm x 1mm) on the glass substrate. It is imperative to keep the blade perpendicular to the top surface and collect the pieces that fly off during the process. Figures 4.14 and 4.15 show the piezoelectric cutting and the transducer after construction respectively.

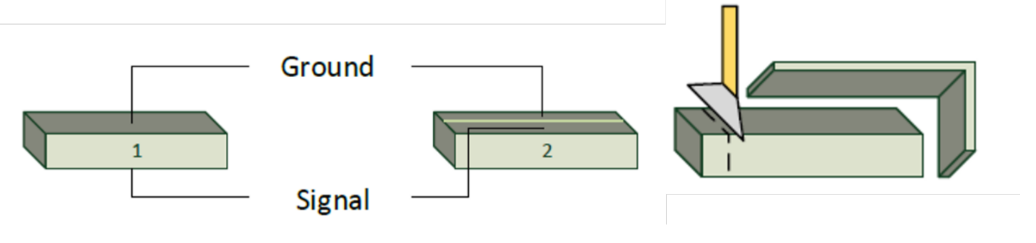

Figure 4.5 The construction of piezoelectric transducers.

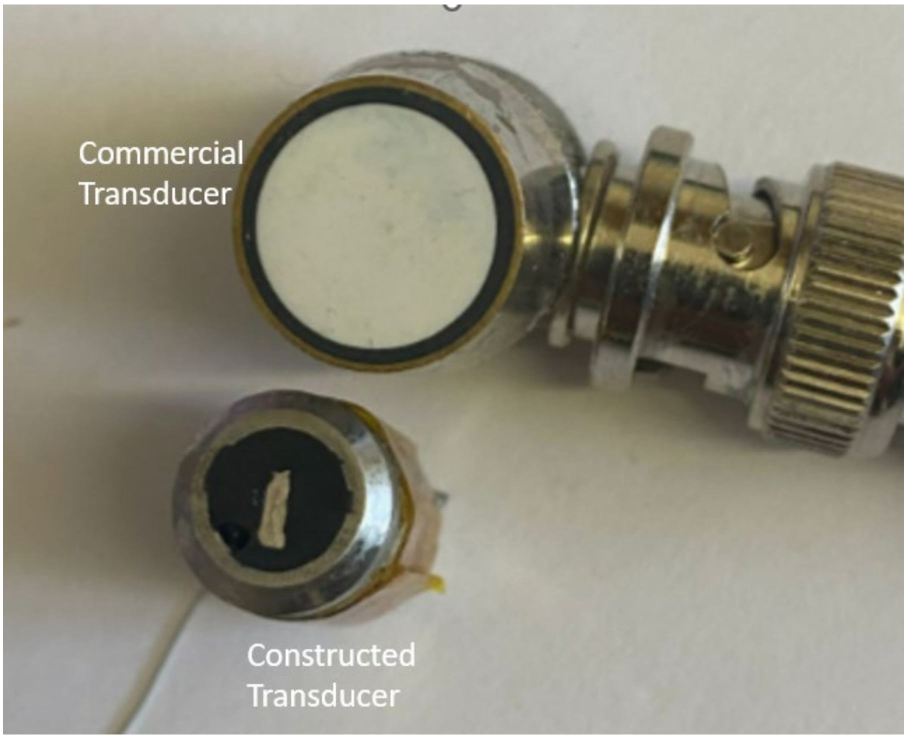

Figure 4.6 The white area in the sensors shows the piezoelectric surface area that comes in contact with the samples; smaller constructed sensors vs. larger commercial transducers.

5.6 Part B The Initiation of Measurement of Single and Multiple Layers

The second part of this study involves the application of single materials for ultrasonic measurements. The single materials being used for ultrasonic measurements. These materials were Glass, PMMA, Dental composite, and acrylic tooth like shape materials and ceramic restorations (see Table 4.2). However, for the initial test a commercial 10MHz transducer to calculate the thickness of a two flat glass material samples of 4mm and 2mm and one curved shape glass of 1mm thickness. Also, two flat PMMA materials samples of 2mm and 1mm each.

The first part was to obtain thickness measurements using a similar set-up to that mentioned in Section 4.1. In this test, point A was for the digital caliper thickness, and for calculating the SOS. This was used to measure the thickness of site B to ensure accuracy and compared when using a generalized referenced value of SOS of 5789m/s from the literature. Each specimen (for full details of specimens see Table 4.2) was marked with a permanent marker at two locations on the enamel surface (A and B) (see Figure 4.16). For each specimen, the A marked area was used to determine the SOS in that specimen. The B marked area was used to measure material thickness with ultrasound, which was then validated with digital calipers.

Marks were made on the front surfaces. For greater accuracy of measurement, the SOS which is essential for calculating the size, is preferably taken from the closest point to the measured thickness as possible.

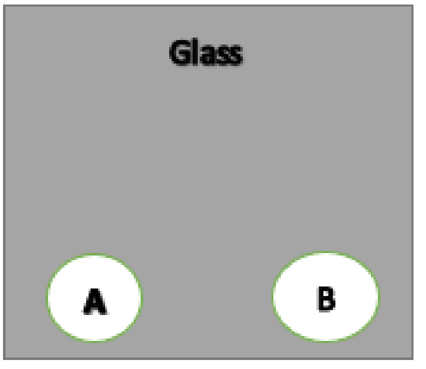

Figure 4.7 Specimen points A where SOS is calculated and B for ultrasound thickness measurements.

Table 4.2 The specifications of the samples used.

Material	***Descriptive***	***Justification for selections***
Glass	*Various thickness and shapes of 8, 4, 1 mm glass flat and 1mm curved surfaces*	*Acoustic properties similar to enamel*
PMMA	*Different thickness and shapes of 8, 4, 1 mm glass flat and 1mm curved surfaces*	*Represent dentin due to similar acoustic properties*
Acrylic tooth shape 	*-Ready-made acrylic teeth size from 1.2-1.5mm.*	*-Shape resemble curvature of central incisors teeth -This can be cut producing the front surface only.*
Dental Composite 	*-layer of 3 mm of thickness that can be reduced to 1 mm -bilayer with glass specimen. - obtaining SOS and thickness changes*	*Dental composite used have similar acoustic properties to dentin. Can be added incrementally and reduced in size, and moulded to different shape*
Metal ceramic restorations 	*Fabricated in the lab from previous dental restoration. Ceramic fused into metal as one combination*	*-Interface geometry of restoration -The thickness resembles a dental restoration*
Enamel Block 	*Flat block of enamel and dentin 8*8*	*Initial measurement as flat block prepared from bovine teeth Help in spot measurement of enamel surfaces.*

5.6.1 Results

The vertical amplitude of the reflected ultrasonic signal echoes was utilised to determine which coupling materials are most effective in transferring ultrasonic energy from the transducer and back (Table 4.3 below). This device (Picoscope) yielded some valuable information. However, difficulties were discovered with alignment and orientation, in terms of compatibility of some transducers, weak signals and amplitude for others, and almost no respond when certain materials are being tested particularly small size of PMMA samples, finally, when teeth were initially calibrated for testing no signals were available in PicoScope device. This limited its application to simple testing. More precise device (FMS) was recommended to be used after, due to its higher signal resolution and amplitude. The ones presented below are the result from the Picoscope device.

Table 4.3 summarises the measurement taken from glass and PMMA.

Material Samples	***Thickness validation caliper Point A (mm)***	***Measured SOS based on thickness from Point A (m/s)***	***US thickness based on Point A SOS (mm)***	***Agreement in thickness between US and Caliper***	***Thickness based on reference SOS 5789 m/s glass and 2757m/s PMMA***(70) ***(mm)***	***Agreement in thickness from SOS reference***(70)
Glass 4mm	*3.9*	*6132*	*3.89*	*99%*	*3.561*	*91%*
Glass Flat 1mm	*1.1*	*6111*	*1.099*	*99%*	*1.008*	*91%*
Glass Curve 1mm	*1.1*	*5000*	*1.1*	*100%*	*1.23*	*92%*
PMMA flat 1mm	*1.29*	*2710*	*1.289*	*99%*	*1.312*	*99%*
PMMA flat 2mm	*1.68*	*2700*	*1.641*	*97%*	*1.676*	*97%*

Also, a signal waveform plot was generated for Figures 4.17 to 4.21 showing the TOF capturing waveform of the materials tested with the Picoscope device. This snapshot from the software as the measurements being taken and before signal analysis. The features showing are helping in understanding the reflections and how the materials thickness can be calculated.

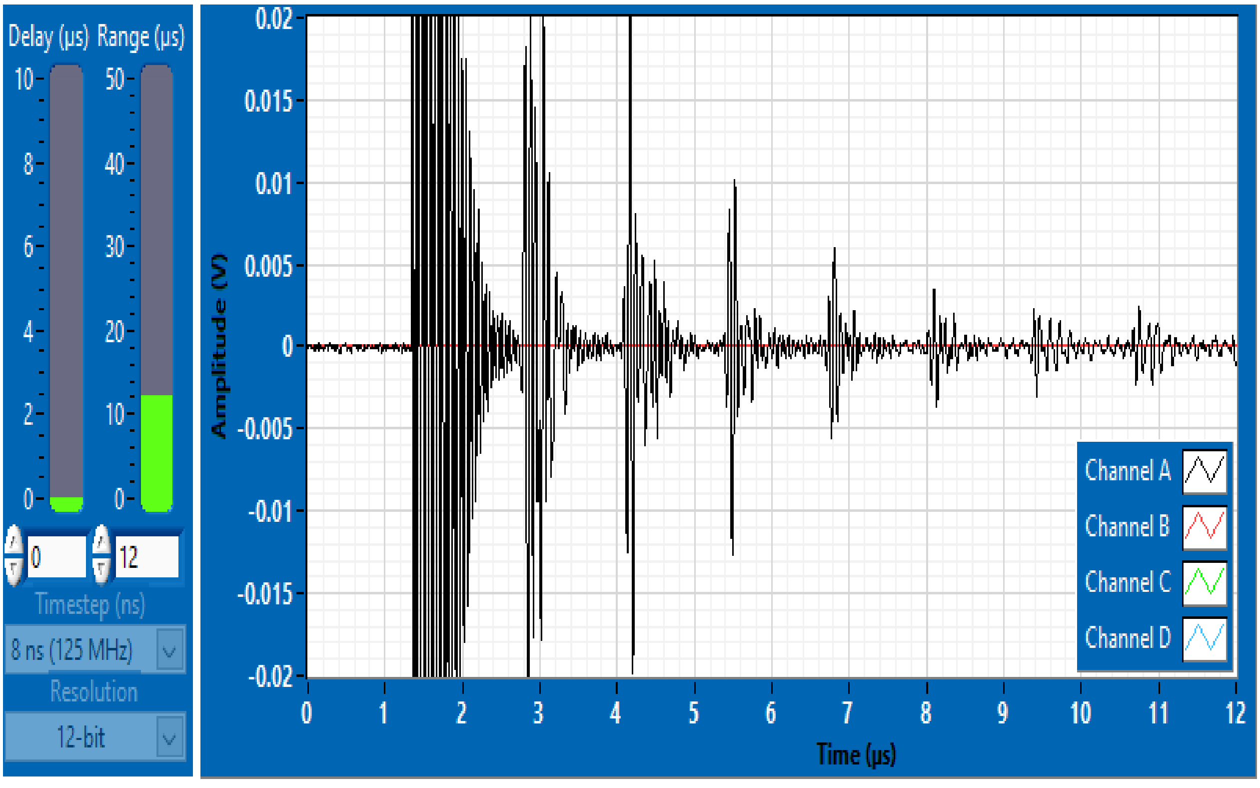

Figure 4.8 Waveform of 4mm Glass sample in Picoscope.

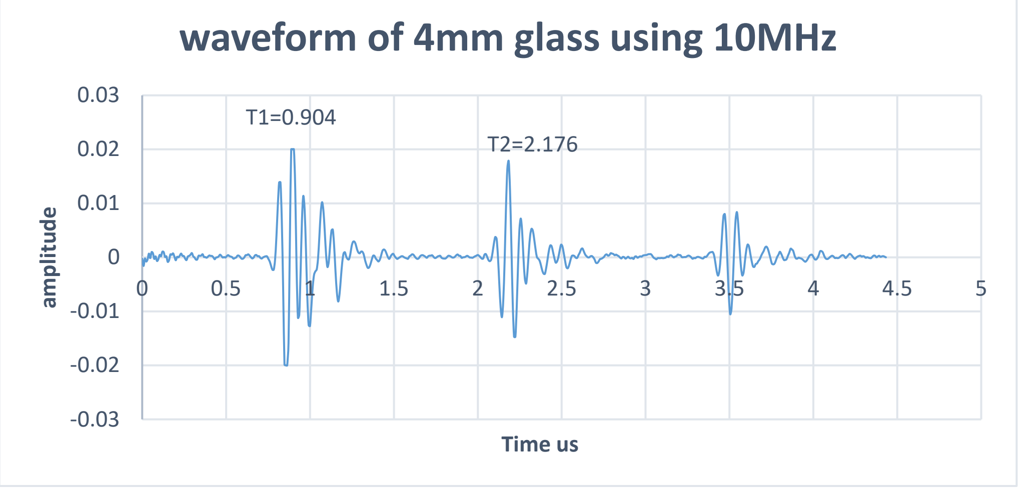

Figure 4.9 Waveform of 4mm glass sample using 10MHz.

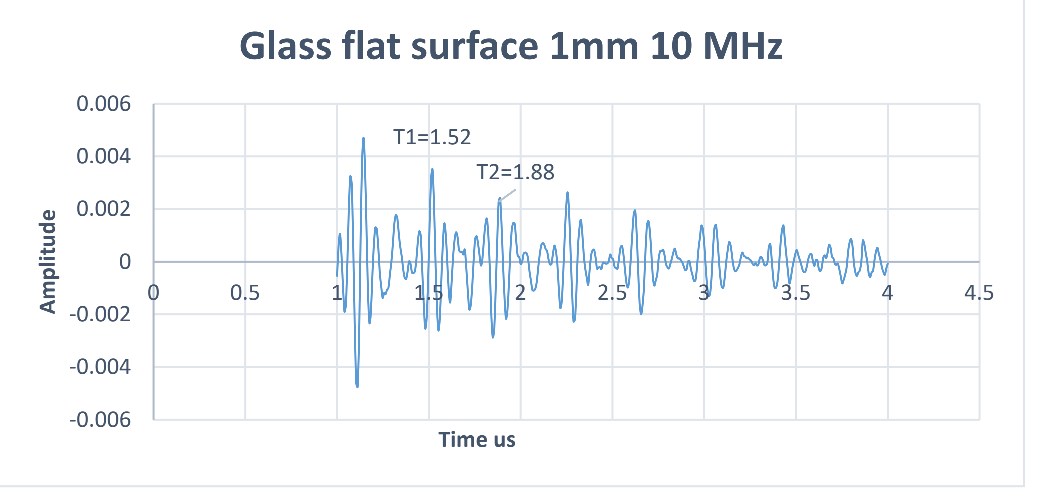

Figure 4.10 Waveform signals of 1mm glass sample using 10MHz.

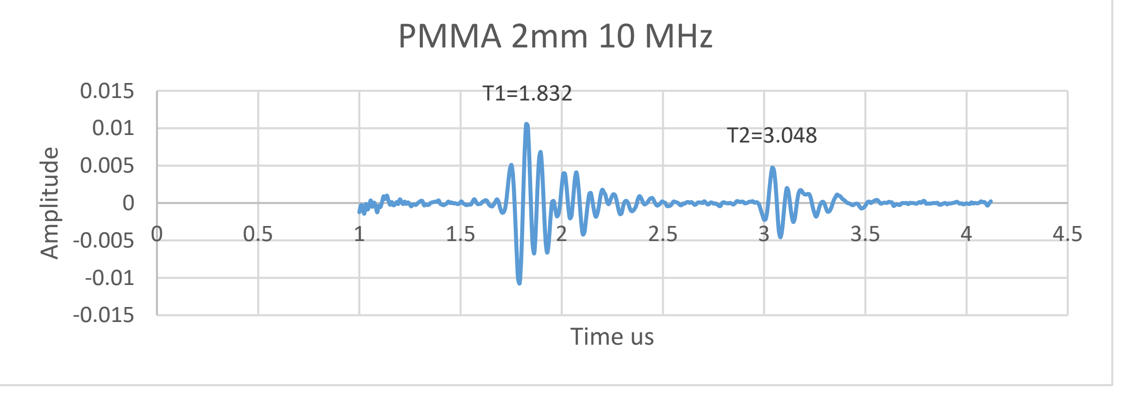

Figure 4.11 Waveform signals of 2mm of PMMA sample using 10MHz.

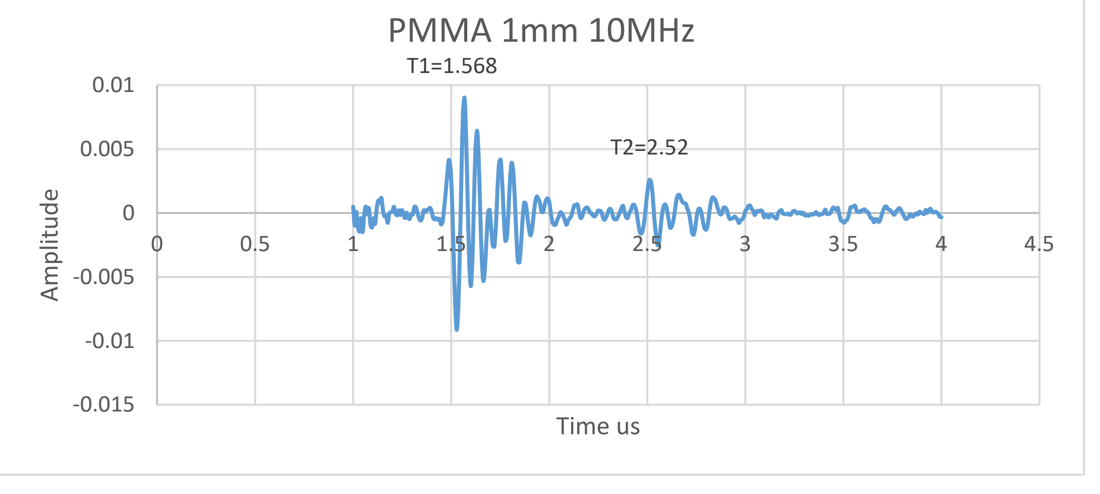

Figure 4.12 Waveform signals of 1mm of PMMA sample using 10MHz.

5.6.2 Conclusions of this Section Based on the Use of Commercial Transducers

A 10 MHz transducer was able to identify layers of the specimen tested in the previous work, the measurement indicated that signals were clear in terms of interpretations of the results, hence, TOF would be calculated and the details obtained. However, to enhance the capability of the instrumentation used in this project, a more enhanced software would seem preferable to continue the work. The FMS oscilloscope contributed to the all of the remaining experimental work. This device acts as pulser-receiver unit similar to the Picoscope used earlier, but with more powerful and meaningful signal and pulse display. Moreover, the samples require multiple measurements with different shapes and properties, these require intensifying and an amplifier set-up to work effectively.

