Effect of surface roughness on quality perception of Laser Sintered (LS) parts

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Abstract

Additive Manufacturing (AM) is a revolutionary technology that in recent years has become increasingly visible in mainstream media and is in the process of being developed for more widespread industrial applications. One of the challenges that has hindered the growth of AM in industry has been the aspect of surface finish, particularly in the use of Laser Sintering (LS). The surfaces produced are often perceived to be of a lower quality than those of other more traditional techniques. One of the ways in which developments have been made to address this issue is to use different post-processing techniques to achieve a variety of surface finishes. These decisions are often made by the machine manufacturers and researchers without any input from the product consumers.

This thesis aims to include the consumer in the surface finish decision-making process. The main focus is to investigate the consumer perceptions of different LS surface finishes and roughness through the utilisation and adaptation of human interaction and social science techniques.

A group of 44 participants performed a number of blind trials on different roughness parts. It was found that up to a certain point a decrease in roughness led to a growth in perceived quality, but this increase was not infinite. All users identified roughness and smoothness as directly relating to quality; whilst other vocabulary was used to describe quality, these did not translate to “real” effects during testing.

Crucially 50% of participants’ opinions of quality changed when allowed to perform a visual assessment of the parts.

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Nomenclature

2D	Two Dimensional
2AFC	Two Alternative Forced Choice
3D	Three Dimensional
AM	Additive Manufacturing
ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
BSI	British Standards Institute
CAD	Computer Aided Design
D	Dictaphone
EP	Exploratory Procedure
F	Female Participant
FAI	Small Fast Adapting Mechanoreceptor
FAII	Large Fast Adapting Mechanoreceptor
FDM	Fused Deposition Modelling
H_0	Null Hypothesis
H_1	Alternative Hypothesis
ICC	Intra-class Correlation Coefficient
IQR	Inter Quartile Range
L	Laptop
LH	Left Handed
LOM	Laminated Object Manufacturing
LRM	Laser Re-Melting
LS	Laser Sintering
M	Male Participant
P1	Participant 1
PUSh	Chemical surface treatment for LS parts
R_a	Arithmetical Mean Deviation of Roughness
RH	Right Handed
R_z	Ten Point Height of Irregularities

SAI	Small Slow Adapting Mechanoreceptor
SAII	Large Low Adapting Mechanoreceptor
SL	Stereolithography
SPSS	Statistical Package for the Social Sciences
STL	Standard Tessellation Language
UV	Ultra Violet

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1 Introduction and Manufacturing Overview

1.1 Background overview

Traditionally, manufacturing techniques have followed subtractive or formative methods to generate parts, whereby products are created from the remaining bulk material or by application of an external force to modify its shape.

Additive Manufacturing (AM) is a useful alternative method that can be used to manufacture complex geometries. To create a product using AM, it is first developed using Computer Aided Design (CAD) software, which is then sliced into thin layers. These slices are then used as a model for the machine to build parts upwards layer by layer. This allows for parts and products to be very detailed without an increase in manufacturing time, as shown in Figure 1.1.

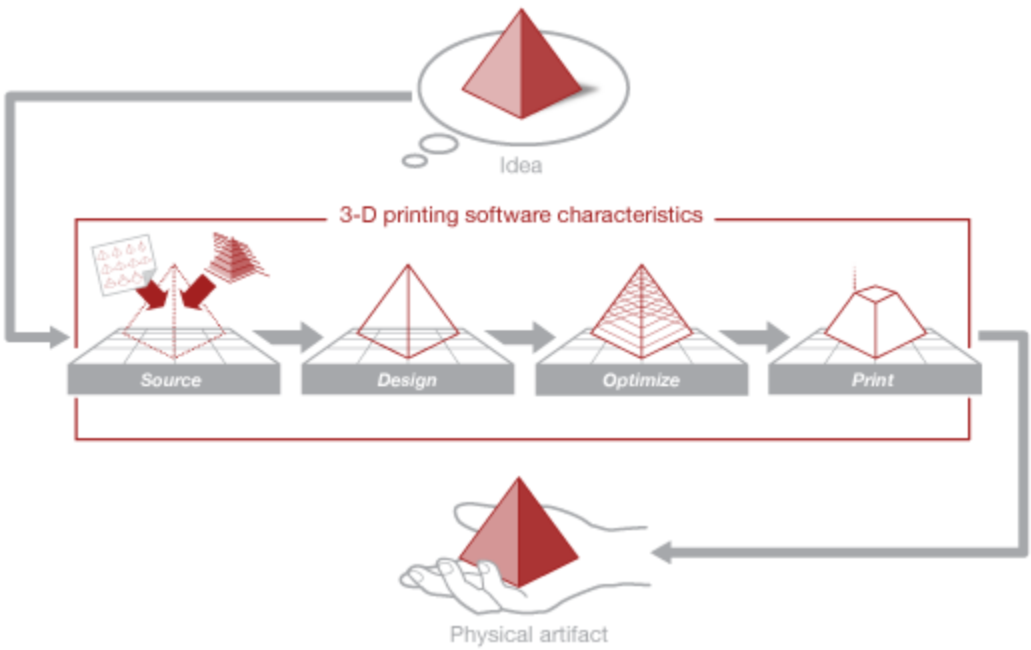


Figure 1.1 - Schematic of the additive manufacturing process [1]

The British Standard of the General Principles and Terminology of AM defines it as:

"*the process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies*." [2]

1.1.1 Benefits

AM has many advantages over its traditional counterparts, including [3]:

Increased design freedom

The manufacturing method of joining layers consecutively gives designers the ability to manufacture parts of high complexity and detailed geometry. This is due to access to internal components of the parts during the manufacturing process that would otherwise be concealed or difficult to reach with tools. The increased design freedom also leads to a reduced need for tooling.

Personalisation

The customisation of additive manufactured parts provides an economic low-volume production whilst also giving consumers personalised parts. This includes many different sectors such as medicine, fashion, engineering, etc. Bespoke parts are often difficult to produce and far more expensive to manufacture using other methods.

Optimisation

AM parts do not need to be pre-designed into modular parts – the parts can be built into their assembly, which encourages far more possibilities in design that have not been available previously. The optimisation of parts can also be improved due to increased geometric complexity that can be achieved through using CAD software. This can lead to improved weight, strength, airflow, heat transfer, etc. An optimised automotive part is shown in Figure 1.2.

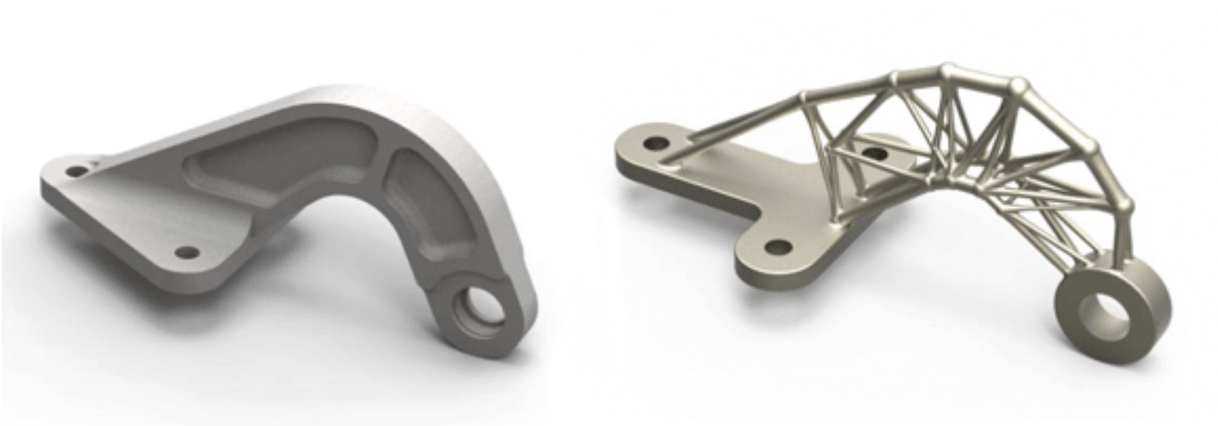


Figure 1.2 - Optimisation of an automotive part [4]. The original part can be seen on the left with the optimised part on the right.

The optimised automotive part in Figure 1.2 shows a part has been manufactured using less material, but that has better strength due to its strategically placed strut composition. This was optimised using a computer simulation software to find the ideal structure for the part.

Time scale

AM is a very quick technique. What used to take days or even weeks to manufacture previously, can now take place in a matter of hours, due to multiple part manufacturing and no need to make moulds beforehand. This leads to a massive saving of cost for on-demand manufacturing models.

Less material wastage

As the parts are built by adding material, there is far less material waste compared to subtractive manufacturing. In some AM technologies, what little waste material there is can be re-used and recycled to create other parts.