5.6.3 Results for the FMS Measurements of Single Samples

Table 4.4 below represents the measurements of the samples from the FMS oscilloscope, with the same technique applied as previously.

Table 4.4 result outlined from FMS measurements of single layers materials.

Sample	***Digital caliper thickness at point A (mm)***	***Calculated SOS at point A (m/s)***	***Calculated thickness based on SOS from point A (mm)***	***Thickness agreement between ultrasound and caliper Specific Sample SOS***	***Calculated thickness (B) based on SOS. General reference 2657m/s*(98) *(mm)***	***Thickness agreement between ultrasound and caliper General SOS 2657m/s*(98)
1 flat 4mm PMMA	*4.4*	*2953*	*4.2*	*95%*	*3.9*	*88%*
Flat 8mm PMMA	*7.4*	*2740*	*7.48*	*98%*	*7.2*	*96%*
Flat 2mm PMMA	*1.8*	*2812*	*1.9*	*95%*	*1.8*	*100% * note the agreement based on TOF of B site measurement*
Curved 1mm PMMA	*1.5*	*2830*	*1.455*	*99%*	*1.4*	*93%*
Flat 4mm PMMA different length	*3.8*	*2585*	*3.9*	*97%*	*4.02*	*94%*
Cylinder shape PMMA	*9.8*	*2745*	*9.6*	*97%*	*9.2*	*93%*

For the purpose of providing some waveform display of the experiment, waveforms have been initiated and produced for the measurement of a 4mm PMMA sample as Point A and B, similarly 8mm materials of flat PMMA and 2mm curved samples of PMMA are shown in Figures 4.22 to 4.25.

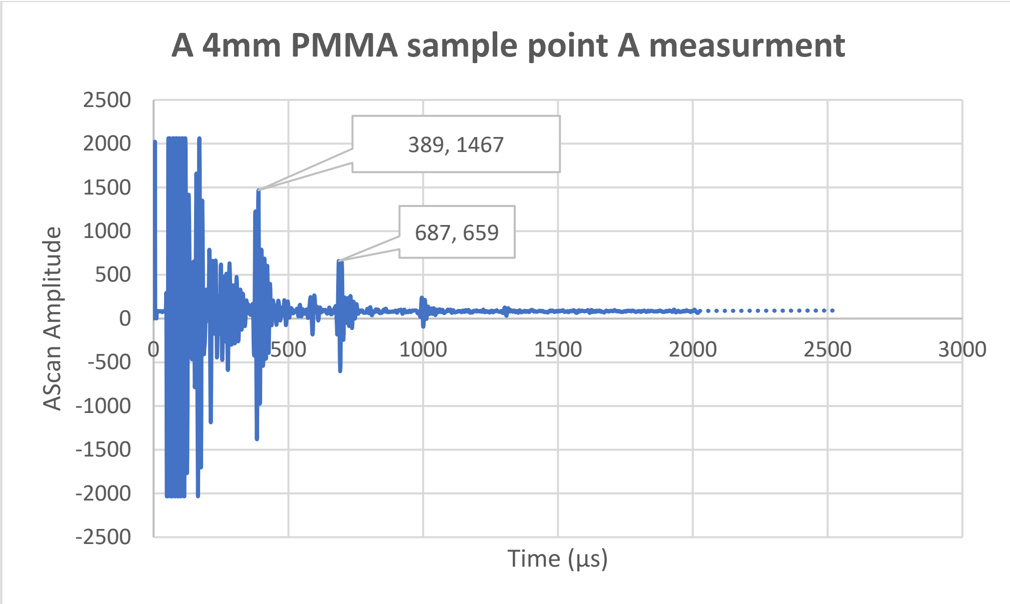

Figure 4.13 A 4mm PMMA sample point A measurement.

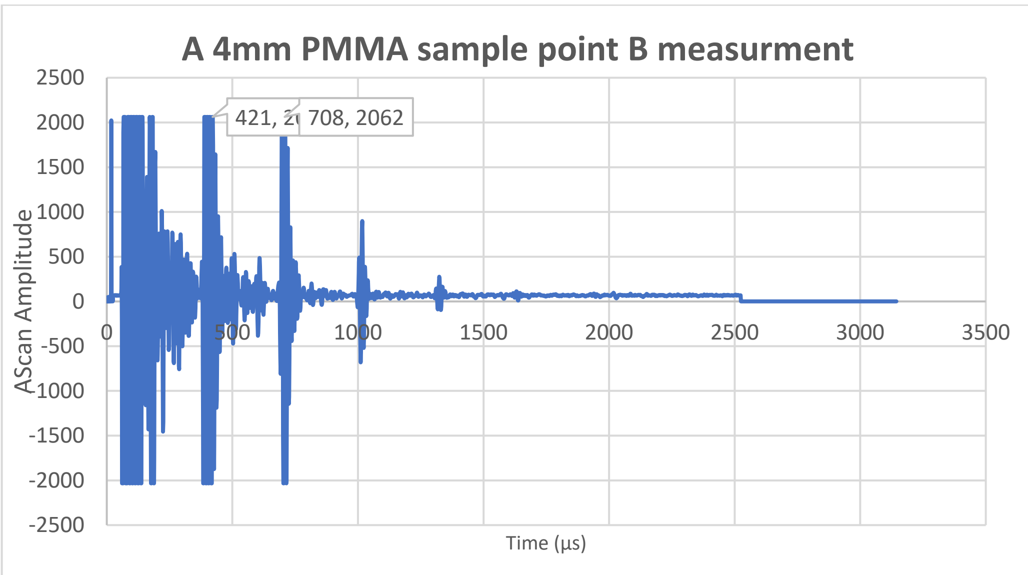

Figure 4.14 A 4mm PMMA sample point B measurement.

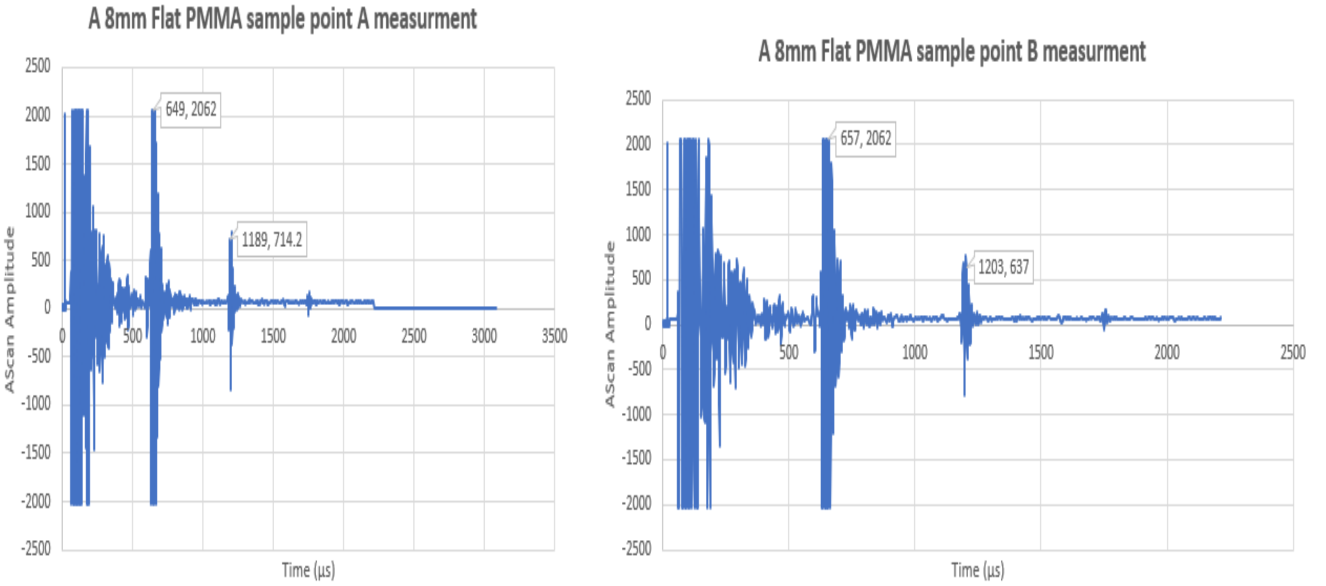

Figure 4.15 8mm flat sample point A and point B measurements.

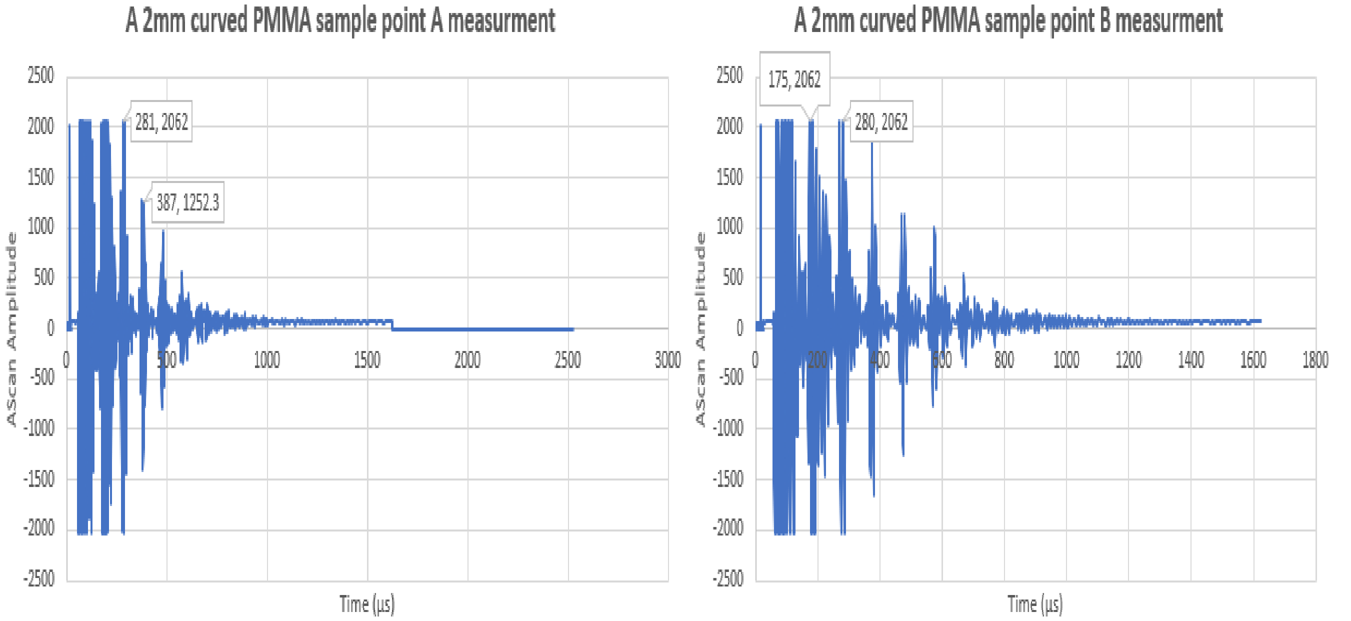

Figure 4.16 2mm curved PMMA sample Point A measurement and point B.

Table 4.5 Thickness measurements for all materials.

Sample Thickness based on source	***Digital caliper thickness at point A (mm)***	***Calculated SOS at point A (m/s)***	***Calculated thickness based on SOS from point A***	***Thickness agreement between ultrasound and caliper Specific Sample SOS***	***Calculated thickness (B) based on SOS General reference***	***Thickness agreement between ultrasound and caliper General SOS***
Acrylic tooth 1mm	*1.2*	*2608*	*1.0*	*83%*	*2500 m/s 0.96 mm*	*80%*
Ceramic material restoration 1.5mm	*1.3*	*5531*	*1.16*	*89%*	*4319m/s 0.90 mm*	*70%*
Dental composite 4mm	*3.6*	*6486*	*4.08*	*88%*	*3306 m/s 2.08 mm*	*58%*
Flat 1mm Glass	*1.1*	*4400*	*1.1*	*100% Note the TOF was same for A and B*	*5789 m/s 1.4 mm*	*79%*
Curved 1mm Glass	*1.3*	*3714*	*1.2*	*92%*	*5789 m/s 1.9 mm*	*68%*
Flat 8mm Glass	*7.8*	*5714*	*7.7*	*98%*	*5789 m/s 7.9 mm*	*98%*
Flat 4mm Glass	*3.7*	*5563*	*3.9*	*94%*	*5789 m/s 4.1 mm*	*90%*

Finally, this result will highlight the outcomes of measurements of the combined double layers, as it can be seen from the waveform plot below signals were differ in intensity when additional sample layers were added. Figure 4.26 left shows the single PMMA of 4mm sample waveform, and right represents the double specimen of PMMA 4mm and 2mm together. Figure 4.27 highlights the waveform of the latter samples together and their time slot.

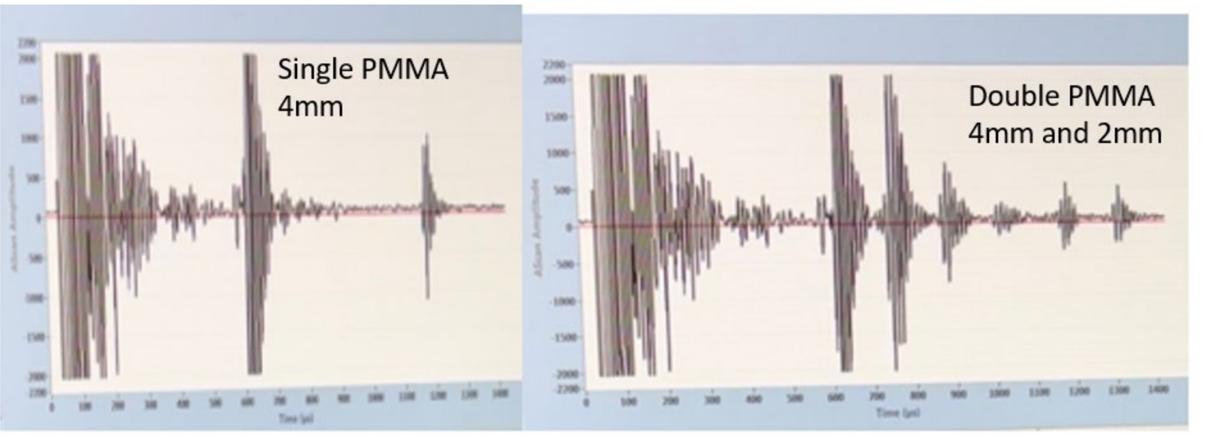

Figure 4.17 Waveform of two specimens.

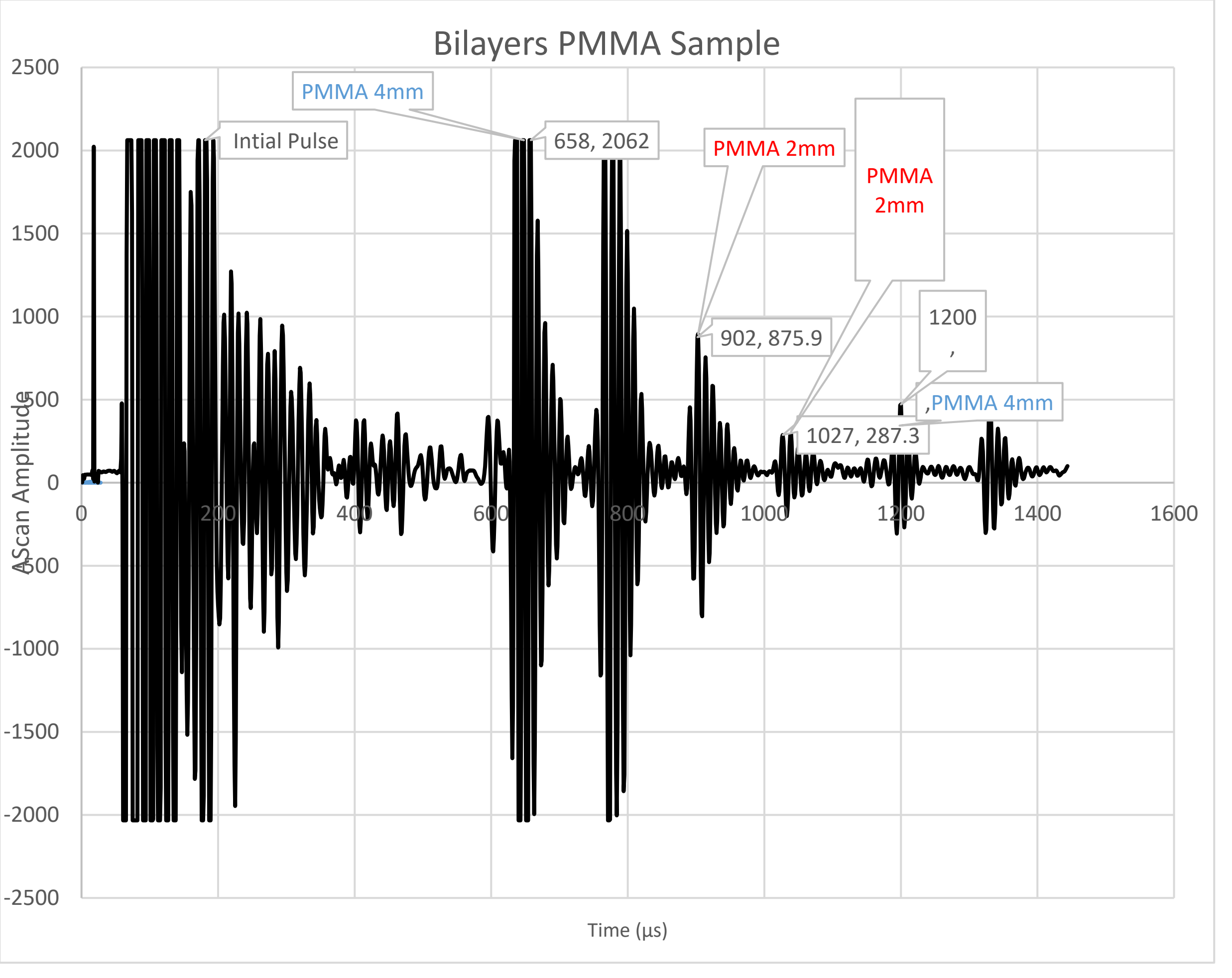

Figure 4.18 Highlighted bilayer specimens of PMMA and their reflections of Double 4mm and 2mm.

For the above figures, having a single measurement first, helps in identifying the signals platform starting from the initial pulse and the reflection from single PMMA sample, as in Figure 4.27 left diagram. when the second material added on top of this sample and a new ultrasonic measurement is taken, the additional reflection in Figure 2.27 right diagram that were not present in the left one, represents the added sample of a 2mm PMMA, hence, these reflections related to the new material added therefore, it is possible to distinguish the two materials. However, this is possible when a baseline measurement of a single material taken first and saved, then any additional sample on top of the baseline material is added, this difference in reflections represent different layers, as it can be seen in Figure 4.28. the double samples were assembled on top of each other, without using a glue or additional cement. For teeth samples this would be useful to look for different reflection of the same sample as this reflection would be related to enamel and dentin layers.