1.1.2 Limitations

Although AM has many useful advantages, it also has some limitations [5]:

Materials

The range of materials available for this technology is fairly limited depending on the particular method and the cost of the available materials is high, which has led to limited use in industry. The material costs are often higher due to the pre-manufacture preparation needed to make the materials viable for different processes. Also, the mechanical properties, accuracy, geometric tolerances, etc. are not always obtained on every build.

Component size

The size of the build envelope [2] is dependent on the AM technology used and the size of each machine. The size of the build envelope and processing time is different for each machine and technology. This is often a limitation when large parts need to be manufactured especially in laser-based processes [3].

Integrity of parts

The integrity of parts such as mechanical properties, accuracy, geometric tolerances and surface finish [6] are all build factors that are being developed and improved [7]. Depending on the method of AM An example of poor surface quality is shown in Figure 1.3.

Figure 1.3 - An example of a poor surface finish to an AM part [7]

Training

Due to the freedom of design available in this method of manufacture, this tends to encourage informal design methods, which may cause extra problems once a product is made. It is essential to still carry out finite element analysis before a build to check how the stresses and strains will react in the material and ensure that the correct decisions are made through experienced training in software and the different machines.

It is the integrity of the surface finish of AM parts that provides the main focus for exploration in this project.

1.2 Aim and approach of project

Currently, machine manufacturers and researchers are the most prominent decision makers in the advances of AM; industrial input is increasing, but end-use consumers have yet to be involved.

1.2.1 Aim

Surface finish is one key aspect that is often portrayed as a challenge for AM, especially for the Laser Sintering (LS) method which will be studied in this project. It is widely believed that AM products do not have the immediate quality of surface finish that industry requires to take on this type of manufacture [7]. However, to date there is a lack of consumer input regarding this issue. Therefore, the aim of this project will be:

To utilise and adapt social science techniques to investigate perceptions of different surface finishes, particularly LS parts.

1.2.2 Approach

Application focus

To carry out this aim, the application focus had to be something that a consumer would be familiar with and use frequently with their hands to follow in line with haptic exploration techniques outlined by Lederman and Klatzky [8-10]. To coincide and follow on from work carried out by a Masters student, it was decided to use mobile phone cases as the application focus for this project.

Consumer focus

The target audience for this project was the average young consumer, ranging in years between 18 and 30 years. This particular audience was chosen as it was seen to be the group of people who would be the most likely to spend money on consumer goods of a higher quality (such as mobile phone cases), due to extra disposable income [11].

Structure

This thesis will begin with a review of relevant AM and surface finish literature, before discussing the ways in which people interact with objects, and methods of evaluating their responses. A combination of this literature and targeted focus groups will be used to design and conduct a methodology to assess user perceptions of quality with respect to surface finish. Results will be presented and analysed before presenting discussions, conclusions and further work recommendations. The structure of this thesis can be found in Figure 1.4.

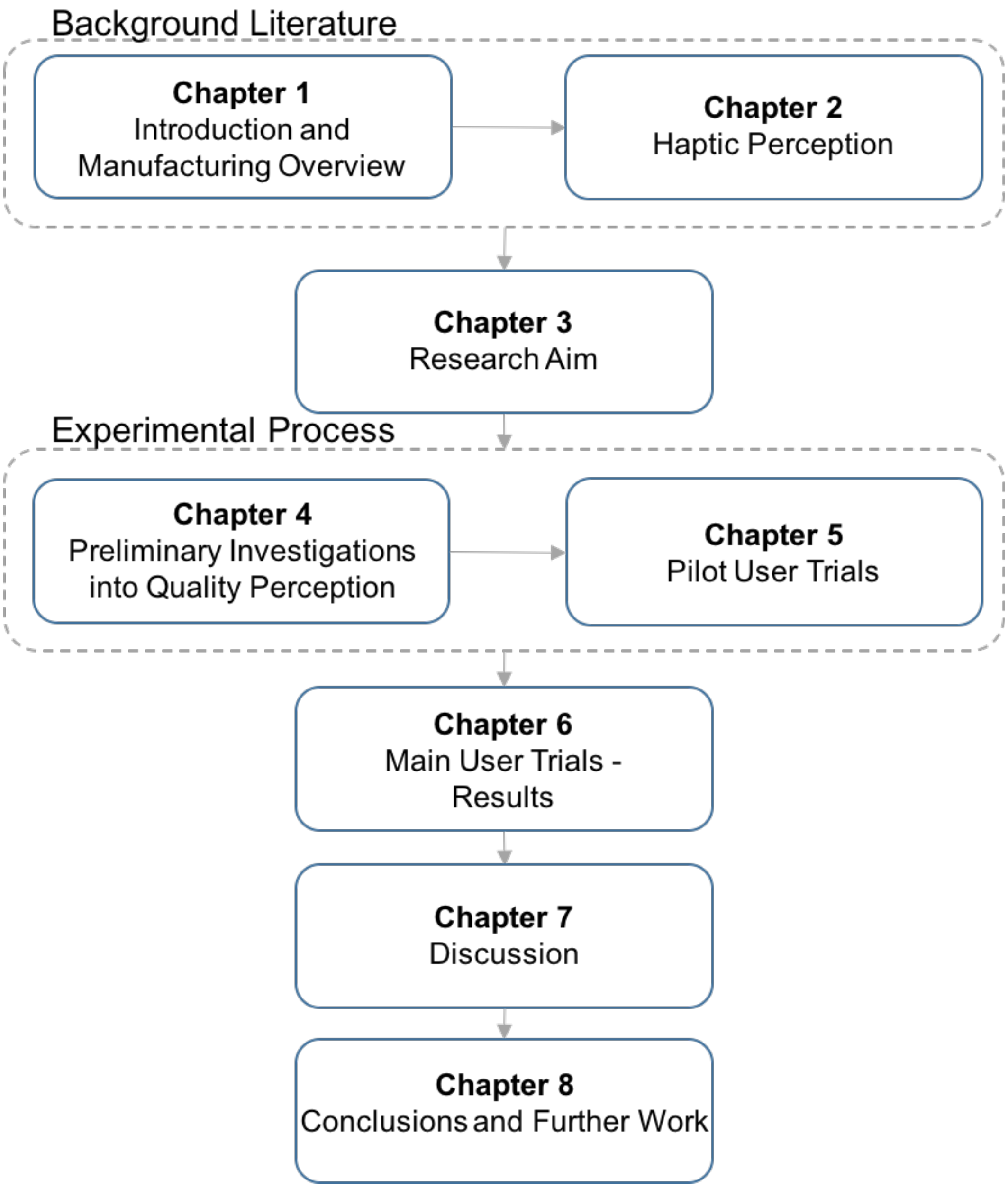


Figure 1.4 - Schematic of thesis structure

1.3 Manufacturing

Manufacturing has developed throughout time, not only in size on a very large scale, but through its adopted methods as well. The verb to manufacture is "the action or process of making or producing articles, material, or a commodity (in modern use, usually on a large scale) by physical labour, machinery, etc." [12]. As technology has developed, so have the methods used in manufacturing.

There are three main methods of manipulating materials in manufacturing: subtractive shaping, formative shaping and additive shaping [13] as shown in Figure 1.5.

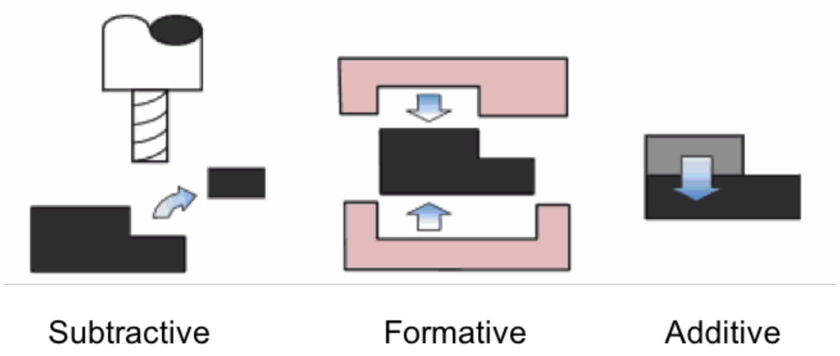


Figure 1.5 - The three main methods of material manipulation. Adapted from [14].

The British Standard for AM general principles terminology states that these three manufacturing processes are [2]:

- Subtractive shaping – the desired shape is acquired by selective removal of material, examples: milling, turning, drilling, EDM, etc. One main advantage to this method is the ability to machine very thin and detailed parts, like a living hinge, which cannot be manufactured through other processes. However, there are limitations in the geometries it can produce.
- Formative shaping – the desired shape is acquired by application of pressure to a body of raw material, examples: forging, bending, casting, injection moulding, etc. This allows a wide variety of materials for high volume manufacturing, with low costs per part. However, tooling is often needed afterwards with long lead times and often at a high cost.