5.7 Discussion and Conclusions

The initial testing in this Chapter was focused on establishing waveforms, with different sensors, and these were found to be dependent on the frequency and type. Weaker frequencies provided weaker signals in the monolayer. The focus was on determining the approaches' accuracy and whether they could be turned into a practical instrument for capturing dental clinical measurements. Such a device would aid dentists in early detection of underlying gaps, decay, and any tooth surface losses, and aid in treatment planning, as well as addressing the general lack of enamel thickness data identified by Harris and Hicks (99). Since SOS has been found not to be constant throughout teeth surfaces from one to another, it would be useful to provide a baseline against which samples with genetic, chromosomal, or other abnormalities affecting denture or enamel formation could be quantitatively compared.

It is worth noting that the enamel's structure is not uniform and, as a result, the density varies across the tooth. This means that ultrasonic measurements will have inaccuracies due to variances in sound speed. However, by employing the most appropriate measurement technique, these inaccuracies can be reduced by making comparisons of measurements on the same tooth over time, so as to detect changes rather than an absolute value.

This study explored different set-up instrumentation as compared between Picoscope and FMS, the outcomes were in favour of the use of the FMS, however, the Picoscope and commercial sensors used were sufficient for simple materials with less a heterogeneous structure for instance large 4mm of glass or PMMA. On the other hand, these instrumentations would not be ideal if the surface area is limited such as the case with teeth. Hence, the FMS would contribute to better adaptations.

This chapter also concluded that ultrasound is able to detect thickness of simple materials more precisely when the SOS is determined in the sample at a different site, rather than a general reference SOS. Having said that, the shape of specimen varies considerably, some samples were highly accurate compared to the microscopic measurement even when a generalized SOS is used.

Finally, in terms of coupling materials, water based gel have been used initially, with good adaptations, however, water also seemed to provide similar results, which helps in applying these for the next experimental tests.

When considering bilayer measurements, several factors come into view. Initially, the thickness of the layers was measured, followed by tracking changes in this thickness, a process analogous to studying tooth wear. Lastly, identifying any cracks or gaps in restorations, as well as defects in the enamel or dentin, provides crucial information about the state of the bilayers. The scrutiny of three layers bears similarities to the analysis of bilayers. It starts with the observation of the layers, followed by enabling thickness measurements. Identifying changes in thickness and locating cracks or gaps in restorations, or defects in the enamel or dentin, form the next steps in this investigative process.

Chapter 5: Ultrasonic Measurements of Bovine Teeth

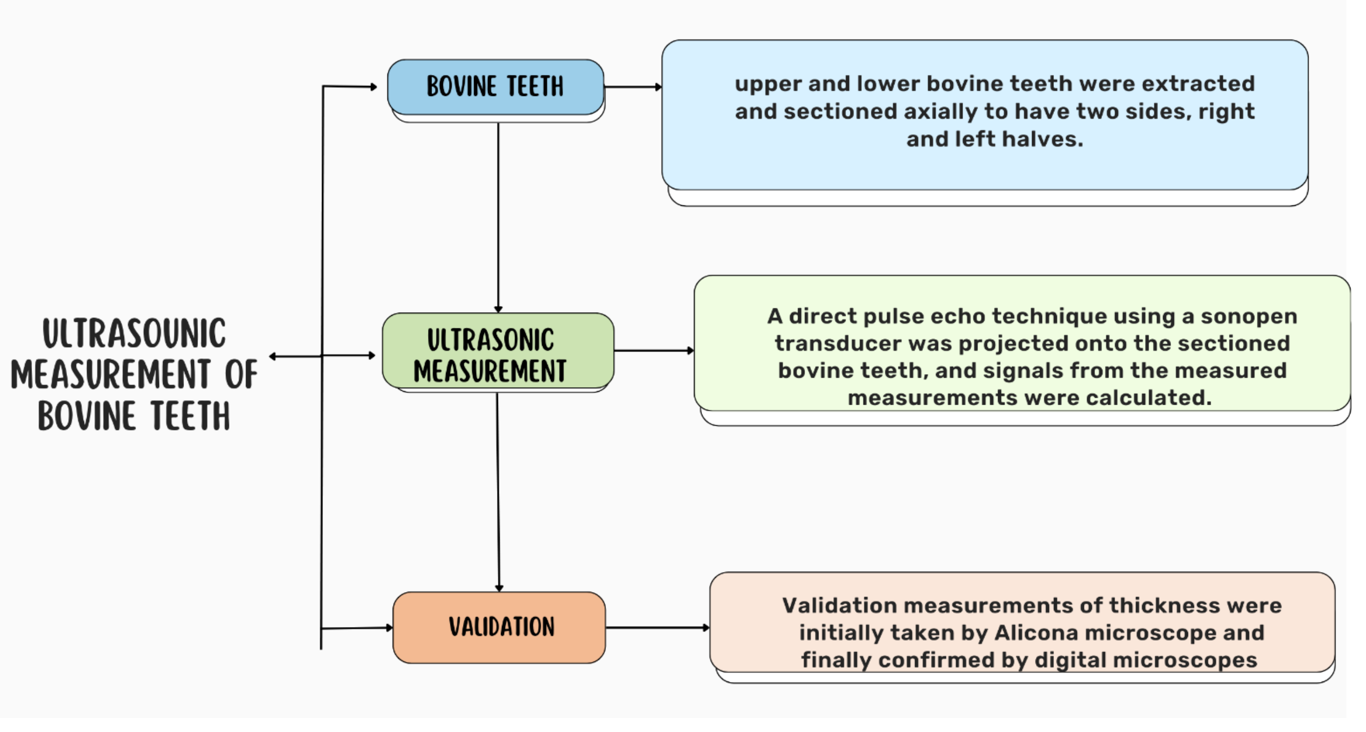

Figure 5.0 Flowchart shows the experimental method in this chapter

The purpose of this section is to delve into the potential of ultrasound to gauge bovine teeth thickness, particularly when tooth surface loss (TSL) is emulated to mimic dental wear. The selection of a relatively rudimentary method, such as A-mode ultrasonography, was guided by the requirement to evaluate specific dimensions of enamel tooth structure, laying the groundwork for the development of diagnostic devices suitable for dental practice.

One central premise was to execute a set of point measurements on the labial or buccal surface of the tooth, as opposed to a comprehensive analysis akin to the procedures involved in 3D laser scanning and image registration. Given the uniform contact of erosive materials with the labial surface of the tooth, a selection of spot measurements should suffice in monitoring erosive TSL.

While laboratory measurements of teeth often involve destructive methods, it should be highlighted that the pulse-echo ultrasound approach allows for the non-destructive acquisition of thickness measurements, as illustrated by (89). It is important to note, however, that a number of studies have presented findings in contrast when comparing such data with histology, a gold standard in the field.

One potential source of discrepancy across studies could be the assumed speed of sound (SOS) within the enamel, a parameter that has typically been sourced from the literature. Nevertheless, it is well acknowledged that the SOS within enamel tissue is subject to variations, with enamel rods being a key determinant. Specifically, sound propagation is more rapid when enamel rods are parallel to the sound beam and slower when oriented otherwise.

Given the backdrop of these observations, the central aim of the present section is to investigate the capability of ultrasound measurement to consistently procure approximate dimensions of tooth structure and to monitor tooth surface loss. Concurrently, the hypothesis to be tested posits that ultrasound is capable of providing data that align closely with those derived from the validation methods, specifically measurements obtained through Alicona and digital microscopy.

6.1 The Materials and Methods

Specimens generated from human teeth are preferred for in vitro and in situ dental research because they allow for testing of the study hypothesis in a more clinically relevant substrate. However, some disadvantages and limitations with the use of human teeth exist (100). They are often difficult to obtain in sufficient quantity and with adequate quality, since many are extracted due to extensive caries lesions and other defects (100). It can also be challenging to control the source and age of the collected human teeth, which may lead to larger variations in the outcome measures of the study (101). Furthermore, the relatively small and curved surface area of human teeth may also be a limitation for specific tests requiring flat surfaces of uniform thickness (101). Finally, awareness of the infection hazard (102) and ethical issues (103) have increased. Therefore, alternative substrates have been proposed and used in dental research

Several types of non-human teeth have been utilized as substrates for in vitro and in situ dental experiments. Common examples are primate, bovine, swine , equine , and shark teeth (104). However, bovine teeth have been the most widely used substitute for human teeth in dental studies (105) Bovine teeth are easy to obtain in large quantities, in good condition and with a more uniform composition than that of human teeth. Furthermore, bovine teeth have a relatively large flat surface, and do not have caries lesions and other defects which might affect the outcome (100). Different studies covered seven main categories to compare human teeth to bovine in terms of their morphology, chemical composition, physical properties, dental caries, dental erosion/abrasion, and bonding/adhesive strength (104). Most features are similar to human teeth, one difference noted that larger diameters were found for bovine crystallites, with a bovine: human ratio of 1.6:1(106).

6.1.1 Bovine Teeth Selection and Storage

Bovine teeth were extracted using forceps in dental school, the teeth involved upper and lower jaws. An aggregate of 10 bovine teeth underwent sectioning into two halves each, yielding 20 samples. After their roots were meticulously cleaned of residual soft tissue using a spoon excavator, a toothbrush, pumice powder and stone, the teeth were submerged in distilled water and subsequently stored in a solution of 0.1% thymol (Sigma Aldrich, MO, USA). To maintain their hydration, the teeth were ensconced in the thymol solution and refrigerated at five ºC within the laboratory environment.

6.1.2 Sectioning of the Central Incisors

In the realm of dental research, particularly concerning the sectioning of central incisors, meticulous attention to detail is paramount. The process begins with a rigorous inspection of each tooth crown for symmetry, particularly focusing on the medial aspect. Moreover, this is essential to ensure the sections incorporate both the right and left sides of the tooth, located within acoustically superior regions, a critical factor for precise analysis. Consequently, a total of 10 incisors were longitudinally sectioned using a cutting apparatus equipped with a water-cooled diamond cut-off wheel of 250 μm, a method chosen for its precision and ability to reduce thermal damage during sectioning.

The sectioning procedure resulted in a pair of specimens for each tooth, encompassing both the right and left sides and spanning from the crown apex to the root end. Notably, these specimens represented the incisal, middle, and cervical thirds of the tooth, facilitating comprehensive measurement and analysis. Furthermore, to ensure clarity and visual understanding, Figures, 5.2, 5.3 and 5.4 in the document are cited as exemplars of these sectioned samples. Moreover, some sections were to yield a block of polished enamel and dentin (designated specimen A) and a block of polished dentin (designated specimen B), and designated as specimen C, Figure 5.1 the shape of the enamel dentin block different from the central incisors used in figure 5.2, and 5.3 after sectioning. The block of enamel and dentin samples were originally obtained from manufacturer of dental samples, these blocks were polished and square cut from the manufacturer, unlike the rest of the teeth samples were extracted from a cow head using surgical forceps at dental school, and sectioned after that. The teeth were not all in ideal shape and status, as some slightly damaged during the sectioning obtaining thin enamel layers, while others have a rough surface.

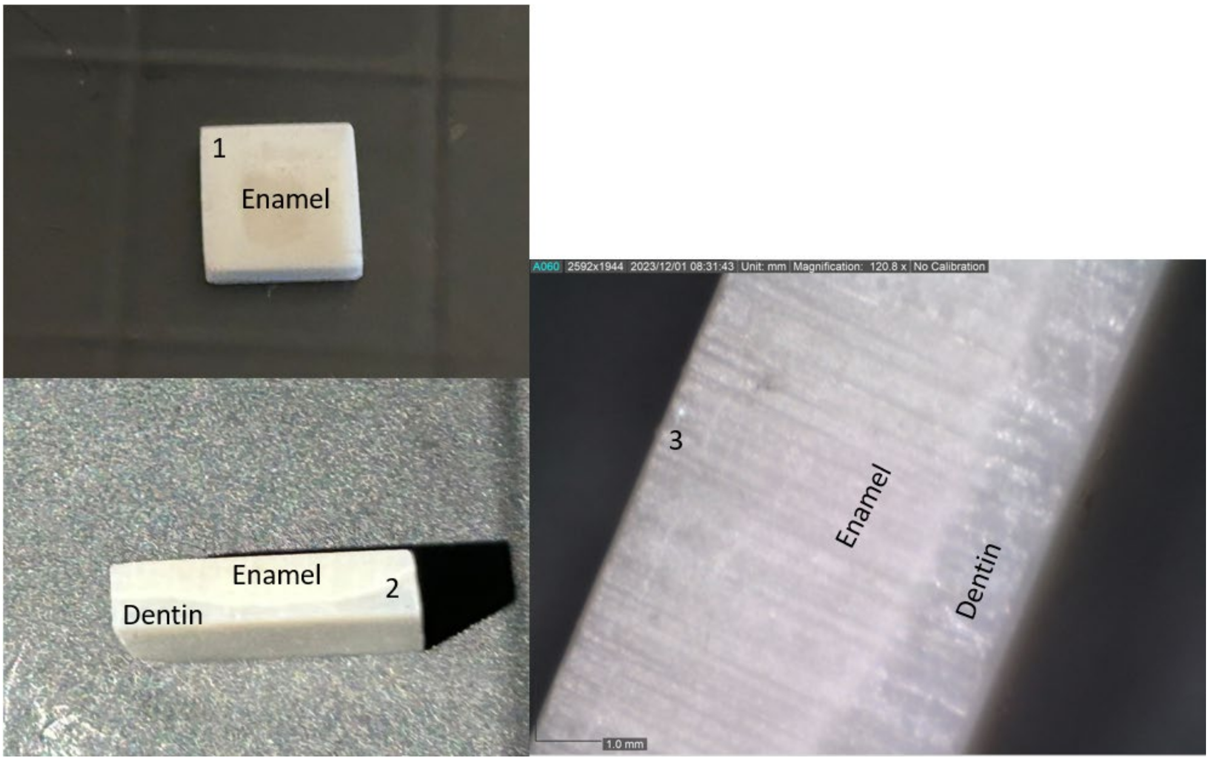

Figure 5.1 the Enamel Dentin Block, 1 top view of the tooth block, 2 side view of the tooth block tooth, and 3 side view of the tooth block under the microscope.

Figure 5.2 An example of the whole tooth attached after sectioning.

Figure 5.3 The same tooth after sectioning into two halves longitudinally to produce enamel dentin and pulp, some of teeth the pulp already calcified does not represent a space inside.

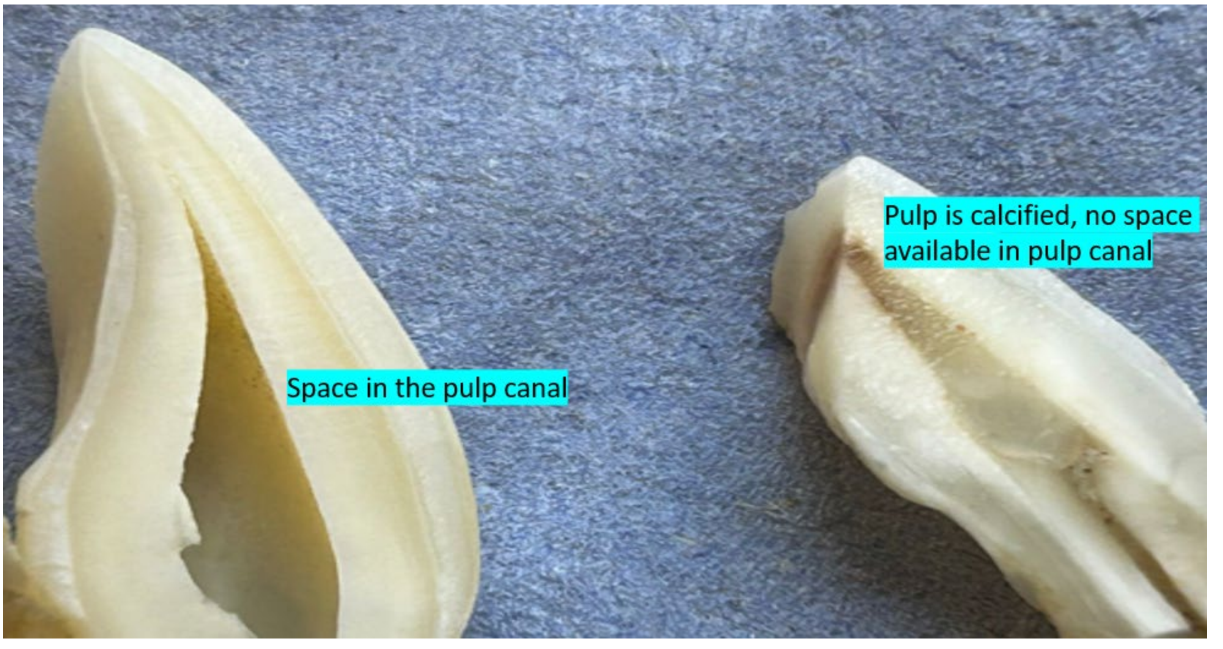

Figure 5.4 An example of a tooth has a space inside the pulp (left) and without space (right). This may contribute to different signal reflection in favour of the samples that have space in pulp area.

6.1.3 Sample Marking

The surface of each sample was marked at four locations along the enamel using a permanent marker. These markings, labelled "S" for SOS and "T" for thickness(107), were subsequently used to guide measurements. Specifically, the area marked "S" was leveraged to calculate the SOS within the respective specimen, with its thickness previously determined through digital microscopy. Once the SOS was computed, it was then used to calculate the enamel thickness at the "T" marked location. similar to the set ups used for Chapter 4 measurements. This measurement was then validated using digital microscopy.

6.1.4 Ultrasonic Apparatus Set-up

The configuration of the ultrasonic apparatus was analogous to that used in Section 4.1. Given the size of the specimens, dental boxing wax (00609, Kerr, CA, USA) was employed to secure the samples to a microscopic glass slide, thus preventing movement or instability during ultrasound readings at pre-marked regions.

In order to establish a direct contact for the pulse-echo method, a 15MHz focused transducer (VR-260, Olympus® Inc., Waltham, USA) Sonopen was linked to the enamel surface using a gel based couplant, with a Perspex disposable delay line with a 2mm tip (71).

The use of a Sonopen transducer was preferred for teeth over the manufactured sensor discussed in chapter four, because it was suited for teeth, it has a removable delay line that is applicable to the transducer, which is not possible for the manufactured ones. Also, it has better compatibility with the software FMS when measuring teeth, as this was not achievable with the customized sensor. In terms of practical considerations, the Sonopen sensor was easier to apply on teeth as it has a pen shape grip and like dental handpiece device that is used dental practice. Finally, signal reflection is achievable once applied on teeth, this is not the case when the manufactured transducer used on the same teeth.

The diameter of the tip of the transducer being 1.5 mm limited the entrance of the tip. So, the measurement area for the ultrasound, limited by the tip of the transducer, is approximately 1.7 mm^2

Excitation of the transducer was facilitated by an FMS device's pulser-receiver unit, and resultant waveforms were displayed on a digital oscilloscope of the same monitor, with particular software features under consideration. Once discernible enamel layer echoes were identified on the oscilloscope, an average of 100 echoes were recorded and subsequently analysed through Microsoft Excel.