- Additive shaping – the desired shape is acquired by successive addition of material. This produces complex geometries easily and eliminates the need for tooling. However additive shaping is limited in material choice, tolerances and number of parts that can be made. This thesis focusses on this method of shaping.

1.3.1 Additive Manufacturing (AM)

The additive process is a method of manufacture that is still developing. AM technology applies the additive shaping principle and thereby builds physical 3D geometries by successive addition of material [2]. AM can also be known as 3D printing, and other historical terms are additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, solid freeform fabrication and freeform fabrication [2].

Process

There is a general method that most additive manufacturing processes follow as explained by Gibson, Rosen and Stucker [15]. The process is illustrated in Figure 1.6.

Figure 1.6 - An overview of the AM process. Adapted from [16]

File preparation

Firstly, a design is created on a piece of CAD software. This describes the external geometry of the product in three dimensions, showing what the end product should look like. Once this is complete, the Computer-Aided Design (CAD) file must then be converted to a Standard Tessellation Language (STL) format. This is a triangulated format where the surface is covered in a mesh of triangles that are used to reference points on the surface of the design. The STL file describes the external closed surfaces of the original CAD model and forms the basis for the calculation of the slices. This generates the correct size, position and orientation for building.

Build set-up

This file is then transferred to the additive manufacturing machine. Once the machine is set up with regards to build parameters, the build then takes place, with some processes using extra material to support the part as it builds.

Physical

The build is a mainly automated process and only superficial monitoring needs to take place to ensure there are no errors. Once the build has taken place and the machine has had sufficient time to cool down if necessary, the parts and supports can then be removed and post-processed if need be. A flow chart of the generic process chain is shown in Figure 1.7.

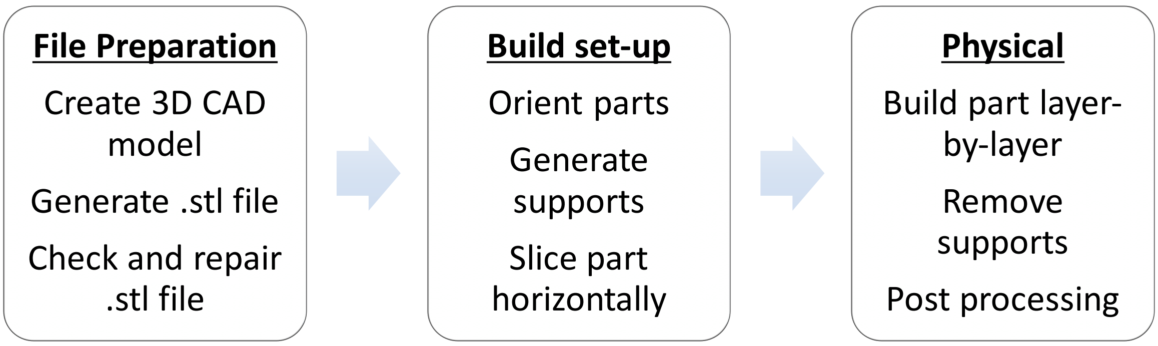


Figure 1.7 - Flow chart showing the generic process chain of Additive Manufacturing

1.3.2 Methods of Additive Manufacturing

The British and American Society for Testing and Materials (ASTM) standard states that there are 7 different process categories for AM [2]:

Binder Jetting

Binder jetting is an AM process in which two different materials are used, a powdered material and a bonding agent. A layer of powder is spread across the build bed and then a liquid bonding agent is selectively deposited to join the powder particles together for each layer [17]. After each layer is complete, the build bed is lowered by the layer thickness and then the process repeats until the complete part is finished in the powder bed. Figure 1.8 shows the schematic of the Binder Jetting process along with the different coloured binder feeders to create coloured parts.