The primary measurements were conducted on an intact tooth surface, aiming first to identify the enamel-dentin junction (EDJ), thereby determining enamel thickness and validating this measurement using a microscope, an example of electronic microscope image is used in Figure 5.6 and an Alicona image of the sectioned tooth in Figure 5.5, however, these two methods were not applied for measurements, instead a digital microscope was used for a validation of thickness measurements (see Figure 5.10). Alicona microscope is used mainly in 3D surface measurement, It enables the measurement of complex surface geometries with high resolution and accuracy. It provides detailed surface analysis, including roughness, form, and dimension measurement, which could be beneficial for further research, considering wear in teeth and roughness of enamel surfaces. However, initially, it was used here for thickness measurements, as shown in Figure 5.5. It was eventually replaced though with a digital microscope as this was easier use and its small and portable size facilitated the purpose of the research more than the Alicona microscope.

In the latter part of this chapter, the focus will shift to enamel layers subjected to the creation of cracks or defects. Here, ultrasonic measurement will be employed anew to discern the differences between sound and defective tooth structures, thereby underscoring the value of ultrasound in monitoring changes in teeth, inclusive of TSL. Hence, obtaining thickness measurements and SOS of these teeth is crucial for the understanding of the reflection of signals and comparing for any future damages that occur by using ultrasonic measurement.

Figure 5.5 Tooth images using a Alicona.

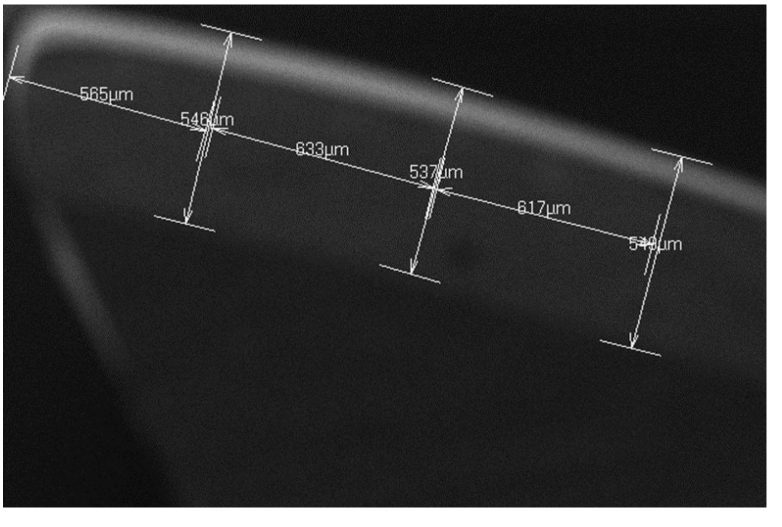

Figure 5.6 Electronic microscope image of the sectioned tooth.

6.2 Results

The analysis of Table 5.1's measurements reflects the propagation of ultrasonic energy through various dental substrates, revealing the relationship between ultrasonic sensor readings and those acquired by a digital microscope. Importantly, the table does not explicitly denote the efficiency of ultrasonic energy transport through different layers; rather, it juxtaposes thickness measurements to gauge the ultrasonic method's precision against a validated technique. Furthermore, the results indicate variability in measurement accuracy, particularly when considering the prepared enamel block and the intact tooth surfaces of samples 7 and 8. Additionally, while challenges were noted in the alignment and orientation between enamel and sensors, the data captured underscores the feasibility of using ultrasound in intact dental structures.

Moreover, the sectioned teeth, numbered 1 through 10, and the polished blocks, identified as A, B and C, offer a contrast to the unprepared tooth samples, providing a comprehensive basis for comparison. Nonetheless, the measurements detailed for the known samples serve as a testament to the potential of ultrasonic evaluation in dental materials research, with the variance between the ultrasonic and digital measurements providing insight into the method's reliability and areas for enhancement.

Table 5.1 Teeth measurements

Tooth number	***Thickness US (mm)***	***Thickness Digital (mm)***
7	*0.95*	*1.028*
8	*1.12*	*1.203*
9	1.05	1.13
10	1.15	1.22
Block (A)	*1.3*	*1.167*
Block (B)	1.25	1.33
Block (C)	1.1	1.2

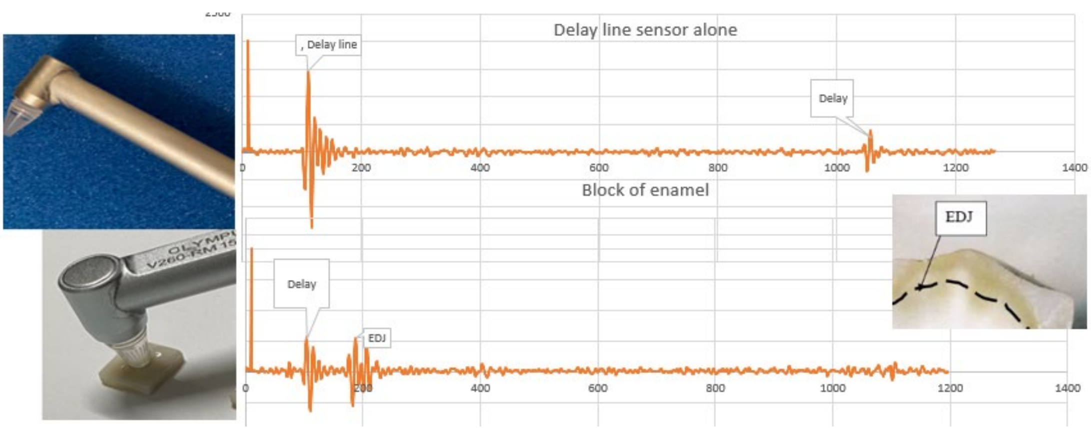

Figure 5.7 The initial pulse in this plot is removed to highlight the signals from the sensors and the tooth (upper plot just sensor and delay line, lower plot sensor, delay line and specimen), image of EDJ (61).

Figure 5.7 illustrates two separate oscilloscope traces capturing ultrasonic signals. The upper plot shows the signal from a delay line sensor alone, while the lower plot includes the signal from the sensor, delay line, and a block of enamel. In both plots, the initial pulse has been omitted to focus on the subsequent signals. Notably, the first significant peak in each plot represents the delay introduced by the sensor set-up, labelled as 'Delay'. In the lower plot, an additional peak marked as 'EDJ' (Enamel-Dentin Junction) can be observed, indicating the sensor's response after encountering the enamel block. This peak is not present in the upper plot, which lacks the enamel specimen, underscoring the impact of the enamel on the signal's travel time. The graphical representation indicates the sensor's ability to detect differences in material properties, as evidenced by the presence of the EDJ peak when the enamel is included in the measurement set-up.

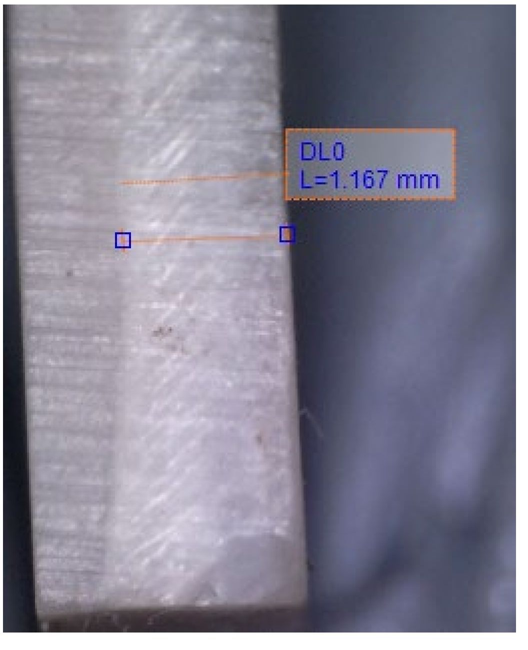

Figure 5.8 Same enamel block (as measured in Figure 5.6) assessed using a digital microscope.

Figure 5.8 displays a digital microscope image of the same enamel block that was previously measured in Figure 5.7. This image reveals the enamel block's detailed surface and the precise measurement of its thickness, indicated by the label "DLO" with a length of "L=1.167 mm." The clarity of the image allows for the distinction between the enamel and dentin layers, although, unlike actual tooth samples, there is no pulp chamber present in this enamel block. The quality of the image under the digital microscope differs from the ultrasonic signal waveforms discussed in earlier chapters, where amplitude and reflection characteristics are recorded differently. For a comparative analysis of these differences in signal behaviour, readers are directed to reference Figure 5.7, which illustrates how the ultrasonic signals translate differently when interacting with the enamel block as opposed to the intact teeth samples, likely due to the absence of complex internal structures like the pulp chamber in the enamel block.

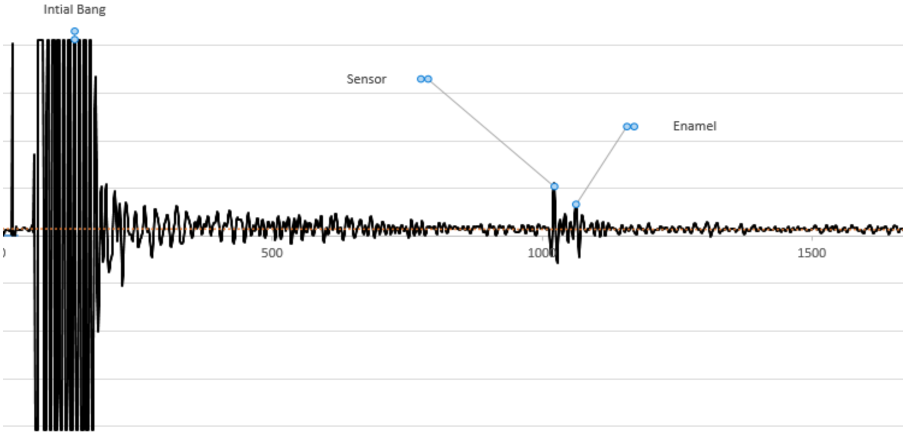

Figure 5.9 waveform of signals related to tooth sample number 7.

Figure 5.9 presents an oscillograph of an ultrasonic signal as it interacts with an enamel sample. The graph starts with a sharp, tall spike labelled as "Initial Bang," or initial pulse which represents the immediate release of ultrasonic energy from the transducer. Following this initial spike, a series of smaller, rhythmic oscillations are visible, corresponding to the ultrasonic waves traveling through the medium. Two key points are annotated on the graph: one marked as "Sensor" and the other as "Enamel." The point labelled "Sensor" likely indicates the moment the ultrasonic signal is received back at the sensor after being transmitted through the medium, while the "Enamel" marker possibly corresponds to the ultrasonic reflection from the enamel interface. The distance between these two points on the x-axis represents the time it takes for the ultrasonic waves to travel to the enamel and back to the sensor. The graph shows a relatively stable baseline with low-level noise, and the peaks corresponding to the sensor and enamel are distinct but not as pronounced as the initial bang. This visualization allows for the assessment of the enamel's thickness based on the time delay between the sensor receiving the initial signal and the reflected signal from the enamel surface. The clear demarcation of these points suggests a precise measurement could be obtained from this data.

Similarly, the measurement using a digital microscope was carried out for tooth number 8 and shown in Figure 5.10. The measurement of the specific area made in order to obtain the thickness is shown in Figures 5.11 and 5.12, these thickness calculations represent the thickness of the enamel structure at the desired site, it is the same point where the ultrasonic probe was pointed. Also an example of unequal amount of enamel structure seen in the enamel surface is shown in Figure 5.13.

Figure 5.10 Tooth number 8 full image of digital microscope of sectioned tooth showing both sides buccal and palatal, noted an enamel split this would serve as a reference point when measured with ultrasound.

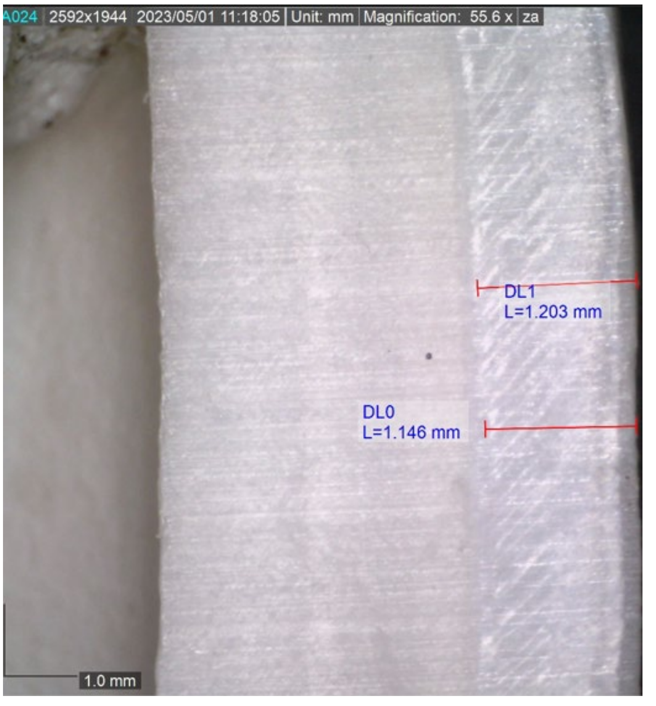

Figure 5.11 Tooth number 8 enamel thickness measurement with digital microscope.

As labelled in Figure 5.10, the use of microscope to obtain a validated thickness is useful, the differences in structure and thickness are highlighted. The same tooth measurement produced by the digital microscope is shown in Figure 5.11, but with more focus on the buccal side, where the ultrasonic measurement was taken.

Figure 5.12 Measurement of enamel structure thickness in different spots using a digital microscope (some inaccuracy with the lines).

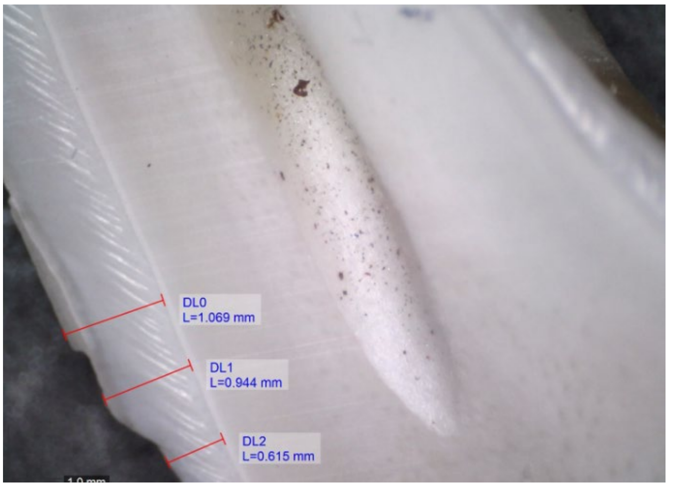

Figure 5.13 Example of reduced size of enamel in different area (based on the nature of sample) they are varies in enamel distributions, when teeth were sectioned not all samples were equally sized produced.

Figure 5.14 Tooth number 7 Sensor delay line in contact with enamel side of right section of a central incisor.

Figure 5.14 captures a close-up view of tooth number 7 with a sensor delay line in direct contact with the enamel on the right section of a central incisor. The delay line, which appears as the ribbed, dark structure on the right side of the image, is aligned against the smooth, white surface of the tooth enamel. The scale at the bottom left indicates a 1.0 mm measurement for scale reference.

The image raises a point of consideration regarding the alignment of the delay line with the tooth's surface. Achieving an exact 90-degree angle between the delay line surface and the enamel is critical for accurate ultrasonic thickness measurements. Any deviation from this perpendicular alignment could result in measurement errors. This challenge is particularly relevant as the tooth surfaces are curved and the delay line is rigid, making perfect alignment difficult. The image does not explicitly discuss these alignment challenges, but it is implied that this is a crucial step in the measurement process. Furthermore, the contact point depicted here is where the ultrasonic measurements are conducted. The earlier Figures, 5.12 and 5.13, likely show variations in thickness across the tooth surface, which this setup is designed to measure. This image serves as a visual reference for the precise point of interaction between the ultrasonic equipment and the tooth structure, a factor that is essential in the study of enamel thickness and health.

Table 5.2 in the study juxtaposes ultrasonic measurements employing a direct contact method, as depicted in Figure 5.14, against those obtained using a digital microscope. Significantly, this comparison is pivotal for validating the ultrasonic method's accuracy. Teeth labelled A, B, and C, sourced differently than the rest, demonstrated variance chiefly due to the timing of their acquisition. Moreover, these variances are critical as they highlight the potential impact of sample age or condition on measurement accuracy. The rest of the teeth, numbered from 1 to 10, represented only the right side of each tooth, an important detail for consistency in data comparison.

Discrepancies between the ultrasonic and microscopic measurements are notable and warrant attention. For example, Tooth A showed a high concordance of 98% between the two methods, indicating a mere 2% difference. Conversely, Tooth 4 exhibited a stark difference of 41% between the ultrasonic and microscopic measurements. This significant discrepancy underscores the challenges in using ultrasound for precise enamel thickness measurement, as it may introduce more errors. Furthermore, the range of agreement percentages, as highlighted in Figure 5.15, suggests that multiple measurements were likely taken for each tooth. Clarifying this aspect in the text is essential to understand the averaging process and to evaluate the reliability of the data, thereby enhancing the study's credibility. Understanding why such variations exist, especially in the context of different tooth samples and measurement methods, is crucial for refining these techniques and improving dental diagnostic accuracy.

The variations in tooth thickness measurements presented in Table 5.2, comparing ultrasonic and microscope methods, indeed show significant differences. These measurements are not averages but represent specific points on each tooth, corresponding to the same location where the ultrasonic measurement was taken. This approach ensures a direct comparison between the two methods for each tooth, thereby providing a clear understanding of the discrepancies observed. For instance, Tooth A's measurements are 1.261 mm via microscope and 1.282 mm using ultrasonics, indicating a close alignment. In contrast, Tooth B shows a substantial difference, with 1.121 mm measured by microscope and 1.795 mm by ultrasonics. This pattern of variation across the teeth suggests that factors such as the measurement technique, the precision of the tools, or the inherent properties of each tooth might contribute to these differences.

Table 5.1 Teeth ultrasonic thickness measurements compared to microscope measurements.

Tooth Number	***Microscope Thickness measurement (mm)***	***Ultrasonic thickness measurement using SOS 5700m/s (mm)***(107)
Tooth A	*1.261*	*1.282*
Tooth B	*1.121*	*1.795*
Tooth C	*1.131*	*1.453*
Tooth 1	*1.176*	*1.282*
Tooth 2	*1.004*	*1.824*
Tooth 3	*0.919*	*1.11*
Tooth 4	*1.074*	*1.8*
Tooth 5	*1.181*	*1.28*
Tooth 6	*0.989*	*1.5*
Tooth 7	*1.315*	*1.75*
Tooth 8	*1.141*	*1.67*
Tooth 9	*1.025*	*1.4*
Tooth 10	*1.215*	*1.85*

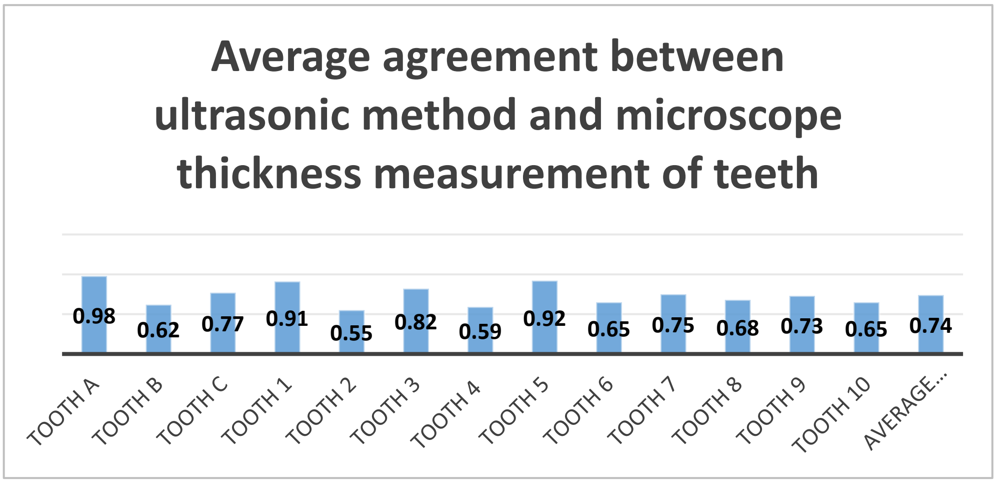

Figure 5.15 Percentage agreement between US measurements and microscope.

Table 5.3 Teeth ultrasonic and digital microscope thickness measurements with their accuracy agreement.

Tooth ID	Type	Size	Microscope thickness (mm)	Ultrasound Thickness (mm)	Accuracy of Ultrasound
Tooth A	Block of Enamel an Dentin	Small	1.261	1.282	98%
Tooth B	Block of Enamel an Dentin	Small	1.121	1.795	62%
Tooth C	Block of Enamel an Dentin	Small	1.131	1.453	77%
Tooth 1	Upper incisor	Large	1.176	1.282	91%
Tooth 2	Lower incisor	Small	1.004	1.824	55%
Tooth 3	Upper incisor	Large	0.919	1.11	82%
Tooth 4	Lower incisor	Small	1.074	1.8	59%
Tooth 5	Upper incisor	Large	1.181	1.28	92%
Tooth 6	Lower incisor	Small	0.989	1.5	65%
Tooth 7	Upper incisor	Large	1.315	1.75	75%
Tooth 8	Lower premolar	Small	1.141	1.67	68%
Tooth 9	Upper premolar	Large	1.025	1.4	73%
Tooth 10	Lower premolar	Small	1.215	1.85	65%

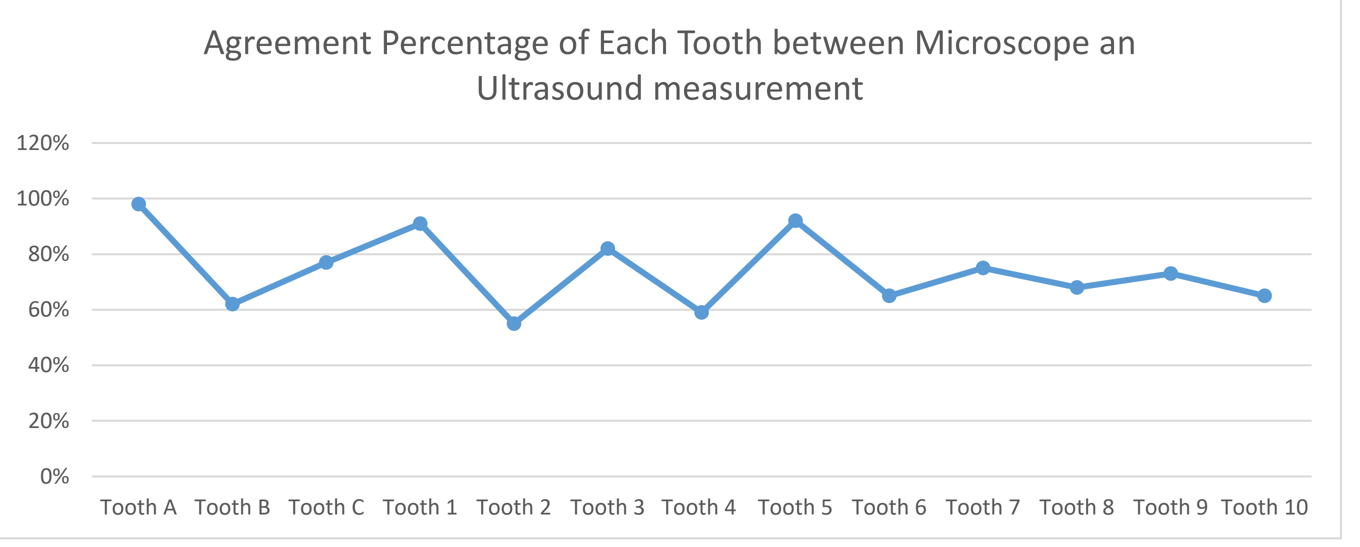

Figure 5.16 Percentage agreement between US measurements and microscope.

Figure 5.15 and Figure 5.16 illustrate the percentage agreement between ultrasonic (US) measurements and microscope evaluations across various dental samples. The x-axis categorizes the samples by tooth numbers 1 to 10 and additionally includes teeth labeled A, B, and C. The y-axis represents the agreement percentage, ranging from 0% to 120%.

The graph shows fluctuating levels of agreement for each tooth, suggesting variability in the accuracy of ultrasonic measurements when compared to the microscope's findings. Tooth A show relatively high agreement percentages, nearing or exceeding 100%, indicating that ultrasonic measurements for these samples are very close to those obtained via the microscope. However, the agreement percentage decreases markedly from Tooth 5 onward, with Tooth 10 displaying a significantly lower level of agreement.

The arrangement of the teeth in the graph follows a mixed sequence with A, B, and C preceding Teeth 1 through 10. For better clarity and logical sequence, it would be more intuitive to present Teeth 1 to 10 followed by A, B, and C, or alternatively, label A, B, and C as Teeth 11, 12, and 13. This would provide a more conventional and clear representation of the data, especially when presenting the actual thickness measurements, which are presumably shown in the subsequent Figure 5.16. Such a sequence would aid in understanding the progression and comparison of measurement accuracy across all samples.

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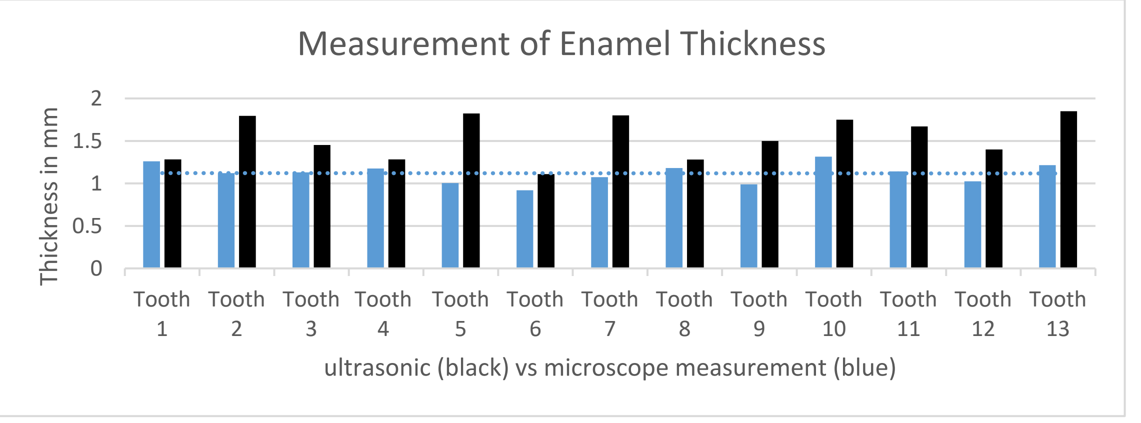


Figure 5.16 Measurement of enamel layer thickness obtained by ultrasonic testing and validated by digital microscope.

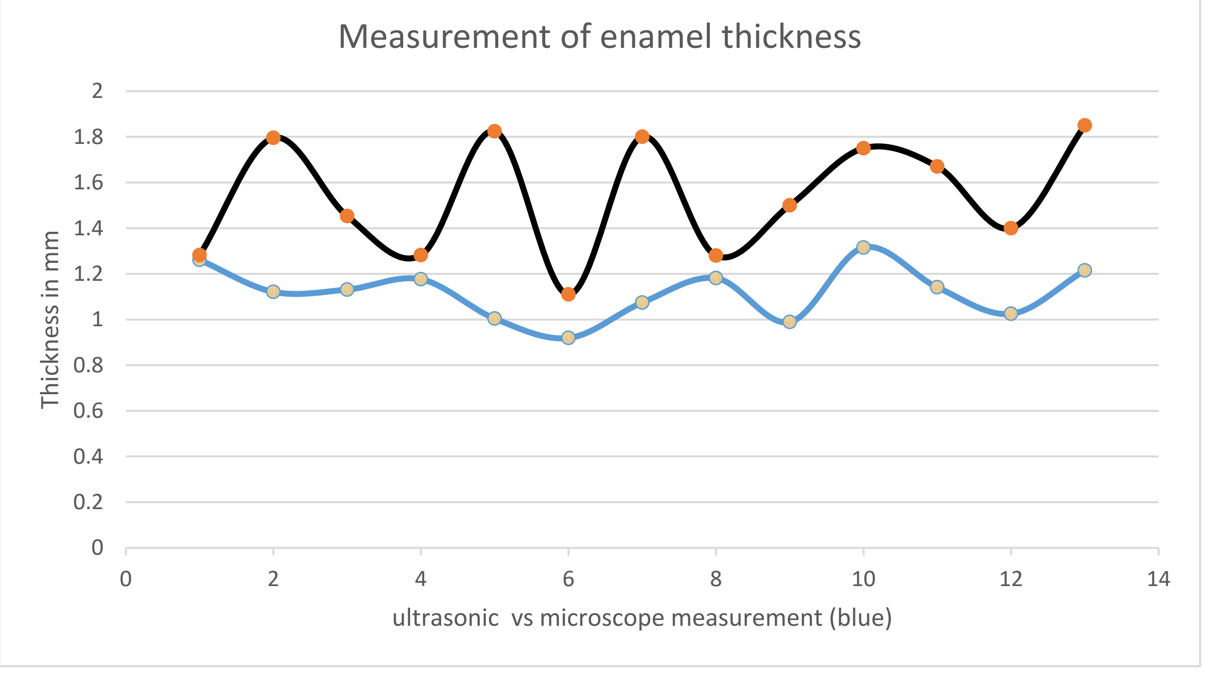


Figure 5.17 Comparison between ultrasound (black) and microscope (blue).

Figure 5.17 is a line graph comparing enamel thickness measurements obtained via ultrasound (black line) and microscope (blue line). The x-axis enumerates the samples, ranging from 1 to approximately 13, indicating individual teeth or enamel blocks. The y-axis quantifies thickness in millimetres, from 0 to 2 mm.

Both lines show oscillations, but the ultrasound measurements display more pronounced fluctuations, with the peaks and troughs of the black line often reaching higher and lower points than those of the blue line. This suggests that ultrasound measurements vary more significantly from one sample to another compared to the microscope measurements.

Notably, there are points where both measurement methods agree closely, as indicated by the orange dots where the black and blue lines meet. Conversely, there are instances, particularly around samples 2, 6, and between 10 and 12, where the discrepancy between the two methods is more pronounced, with the ultrasound showing greater thickness than the microscope. The graph effectively highlights the comparative precision and variation between the two measurement techniques across the sample set.

6.3 Discussion

The challenge of effectively transferring ultrasound signals from the sensor to the target enamel surface is particularly important in dental hard tissues due to the high impedance (Z) values found in enamel and the sensor, compared to the low impedance values in the mouth, such as saliva and water. This discrepancy results in a significant mismatch, leading to considerable signal loss during both transmission and reflection. Engaging materials with intermediate impedance for connection values has historically been a solution to this problem in the field of ultrasound. However, additional factors, most notably the requirement that they be safe for use in the mouth, limit the choice of such coupling materials in the field of dentistry. It has been investigated (64) using different materials, including some dental materials that are used for other indications in dentistry, such as (addition silicone, metal and composite).

As has been noted, the use of delay lines along with the transducer is essential to delineate the first enamel border clearly; hence, the echo from the adjacent enamel surface would not reflect or appear during the excitation period of the sensor and therefore prevent the signal from being lost. The time gap created between the transducer initiation and the first echo received is essential for the ultrasonic measurement of teeth. In this chapter, acrylic material is used as a delay line, which is suitable for the oral environment.

PMMA has a relatively low density and sound speed compared to glass and tooth enamel. This affects the way ultrasound waves propagate through it. Glass has a higher density and sound speed than PMMA, resulting in different acoustic impedance. Enamel has a high density and sound speed, leading to high acoustic impedance. Dentin has a lower density and sound speed compared to enamel, but still higher than PMMA and similar to some glasses (70).

Ultrasound equipment calibrated for PMMA or glass might not provide accurate readings for dental tissues due to impedance mismatches. The choice of ultrasound frequency is influenced by the material properties. Higher frequencies provide better resolution but lower penetration depth. Since tooth enamel and dentin are dense and hard, high-frequency ultrasound (like 15 MHz) (107) can offer detailed images but may not penetrate as deeply.

Glass and PMMA are relatively homogeneous, whereas teeth have complex structures with varying densities (enamel, dentin, pulp). This complexity requires ultrasound equipment capable of handling varying acoustic properties within the same sample.

The choice of PMMA and glass in experiments in chapter 4 was due to their controlled and uniform properties, which make them easier to use in calibration and testing with similar SOS to that of enamel and dentin (98), more specifically no overlying of signals when ultrasonic method applied. However, the significant differences in acoustic properties between these materials and actual tooth tissues necessitate adjustments in ultrasound equipment settings and calibration, for example using Sonopen transducer and FMS software were applicable more than the customised transducer and PicoScope software. Understanding these differences helps in selecting the appropriate equipment and settings to achieve accurate imaging and diagnostic results in dental applications.

6.4 Conclusion and Dental Clinical Relevance

The application of ultrasonic diagnostics to a tooth-restoration interface could indeed yield insights into the integrity of dental repairs. Should a repair fail, a breach in the seal may result, manifesting as a micro-gap susceptible to infiltration by oral fluid and pathogens. Consequently, such a micro-gap would likely alter the ultrasonic echo reflections, detectable as variations in echo amplitude. An intact interface, on the other hand, would maintain a consistent echo profile. Hence, by analyzing changes in ultrasonic echo amplitude, one can infer the status of the restoration-tooth seal. Although not explicitly depicted, a measurement of a tooth with a compromised enamel would further illustrate these principles, underscoring the utility of ultrasonics in identifying subtle variations indicative of restoration failure. The dentist could then determine whether the restoration requires replacement. This feature has already been explored by Denisova et al. (27) Ghorayeb et al. (63) and others. An echo is formed when an ultrasonic wave travels through a substance and reaches an interface. Depending on the features of the interface, the magnitude and amplitude of this echo will be either enormous or tiny. Consequently, two possibilities could be present: The first is a large ultrasonic reflection when the interface has a significantly different impedance value than the materials on either side of it. However, the opposite is true; when minimal echo reflection appears; it means the interface is small. Further investigation on the change of interface material will be discussed in the next Chapter 6, as initiating damage using the impact rig will be highlighted before ultrasonic measurement and after

The precision of enamel thickness measurements via ultrasonography is highly contingent upon the angle of transducer application. If the transducer deviates from the ideal perpendicular orientation, as demonstrated in Figure 5.12, there could be a consequential loss of ultrasonic signal. Due to the tooth's curvature, the echo amplitude received from the enamel surface fluctuates with the angle of incidence. A significant deviation from the optimal 90-degree angle could result in the echo's disappearance. Moreover, the echo is not only sensitive to angle, but also to the enamel surface's roughness, adding another layer of complexity to the accurate assessment of enamel thickness.

In calculating the impact of an incorrect angle, the ultrasound traversing additional material due to angular misalignment must be considered. As depicted in Figure 5.14, incorrect angulation compromises the sensor's ability to capture the true enamel profile, necessitating meticulous attention to the transducer's orientation during ultrasonic assessments.

The results show that ultrasonography may detect interface changes as echo amplitudes (A-mode). Moreover, it can detect the size of enamel structure, therefore, any changes can be identified. When connecting a material to a specimen for ultrasonic scanning, intimate contact is essential. While not ideal, the use of water or gel as a coupling material should suffice for the testing. Ultrasound is capable of identifying the DEJ and facilitating thickness measurements.

Chapter 6: Damage Assessment in Simple Tooth Specimen.

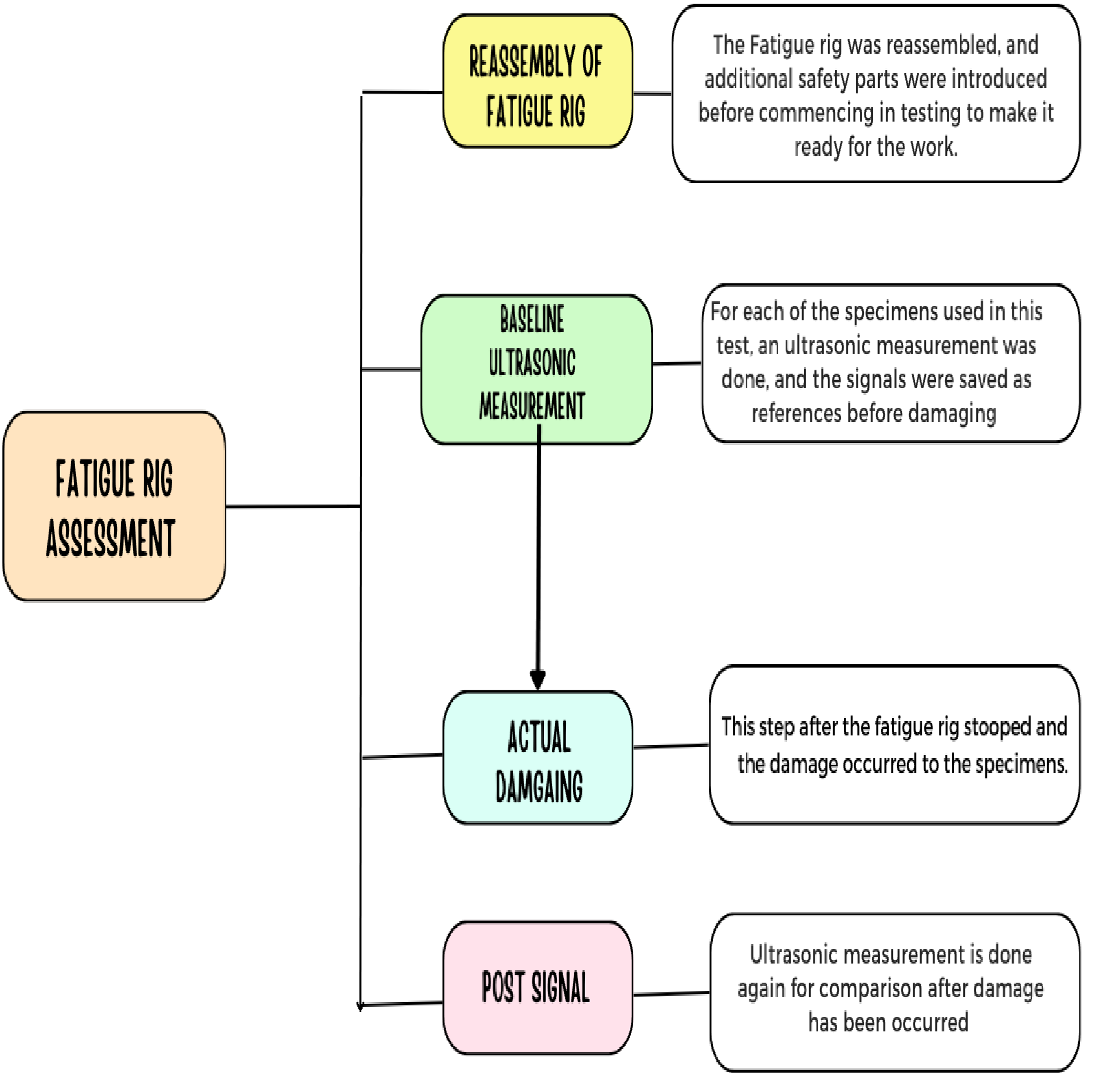


Figure 6.0 Flowchart showing the experimental method in this chapter.

7.1 Introduction

It is understandable that damaged teeth require repair and restoration; however, the major disadvantages of the materials used for replacement restorations are their susceptibility to stress, so they may fail under time-dependent stress. Evaluating the restoration's integrity and the changes that occur when such impacts happen is essential for early management and preventing total restoration failure. As an ultrasonic technique demonstrated its ability to measure layers of varying thickness in the preceding chapters, the purpose of this section is to determine whether ultrasonic techniques are capable of detecting any changes that may result from impact damage (imposed on a test-rig). Several static and dynamic testing methods were used to investigate the mechanical properties of restoration materials, such as strength, hardness, toughness, creep, and fatigue. When the life cycle and endurance of the system are the most important requirements for the restoration designer, the fatigue testing approach is the undisputed design tool for achieving a precise estimation of the desired variables. In this context, fatigue refers to the degradation of strength in an aqueous environment, where upon repeated load application, a failure of the fabricated structure is more likely to occur. This is significant in the dental clinical setting because failure of restorations or any tooth replacement is typically the consequence of a build-up of stress fatigue associated with failure rather than a sudden occurrence of overload (108)

For the purpose of creating some sort of damage to the specimen, a mechanical fatigue testing rig was reassembled and introduced for this purpose (Figures 6.1 and 6.2). Ideally this fatigue tester simply applies an axially aligned load to the specimen. The load is generated from one side by metal discs of different mass and transferred to the indenter at the opposite end of the arm by a leverage arm. The magnitude of the mass (ranging from 4 to 80 kg), the size and location of the load, the directional vector of the load, and the frequency of the load can be varied. The equipment features an automatic cut-off that stops applying the loading cycles when the specimen fractures. The sample will be subjected to a specific load for a set number of cycles. If the sample survives the cyclic load application, the load would be increased by a fixed incremental load for the following fresh sample. The technique would be continued until the sample failed with the specified increased load. For this study the aim was to apply load on the samples and detect changes in thickness/structure with ultrasonic techniques rather than achieving a complete fracture from the specimen. Bearing in mind that the properties of materials can vary significantly, with some materials exhibiting a tendency to fracture more rapidly than others when the same amount of load is applied.

Figure 6.1 The fatigue rig before additional parts were added.

Figure 6.2 The current status of the fatigue rig after the addition of the protective guard, and reassembly.

7.2 Technical Description of the Rig

This machine (Figure 6.1) is customised to have five specimen stations. Every section acts as a station, which utilises a weighted lever arm to apply a ball-end [round] anvil [indenter] to the specimens. The maximum load for each given test could range from 4 to 80 kilograms. The lowest cycle "weight" of zero kilos might be attained by lowering the lever with a rotating cam to eliminate the specimen's load. Each station has a separate counter that is stopped automatically when a sample fractures. The control box is designed to have the on/off switch button and the regulator switch that enables control of the cycle rate; this rate could vary from 30 cycles per minute to 60 cycles per minute, etc. In each corner, the emergency stop switch is easily reached. The simulated impact rig underwent additional modifications in order to make it accessible for use in the laboratory for this specific project (Figure 6.2). With the addition of a covering shield and interlock, this machine has become more secure and safe than before, according to different studies. It will stop running immediately after opening the doors, not just by pressing the emergency stop button. This additional feature for protection prevents any accidental damage that might occur during the machine's running and also allows the operator to examine the sample safely.

7.2.1 Sample Mounting Base

The mounting bases that are fixed in the water bath allow for holding a sample in a horizontal direction. Any requested sample- load alignment can be achieved by designing an adjustable sample holder and fixing it in the sample direction. The indenter can be designed as a flat anvil or a round ball indenter.

7.2.2 The Indenter

The existing indenter (see Figure 6.3) was designed to be an opposing “tooth”. A cushion made from light body impression material supports the base of the 4.25mm ball indenter. This cushion disc works as an absorbent means to simulate the PDL function of the opposing tooth and allows for a slight pressure absorbent for the indenter during the test.

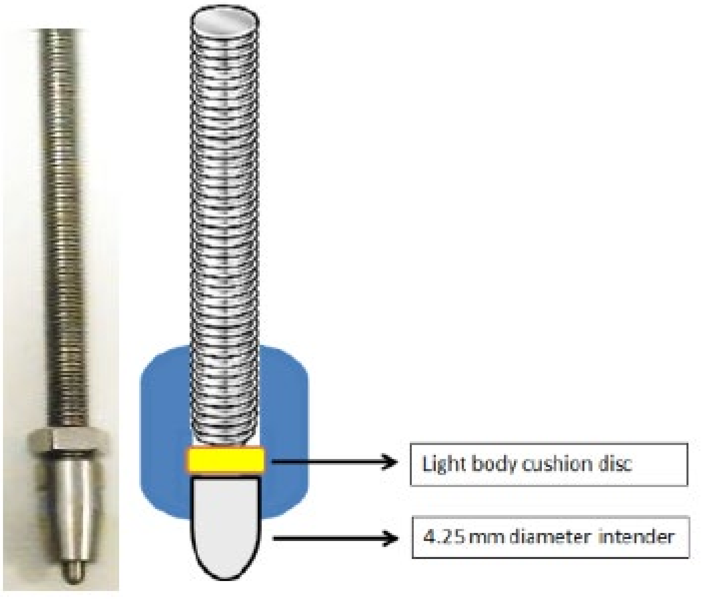


Figure 6.3 The indenter

7.2.3 Thermo-Cycling Heating System

The water pump/heater circulates hot water in the tank at 37°C and at a level of 3cm above the specimens. The limitation of the pump is that air bubbles are occasionally trapped inside the closed water system, which affects the negative pressure within the circulating system and leads to the circulation stopping. Thus, checking the circulation system regularly is advisable.

7.2.4 Load Calibration

The weight of the metal discs in this machine applies the load by passing it through the lever arm to the intender and then to the specimen. It is highly recommended to transfer the weight in the form of a kg unit to the load cell device (Table 6.1). This device offers a calibration of the load through a highly sensitive load cell that imitates the sample of the real test.

Table 6.1 Calibration of load used.

Applied Load material disks (kg)	*Total (N)*
No load 0	180
One metal disc 0.5	215
Four metal disks 2	320
Eight metal disks 4	453
Nine metal disks 4.5	487

7.2.5 Adjustment Points

To start the fatigue test, the right sample's position in relation to the indenter should be certain. The load point from one side of the lever and the indenter from the other side, as well as the sample position in the mounting holder, are interplay relations. Achieving the ideal relation between these three points can be achieved through the adjustment of the nine adjustable points. Each adjustable point is dependable on the other. A back-and-forth adjustment is recommended to secure the sample in its position.

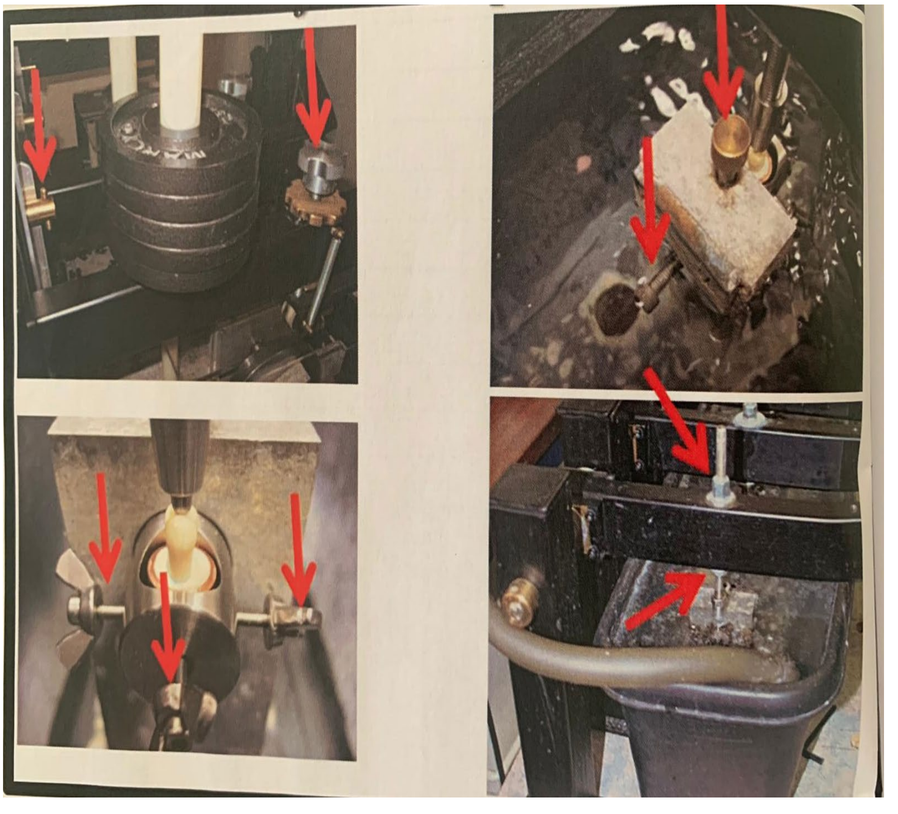


Figure 6.4 arrows shows adjustment points.

7.3 Methodology

Fatigue is the term that describes the phenomenon characterized by localized and progressive structural damage to a material under cyclic loading levels below the fracture strength or under constant conditions over time. Understanding this response is crucial for improving the clinical performance of dental restorations. The fatigue value of any material depends on various factors, such as the nature of the material or structure, the type of applied stress, test environments, load amplitude, and stress cycle frequency. In fatigue testing, the load can be applied as axial, bending, or torsion stress.

Structural strength decreases as subcritical cracks increase when the stress level rises, accelerating the progression of these cracks and eventually leading to complete failure of the restorative material. Consistent with this, clinical evidence indicates that the failure of dental restoration is not typically due to acute overload incidents but rather the accumulation of stress, resulting in fatigue-related failure (109).

When evaluating mechanical test principles, fatigue testing can be performed through various approaches. One is the direct method, known as the "fracture mechanics method," which involves testing an object with an induced crack to investigate crack growth. The other is the indirect method, referred to as "strength measurement techniques," which focuses on measuring the object's strength over a specified time interval to assess the material's fatigue properties (110).

Additionally, fatigue testing can follow different load rate profiles, such as static or dynamic fatigue profiles. Notably, the behaviour of brittle structures under cyclic loading is significantly important and often more critical compared to static profiles, as documented extensively in the literature (111).

The selection of parameters for fatigue testing is a critical step to ensure that the results accurately reflect the conditions under which the materials will be used in real-life scenarios. In this study, the parameters were selected based on a combination of literature review, preliminary experiments, and industry standards. A thorough review of existing research was conducted to understand the common practices and findings in the field of fatigue testing of dental materials. Key parameters such as load magnitude, frequency, and cycles to failure were identified from studies that have shown successful and reproducible results (112).

Preliminary tests were conducted on a small number of samples to observe how the materials responded to various loads. This helped in identifying the ranges within which the materials behaved consistently. However, due to the nature of the work that involves the reassembly of the fatigue rig and adding protective shield for safety considerations, monitoring the ultrasonic measurement while the rig is working was not recommended, therefore, it was only possible to take ultrasonic measurements at the end of the cycles.

Based on the initial results, adjustments were made to fine-tune the parameters. Calibration of the testing equipment was also carried out to ensure accuracy and repeatability of the measurements, more specifically mounting of different specimen into the rig. Ideally, the plan was to introduce the ultrasonic measurement in the middle of the machine cracking however, it was not feasible this time, further research will explore this aspect of ultrasonic measurements in the future. Therefore, the signals were compared only before the damage and after the completion of the whole cyclic.

Determining the load that the restorative material can endure for a specified number of cycles is called the fatigue limit (112). Whereas the term Fatigue life represents the number of cycles the material can sustain at a given load (113).

The purpose of this study was to analyse ultrasonic measurements on a variety of test materials, including simple samples, restorations, and teeth, both before and after an external load was applied. Here is a summary of the experimental method. Specimens were the same as described in previous chapters: glass, PMMA and an acrylic tooth, in addition to a premade crown of metal ceramic restoration. The prepared samples were first scanned with ultrasonic apparatus and the signal waveform was produced to act as a baseline comparison of intact specimens. When samples were in the holders (mounting base) a contact point with intender was determined and fixed to allow repeated load at the same point and avoid movements, the distance from the tip of the intender and the contact point of the surface of each sample stabilised to avoid any discrepancy of force or distance among all the tested materials. Then a load from the rig is applied for the first cycle, each cycle frequency which lasts 60 cycles/minute. The initial tests were for calibrations, to standardise the load and time for all samples. securing all samples in their position which remained in the centre through the experiment. For calibrations starting load was chosen for 0.5kg for the initial measurements and checking any changes of specimen noticed. Then incrementally increased the load to 5kg, until particular glass and PMMA samples shattered, a load was applied and its weight was recorded.

Before applying any load, a baseline ultrasonic measurement was performed on each sample marking the surface point of these measurements, making sure it is the same surface point that received the application of load when the machine was on. A second ultrasonic measurement was conducted on the same samples after terminating the rig's operation. compared these measurements to the baseline data to track any changes. The number of initial tests without ultrasonic measurement were conducted on relevant samples. real-time measurements were not practicable, for monitoring the changes initially, the rig was halted after a specific number of cycles for ultrasonic testing and then continued testing. Only after stopping the load application immediately before the fracture point, the second ultrasonic measurement was taken at this time to examine the signal waveform of the tested materials specimen and compared with the baseline ultrasonic measurements. This exhaustive experimental technique sought to evaluate the effect of load on diverse specimens and recorded data with the ultrasound technique being used as a monitoring tool.

For a separate calibration of detecting ultrasonic measurements changes, a dental bur was used to create a hole inside the enamel and dentin surfaces of a tooth (Figure 6.5), then ultrasonic measurements were taken of this tooth, alongside microscopic image of the same region. The ultrasonic waveform was compared to the previous ultrasonic scan of the tooth when it was intact.

Figure 6.5 showing teeth with no damage intact with dental bur in place before cutting.

7.4 Results

This test results in different ultrasonic signal waveform creations after the initiation of the fatigue rig damage to the specimen. Some of the test samples were not included, mainly due to the fact that, it is not possible to align the sensor with the surface of the specimens. As it can be seen in the figures below, only different signal waveform plots were created before and after the specimen was damaged.

Figure 6.6 provides an ultrasonic response from an undamaged tooth. The x-axis, representing time in microseconds (μs), shows the duration of the ultrasonic scan, while the y-axis indicates the scan amplitude. The plot features two prominent peaks, likely corresponding to reflections from critical interfaces within the tooth structure. The initial large spike near the beginning of the timeline could represent the ultrasonic signal's reflection from the tooth surface or the enamel's outermost layer. Following this, the graph stabilizes into a relatively flat line with minor fluctuations, indicative of the passage of the ultrasonic waves through the uniform structure of the undamaged tooth.

Subsequent figures, which are not shown here, would depict the ultrasonic responses from a damaged tooth for comparison. These would be expected to show variances in peak amplitudes or additional reflections, corresponding to discontinuities or changes in material density where damage has occurred. Comparing these ultrasonic measurements with digital microscope data is crucial, as it would provide a validation of the ultrasonic method against a visual and direct thickness measurement. The different reflections seen in the ultrasonic data could be matched with the physical layers observed under the microscope, ensuring that the ultrasonic method accurately represents the actual tooth structure and can reliably detect damage. Such a comparison would be essential for confirming the precision and utility of ultrasonic diagnostics in dental health assessment.

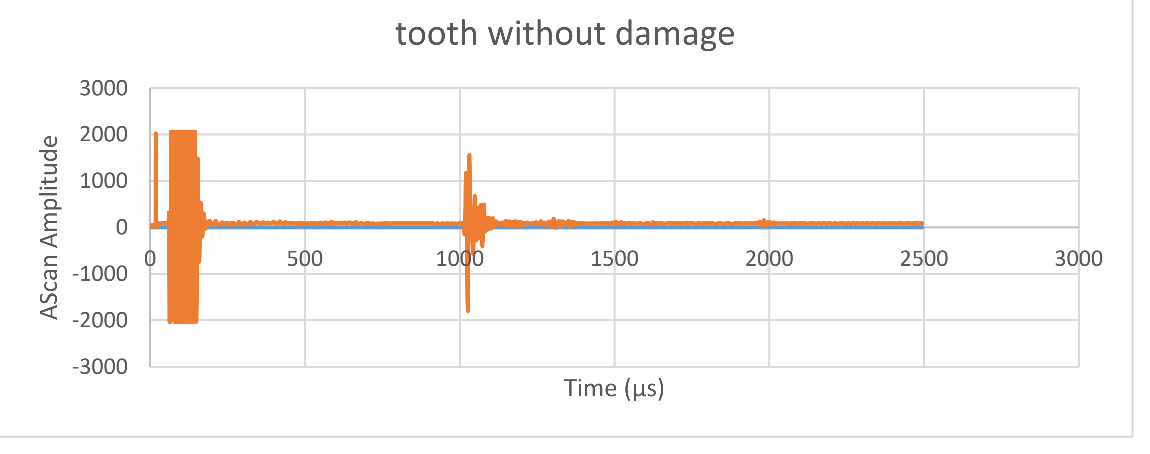


Figure 6.5 ultrasonic waveform for tooth without damage (baseline plot).

Figure 6.6 Represent damages occurring as seen in the microscope.

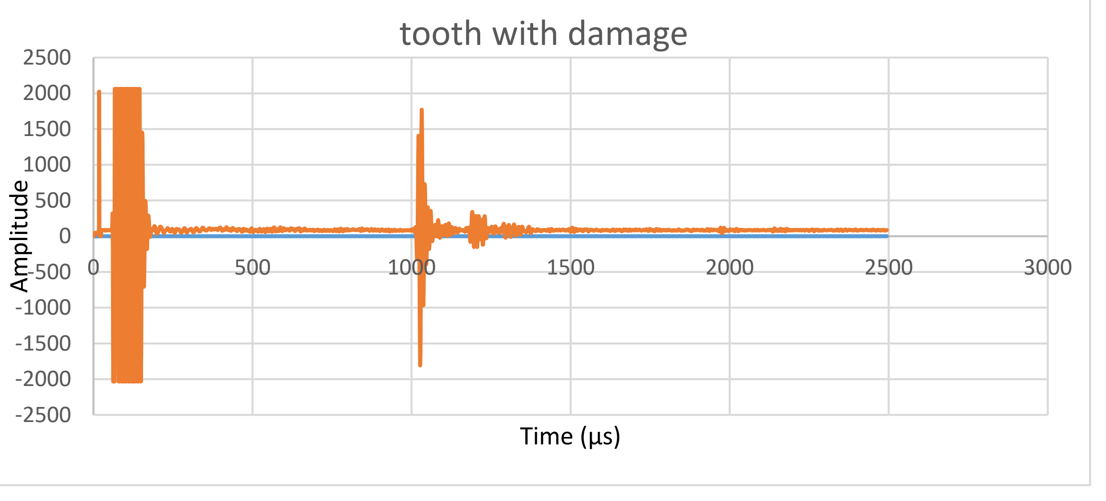


Figure 6.7 signals produced after initiating ad damage to the enamel and dentin surface.

Figure 6.9 presents two contrasting specimens subjected to cyclic impact testing: on the left, a block of PMMA (polymethyl methacrylate) material, and on the right, a ceramic type dental restoration. The PMMA block appears intact and undamaged, suggesting that its thickness has conferred sufficient resilience to withstand the applied stress. The lack of visible damage or marking on the PMMA sample makes it difficult to discern exactly where the impact occurred. However, its transparency and the absence of fractures or deformation suggest that the point of impact likely did not compromise the material's structural integrity.

Conversely, the ceramic restoration on the right exhibits a different fate. It has evidently fractured under the same cyclic impact conditions, but the image does not clearly indicate the fracture plane. The breakage seems extensive, with what appears to be a major fragment detached from the main body of the restoration, hinting at a substantial structural failure. To better understand the damage, the image would benefit from annotations or a clearer view that highlights the fracture plane, providing a visual correlation to the failure mode elucidated by the ultrasonic methodology, which is aimed at detecting such changes in material integrity post-testing.

Figure 6.8 PMMA material not damaged due to its thickness, whereas a ceramic type restoration is fractured under cyclic impact.

In the evaluation of dental materials under stress, ultrasonic diagnostics have demonstrated significant potential in detecting surface alterations and fractures. Utilizing a load level of 5kg, the ultrasonic measurements were taken before and after imposing fatigue impact damage on various specimens, including PMMA and glass samples, as depicted in Figures 6.10 to 6.14. The PMMA material revealed subtle surface changes that may not be visible to the naked eye, indicating the sensitivity of ultrasonics in detecting minute deformations.

In contrast, the glass sample suffered more pronounced damage, with parts completely shattering under the applied load, as shown in Figure 6.12. Despite this, sections of the glass remained intact enough to allow an ultrasonic scan, thus offering a comparative analysis of damaged versus undamaged areas. The metal ceramic restoration crown depicted in Figure 6.15 exhibited similar characteristics to the glass sample when subjected to the same load conditions.

The ultrasonic signals from these tests reveal critical information about the material's condition. Variations in signal amplitude and spacing between waveforms before and after damage can be indicative of changes in material integrity. For instance, a spike in amplitude or a shift in waveform periodicity could signify the presence of a crack or fracture. These ultrasonic signatures provide a non-invasive means to ascertain the extent of damage, offering valuable data that could guide clinical assessments where visual inspection alone is insufficient to detect such subtleties.

Figure 6.10 Glass specimen intact before measurements.

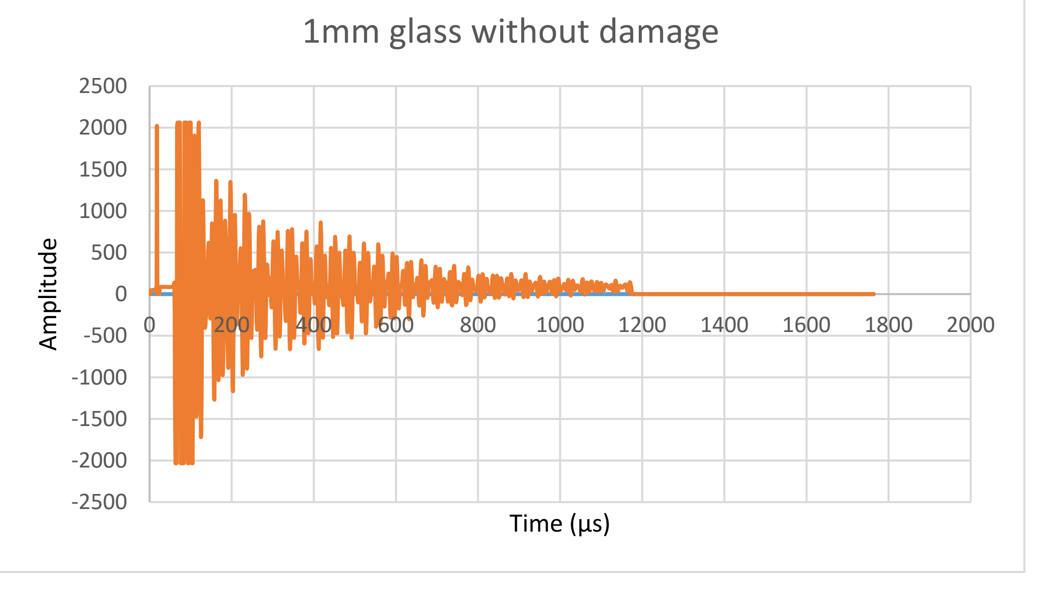
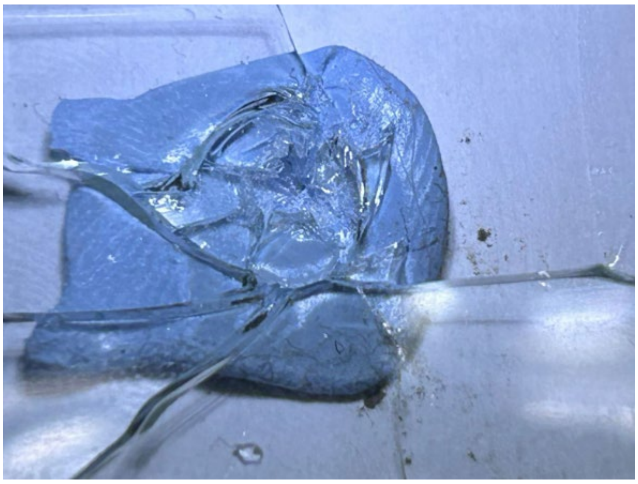


Figure 6.11 Intact Glass of 1mm thickness signal before damage.



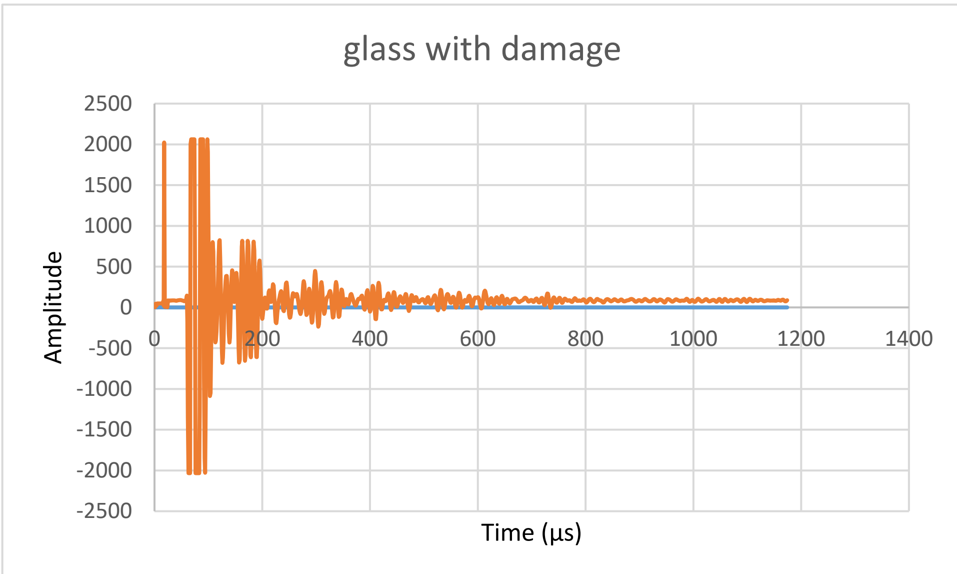


Figure 6.12 Fracture of the glass on top and its reflection signals below.

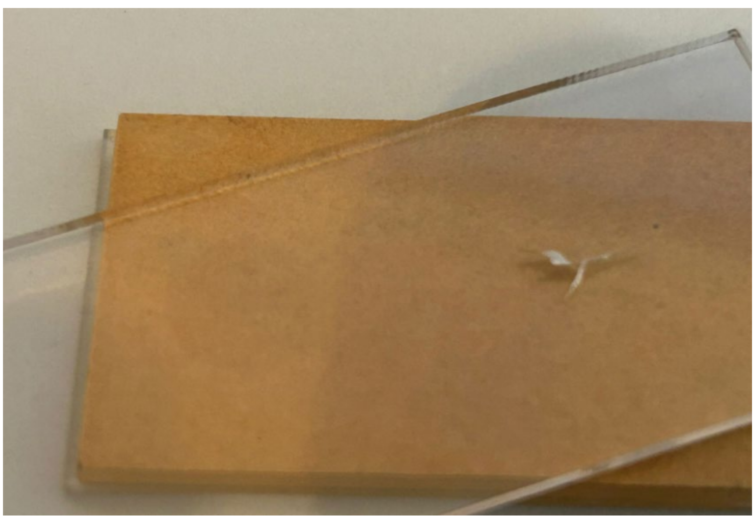


Figure 6.13a part of the PMMA.

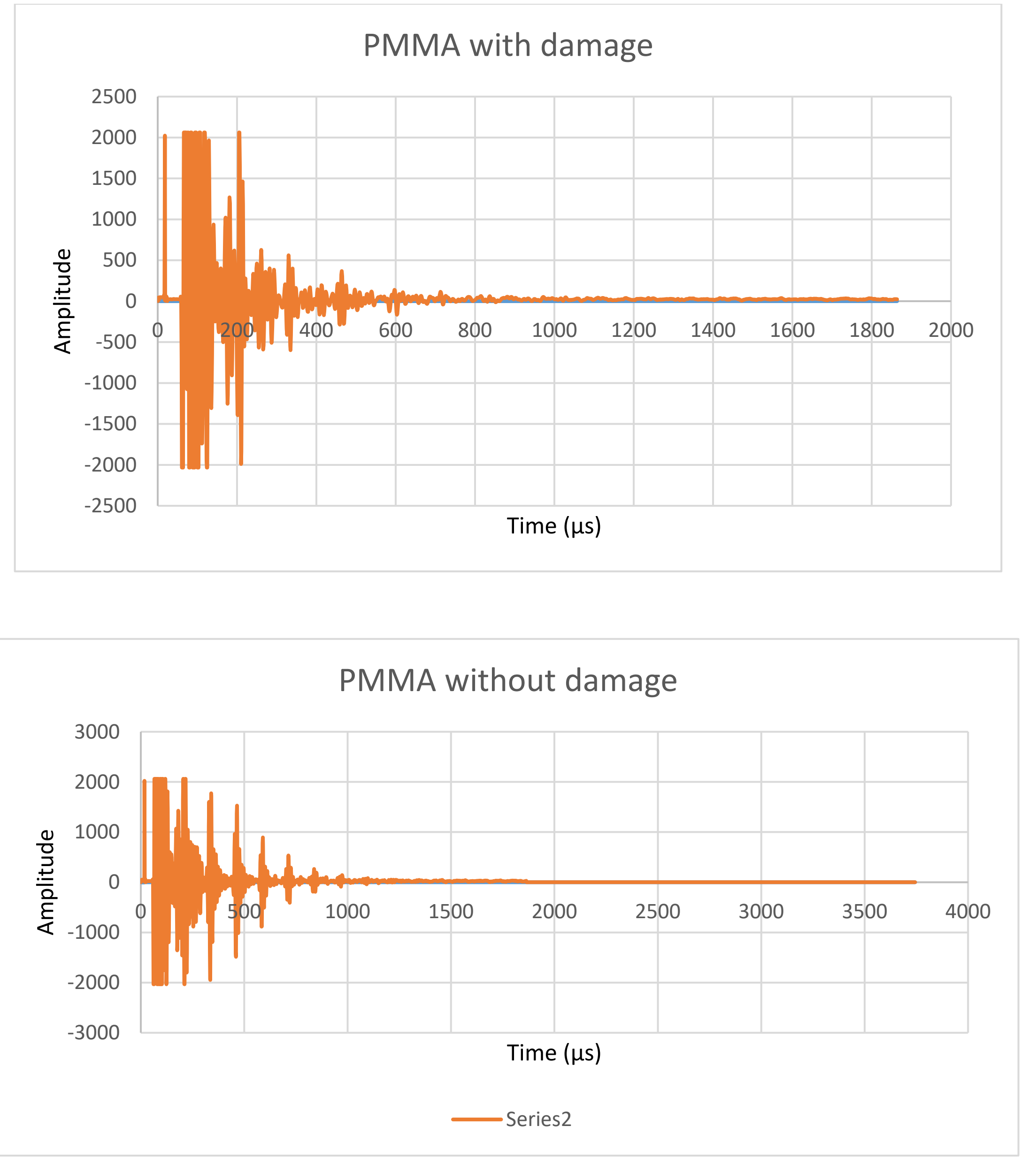


Figure 6.13b Representation of PMMA material signals before and after damage.

On the other hand, an acrylic tooth exhibited a deformation of its shape rather than a complete fracture (Figure 6.14); still, these changes in different materials were noticed when ultrasonic measurements were used after the fatigue rig stopped. Variations of signals formed before and after were noticed. The accurate measurements of the damage were not recorded as some samples were completely shattered; instead, the alterations of the signals were considered a significant result in the change of these materials; therefore, baseline signals served as benchmarking against the second waveform plot. The fluctuations of the signals were considered a change in material surface/thickness as long as they were not identical to the intact sample waveforms.

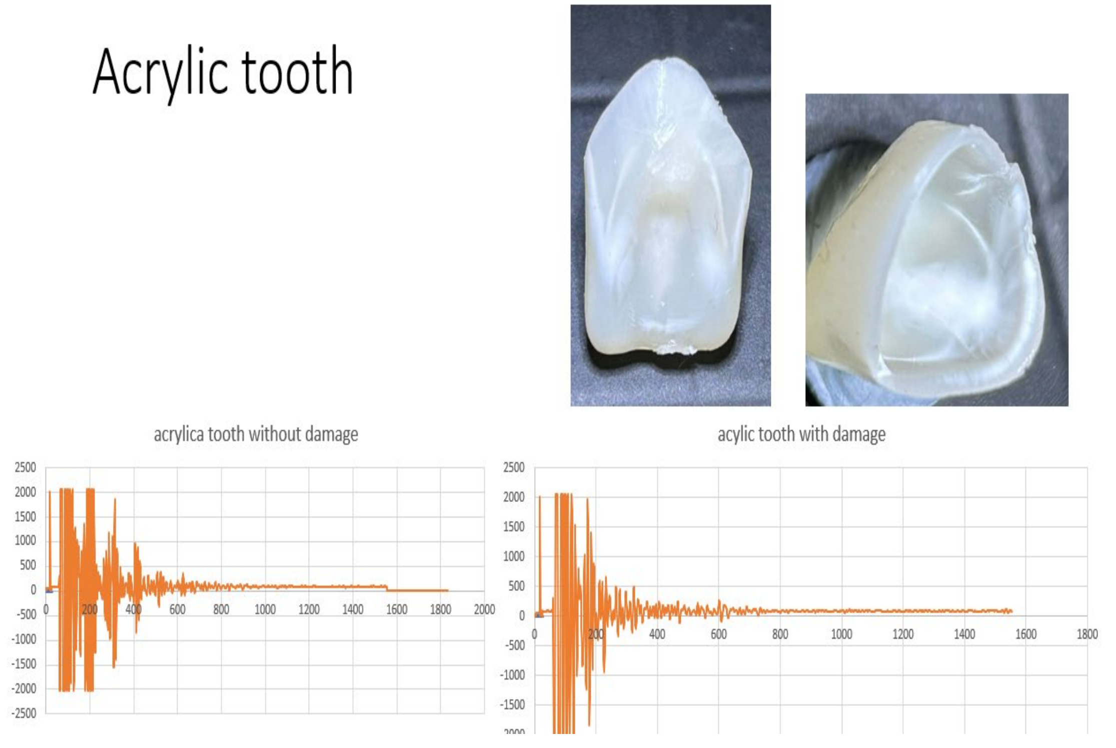


Figure 6.13 acrylic tooth signals before and after the damage.

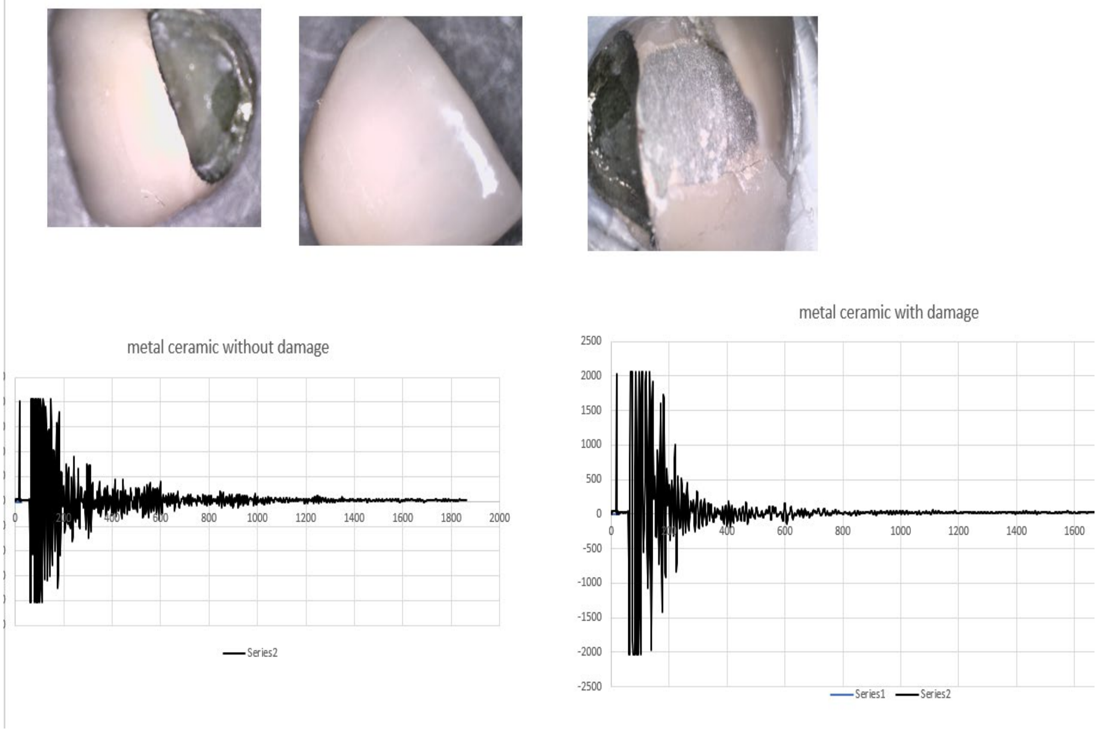


Figure 6.14 comparison between the signal wave sound of metal ceramic before and after the damage introduced by the rig.

7.5 Discussion and Conclusions

Ultrasound was able to determine the changes that occur to the samples after introduction of the impact rig. Some materials were thin therefore, complete fracture occurred, while other thicker remain intact after cycling impact. The findings suggest that the application of controlled loads using the fatigue rig, combined with ultrasonic measurements, can provide valuable insights into the structural changes within restorations. It is emphasized that this experimental procedure is carried out in multiple phases, each with a clear set of objectives. Factors related to the time and the load of each sample were different. However, this test represents the changes that is seen the reflected signals rather than the complete calculations of the damage. Ideally, this can be further investigated to monitor the changes occur in restorative materials in dental practice. For example, some changes happen between the tooth structure and repairing materials used, however, these changes are not visible in the clinic and not always detectable during the x-ray investigations. Therefore, a tool such ultrasound can be used for this purpose. In ideal restoration slight reflection would appear in the interface, however, if a gap happens, a larger reflection is seen that could be an indication of early failure of the restoration. For fatigue rig analysis, it would be ideal to focus on the fracture mode and survival rate of the samples, if the aim was to assess the thickness durability of the specimen. However, in this study the focus instead was to create change of the specimen thickness and evaluate whether ultrasound could detect these differences. Firstly, the specimens had different shapes and exhibit different physical properties, that allowed them to act differently when load were applied, small glass could fracture immediately and a thicker PMMA remain intact after the same application of load introduced. As mentioned, this test served as a way of predicting the changes of materials which in dental practice, assess to evaluate successful of dental restoration hence, the simulation used by the fatigue simulator to mimic that of oral environment.

Natural tooth was only used when created a hole by dental bur not a damage by the fatigue rig, the remaining samples were similar to the ones in previous experiments, this allowed their ultrasonic signals to be analysed. To explain the survivability differences, possible clarification is that some of the materials had less thickness and brittleness than the other samples,

This study, with its limitations, concluded that on the aspect of the interface integrity of restorations, the ultrasonic technique was able to detect the changes that occur within the specimen, but not to the extent that it calculated the exact measurement of these changes. These differences were demonstrated through the ultrasonic signal waveform, which was only possible to identify by comparing the ultrasonic signals before initiating the test. This could be utilised in dental practice when an ultrasonic scan of a repaired dental restoration is done once the replacement is finished. Subsequent ultrasonic scans, then compared with the baseline signals, may contribute to monitoring the interface integrity of restorations, making interventions to fix and repair any gaps more effective. Therefore, the chances of successful treatment can be increased. Unlike the current method of using x-rays, it has its limitations when it comes to the interface evaluation of restorations.

In terms of applying the ultrasonic measurements into the samples before the damage occur, the reflections in non-damaged samples typically exhibit stable and consistent signals for ultrasonic waveform. This typically happen as the purpose of the initial ultrasonic testing is to have a baseline reading of samples. The non damages samples showed stable amplitude, the signals remains constant throughout the testing period, when the load is applies while testing with ultrasound a indicating that the material is enduring the cyclic loads without significant degradation. Also, there was minimal fluctuations or noise in the signals, reflecting the material's ability to withstand the applied loads without microstructural changes or defects. The frequency of the signals remains unchanged, showing that the material is maintaining its integrity under cyclic loading conditions.

Post-testing visual inspection of the samples can corroborate signal analysis findings. Visible cracks, deformation, or material loss confirm the presence of damage in some samples, while others exhibited a complete fracture and separation. This technique would be improved if implemented in during the cyclic load testing of ultrasound, this helps identify possibly the starting point of change in the materials through the signals. This can provide detailed insights into the microstructural changes that occur during fatigue testing, further validating the signal analysis. This could improve clinical cases as some teeth exhibiting slow change in their internal structure due to decay, crack or failed restoration bond, if ultrasound was able to detect changes in thickness of the samples, it could be an appropriate application in the clinic for monitoring and diagnosis.

Signal analysis allows for the early detection of damage before it becomes visible to the naked eye. This is crucial for preventive maintenance and timely intervention when applied in clinical settings. As a continuous monitoring of signals during fatigue testing provides real-time insights into the material's behaviour, enabling immediate detection of any anomalies. However, this was not done in this experiment, further research and experiments should consider this method. However some limitations of this technique should be mentioned firstly, the accuracy of the signal analysis can be affected by external noise or interference, which may obscure subtle changes indicative of early damag**e.** Secondly, different materials may exhibit different signal responses to damage, requiring tailored analysis methods for each material type, for example the material tested in this experiment, were not of the same size and type therefore, the result were not significantly similar**.** Thirdly, as with the ultrasonic measurements, the interpretation of signals can be complex, particularly for materials that exhibit nonlinear or unpredictable behaviour under cyclic loading. Expertise is required to accurately discern between normal variations and damage indicators. Finally, the precision and sensitivity of the testing equipment play a significant role in the accuracy of signal analysis. Limitations in the equipment's capabilities can affect the reliability of the results. This would be improved and analysed when a specific sensor is mounted or fixed on the surface of the sample while the fatigue rig is being loaded, this present real time evaluations as capturing signals during damaging the samples.

To reliably obtain result data, essential test parameters such as the indenter contact area with the sample should be applied. However, in this test, it was not possible to adjust the head of the indenter for each specific sample. Instead, each station was equipped with a steel round-head indenter with a diameter of 4.25mm(112), capable of delivering axial load as a compressive force to the opposing surface of the specimens. Regular checks and secure positioning were necessary to prevent any movement of the samples during testing. The samples were secured in holders to maintain a constant cyclic impact fatigue, ensuring that the ball of the indenter remained in contact with the sample surfaces throughout the study.

Ideally, it would have been beneficial to pause and take ultrasonic measurements before catastrophic damage occurred to assess changes in the materials being tested. These changes could then be validated through ultrasonic signal waveforms. However, this was not possible due to time constraints and the availability of the rig, as part of the research involved reassembling and properly functioning the rig. Therefore, it is recommended for future research to utilize the fatigue rig with ultrasonic measurement for more samples and techniques to gain deeper insights into material changes and their ultrasonic signatures

Glass sample were not ideal as the tendency of fracture was high, however, the aim in this study was to analyse the changes in signals platform when ultrasonic measurements introduced rather than identifying the starting point of damage. Acrylic tooth shaped of 1.2mm was also used for the same testing, compared to glass the acrylic tooth was able to withstand and slight deformity happened which can be seen visually with naked eye, in the support to this damage ultrasonically, a trend of changes in the reflection and amplitude was also noticeable, this in particular indicates that changes in material shape was happening and ultrasound was able to identify this change in form of signal fluctuations when compared to the undamaged signals of the same sample.

Moreover, another sample of PMMA was used in this study, thickness of 4mm, as previously mentioned a single baseline ultrasonic measurement was taken before commencing the rig damaging. The outcome of this test was not a complete separation, rather was a point damage that led to crack round the surface area of the sample, this was seen visually. The ultrasound measurement indicated changes in the signal waveform as well. However, this sample appears to have more withstanding behaviour compared to the previous specimens, due to the thickness of the material used and the surface area of the indenter when it encountered the surface of the PMMA sample, as it was not covering the whole surface area, this was the case for all samples.

A model of restoration was also used, which was mainly a metal ceramic crown, the opposing side that facing the indenter was ceramic, and it was completely fractured, and the underlying metal appeared visually, and changes of the signals was noticeable after ultrasonic measurement too. Central incisor tooth was used in similar test method, however, a hole was created with dental bur rather than under cyclic load of fatigue rig, and ultrasonic measurements showed that less reflection and amplitude after the damage compared to before the hole created of the tooth.

Chapter 7: Conclusions

8.1 Outcomes of The Work

The present doctoral study makes a comprehensive exploration into the potential applications of ultrasound as a viable means to measure enamel thickness and assess the thickness of glass and polymethyl methacrylate (PMMA) samples. Informed by an extensive review of relevant literature, rigorous implementation of experimental procedures, and a thorough analysis of the data, the research has given rise to some key findings.

Foremost among these is the substantiation of ultrasound as an efficient methodology for the quantification of enamel thickness. The employed process utilises ultrasound waves of 15 MHz frequency, effectively discerning the thickness of enamel by identifying the (DEJ). The ability to locate the DEJ is a critical element in the understanding of tooth health and facilitates the diagnosis of dental conditions, such as (TSL). As part of the study, a detailed yet simple procedure for measuring enamel thickness using ultrasound has been outlined, while the accuracy of the technique has been further verified through tooth sectioning and microscopic methods.

Beyond the immediate field of dentistry, the study has broadened the application of ultrasound to include the measurement of glass and PMMA sample thickness. The research points towards the potential use of ultrasound as a non-destructive method for gauging and monitoring the thickness of these materials. The ability to conduct precise thickness measurements is of utmost importance in the realm of dentistry, particularly in the context of evaluating tooth condition and determining the structural integrity of restorations.

In a more specific observation, the study has shed light on how the thickness of an aluminium bar can be swiftly assessed using simple signal processing methods. As per the study's findings, the resultant accuracy can range between 2.1% and 5.4%, given the variations in micrometer-measured thickness. Such an approach does not require a priori knowledge of the aluminium's thickness or necessitate access to both sides of the bar. Nevertheless, significant errors can surface when the same methodology is applied to measuring the thickness of teeth layers and interface gaps. The possibility of error is particularly high in cases where there are multiple, thinner layers, a scenario commonly encountered in teeth. In this context, the transducers used can only provide an approximation. In applications where the assessment of restored teeth interfaces or the evaluation of enamel structure thickness is required in instances of tooth wear, there is a clear need to develop sensors that are specifically designed to be compatible with the specimens under investigation.

Moreover, the research findings also demonstrate that ultrasonography can detect changes in interfaces as echo amplitudes (A-mode). In addition, the size of the enamel structure can be discerned, enabling the identification of any changes therein. When a material is attached to a specimen for ultrasonic scanning, the study emphasises the need for intimate contact. Although not ideal, the use of water or gel as a coupling material should suffice for the testing process.

Furthermore, the research acknowledges the potential challenges and limitations that could be encountered in the use of ultrasound for the measurement of enamel, glass, and PMMA. Among the factors that could impact the precision and reliability of ultrasound measurements are the properties of the material, surface roughness, and variations in acoustic impedance. The research proposes several potential solutions and techniques to counter these challenges, including the use of signal processing algorithms, calibration processes, and advancements in transducer designs. Notably, the research has seen the successful implementation of a Sonopen delay-line transducer. Owing to its size, shape, and resemblance to hand piece instruments used in dental practice, the characteristics of the transducer make it well-suited for tooth measurements, and it may be of potential utility in a clinical environment.

Different techniques, and method being used to classify the intensity of tooth wear, however, the challenge of determining the early changes that occur on teeth structure still needs to be confirmed.

Moderate tooth wear has a certain physiological significance, which is useful for improving

masticatory efficiency and reducing the susceptibility of dentition to disease and malocclusion (114,115). But ,if not detected earlier and treated further poor mastication altered, hence poor dental health established and may lead to hypersensitivity of the dentin (116)

It is estimated that under mastication force inside the mouth ranges from 10 N to 150 N (115) bearing in mind limitation of mouth opening. The test applied in chapter 6 were more of a changes that may occur and detected by the use of ultrasound, it is therefore, not calculating the exact size of the damage, rather the discontinuity of its structure. Also, if the wear induced it would be beneficial to use a device such as the Alicona to highlight any surface roughness or alterations after the impact rig load on the same specimens, due to time limitations this recommended to be don for future research.

Tooth wear remains one of the most complex and challenging phenomena involving physical, mechanical and chemical processes. Further investigation in understanding the behaviour of wear in teeth would seem helpful in enhancing the knowledge of this condition, and its monitoring which appears to be practical by using ultrasonic method as it has been established in this study.

It’s also worth mentioning that the surface of specimen used were not entirely the same as enamel layer, the latter exhibit different fracture toughness which reduces during dry time and when cyclic impact loading on its surface, both demonstrate some sort of alterations hence, some of its surface loss. Although, ultrasound did notice some changes on the surface of specimen, it is essential for further research to focus and move on enamel layers for the impact rig instead of the tissue like materials that were used, to enable the

8.2 Limitations and Challenges

The following limits and difficulties may develop when ultrasonic methods are used to test enamel thickness and monitor tooth wear on glass and teeth: Surface Imperfections: Surfaces of teeth and glass and PMMA samples may include flaws such as fractures, surface roughness, or uneven structure. These imperfections can affect the transmission and reflection of ultrasonic waves, resulting in erroneous measurements and potentially misleading conclusions. Some teeth were partially damaged during sectioning, hence, the size of the samples were not accurately equals in all samples.

When it comes to assessing enamel thickness, ultrasonic methods may have limited resolution capabilities. Enamel is a thin and fragile coating, and the precision of ultrasonic measurements may be impacted by the technique's capacity to detect minute variations in thickness. This is seen clearly in case of TSL, the changes of lost enamel is not great in short term.

Glass and simple specimens used and the teeth have different acoustic characteristics, which might be a difficulty when using ultrasonic method to both materials. The ultrasonic vibrations may interact differently with each substance, resulting to potential variances in measurement precision and consistency. As it was the case when measuring single glass compared with the teeth ultrasonic measurement which was challenging.

Ensuring consistent and accurate measurements across multiple equipment and operators is essential for any ultrasonic techniques-based investigation. Calibration methods and standardisation standards must be done with care to reduce measurement inaccuracies and assure the precision of the results.

Enamel thickness can vary considerably between and among people, as well as between teeth of the same individual. This natural variance might make it challenging to create an appropriate reference point or baseline for assessing tooth wear.

Ultrasonic equipment capable of precisely detecting enamel thickness may be inconveniently unavailable to all researchers and dental practitioners. This restriction can inhibit the technique's widespread implementation and restrict the quantity and variety of the research sample. However, in this project simple technique have been used to enable repeatability and application of this measurement to be used in dental clinic environment.

If this application to be used in practice for pilot study, during ultrasonic measurements on teeth patient participation and compliance is needed when conducting investigations. During the technique, some individuals may suffer discomfort or fear, which might impair their desire to participate or the quality of the data collected. It’s understood this study is proof concept however, applying it to clinical environment for repeatability of measurement rather than obtaining an absolute value would be highly recommended for the first next step after this project. As repeated measurements over time are required to monitor tooth wear over longer time periods. However, longitudinal studies utilising ultrasonic methods might be difficult to undertake due to participant attrition, differences in tooth placement, and changes in enamel properties over time.

Another point to consider is ultrasonic procedures for measuring enamel thickness and monitoring tooth wear require experienced operators who are well-trained in the use of the equipment and interpretation of the data. Inexperienced operators may contribute measurement mistakes or inconsistencies, compromising the study's reliability and validity. In order to verify the accuracy and reliability of ultrasonic measurements for monitoring enamel thickness and tooth wear, validation against other well-established techniques or comparative data is required. Obtaining such validation can be difficult, especially in the absence of comparative research or defined techniques. It is essential to highlight that these restrictions and obstacles can be overcome by continued study and field developments. When planning studies and interpreting the findings acquired from ultrasonic monitoring of enamel thickness and tooth wear, researchers and dental practitioners must carefully evaluate the aforementioned variables.

8.3 Recommendation for further research.

In this study explored potential applications of ultrasound as a proof concept to measure the size and identify changes in thickness of samples. Ultrasound technique serve as non-ionising imaging tool, it was safe to use in this research. However, not all the initial objectives were achieved, this section outlining the next steps that should be taken to build on the research further. In this thesis, contributions have been made on a proof concept of the usefulness of ultrasound techniques in dental practice . However, some adaptations, numerical tests and possible experimental work have been left aside for the future.

For the software and equipment, the Sonopen transducer was ideal for the measurements of teeth samples, with the FMS oscilloscope, an improvement that could yield more definitive results is recommended for the equipment.

Having more teeth tested would benefit the outcome of the research, therefore, it is advisable to do more ultrasound measurements on both human and bovine teeth. Ideally, obtaining measurements from sectioned teeth as well as intact teeth. These measurements should be aimed at identifying the thickness in different spots of the same samples, as the thickness of enamel size is not equal round the tooth. Having done that allows precise calculations and identification of small area of teeth. Moreover, some data can be taken from these measurements such as the speed of sound of each tooth and every spot, if it differs, once ultrasonic measurements are taken, signal analysis can be done in more detail to evaluate such data.

Validating the ultrasound techniques using a wider variety of natural teeth and dental conditions to ensure the findings are generalisable across different types of dental restorations and patient demographics is important. This could demonstrate the ability of ultrasound to measure thickness of some of the materials, however, it would be beneficial to include more dental related restorative materials that are being used for replacement options, such as Emax, Zirconium, dental composite, and dental ceramics. By obtaining the thickness and then inducing certain damages, cracks and gaps, the capability of the ultrasonic technique in assessing the changes can be determined. This refers to explore the interface between the remaining tooth structure and the replacement, one of the objectives were not succeeded in this research was integrity of restorations monitoring, therefore, it is recommended for further work research.

After having more data from the ultrasonic experiments next step to start a pilot study in clinic on patients, and then conduct comprehensive in vivo studies involving a larger and more diverse patient population to evaluate the real-world applicability of ultrasound for monitoring TSL in clinical settings. The rate of TSL is not constant, therefore, it is recommended that achieving a repeatability of measurements of certain period of time for the same patients could support the effectiveness of relatabilities of ultrasound techniques in monitoring teeth thickness, hence, evaluate any loss of enamel structures that could happen. For example, the first pilot could focus on repeating ultrasonic measurements on patients on the same spots every week for a month, just to ensure the repeatability of measurements, and another set of measurements on patient with longer interval time, such as every six months, to detect any changes in between visits.

Similar to concept being suggested in this study, the fatigue rig could be used for creating the damages, and cracks to specimen. However, the samples should have a set parameter and it is recommended to have multiple ultrasonic measurements for them, to evaluate any changes in signals as the same time the machine is running. This could help in evaluating when the initiation of cracks are happening, rather than waiting for the compete damage or till the rig stops.

To develop a device that has ultrasonic measure to monitor teeth status, research should be done on numerical analysis, and modelling the measurements of teeth and restorative materials. These modelling should simulate the damages conditions that encounter teeth in patients, such as cracks, decay, reduce in thickness and loss of underlying sealing or gaps created under restorations. The finding of such modelling validates the result experimentally in vitro. Hence, more detailed information about the feasibility of ultrasonic device is possible. It is suggested that this method could be applied clinically, perhaps either as Sonopen sensor measurements similar to the techniques used in this research, or creating a device for instance similar to surgical stent mouth guard that has some ultrasonic sensor inside for measurement. However, this can be achieved after further research is done in the lab.

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