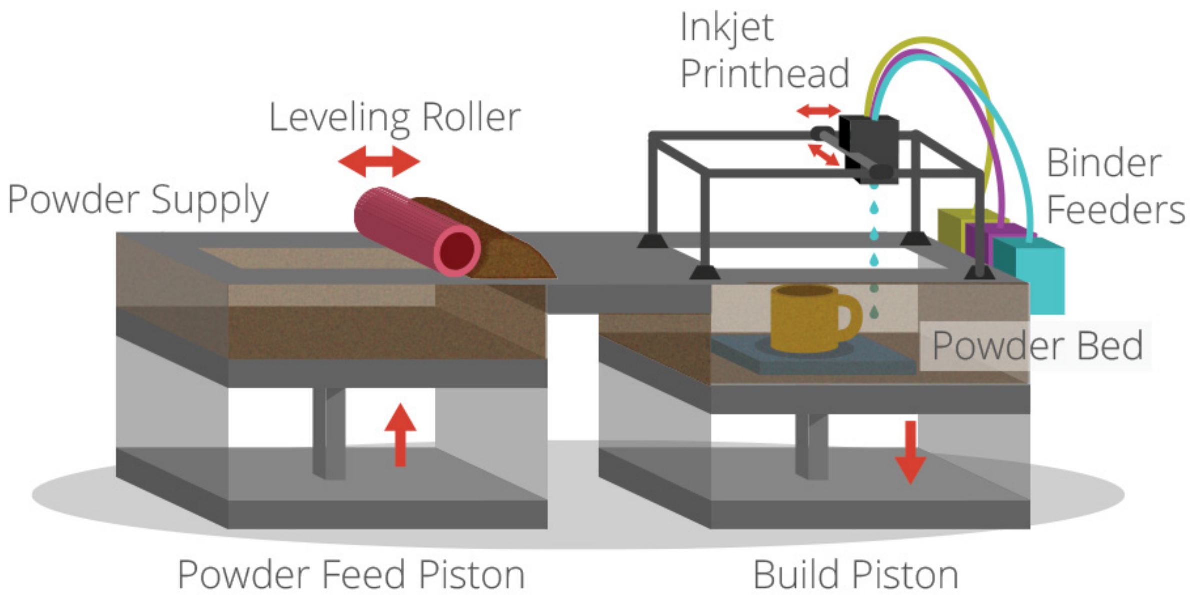


Figure 1.8 - Schematic of the Binder Jetting AM process [18]

Directed Energy Deposition

This is an AM process in which focused thermal energy is used to fuse materials by melting as they are being deposited. It is often used on already existing parts for repairs or to add features [15]. Material for this method is usually either in wire or powder form, which is deposited from a nozzle on a multi-axis arm onto the surface of the part to be repaired. This material is then melted using either a laser or electron beam. The layers are deposited on top of one another until the repair or feature is complete [19]. Figure 1.9 shows the process used by a type of Directed Energy Deposition named an Electron Beam Gun.

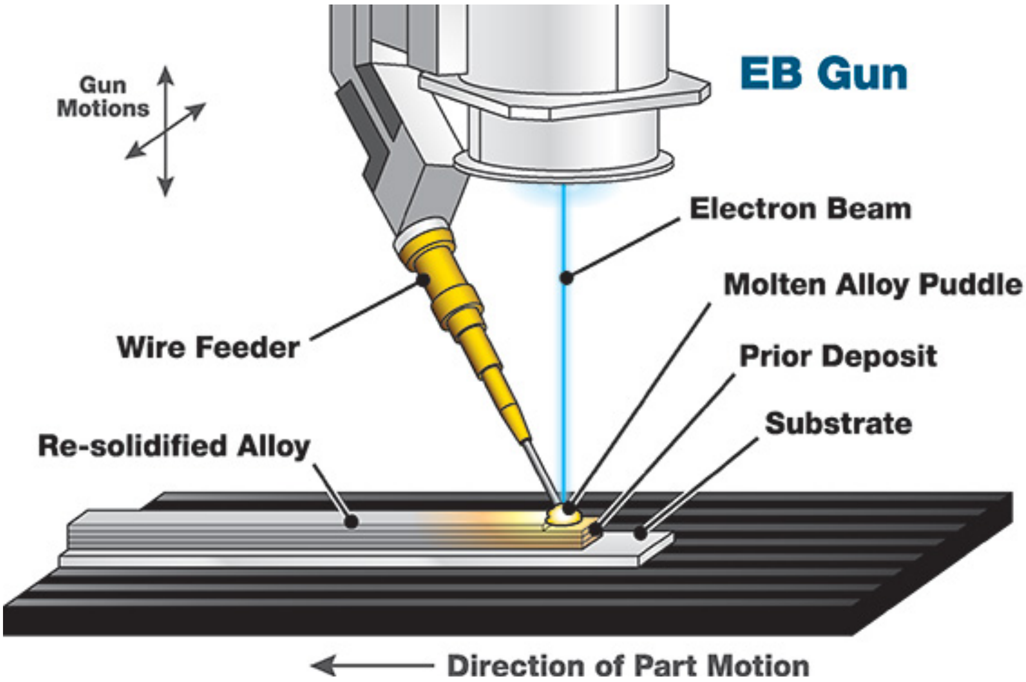


Figure 1.9 - Schematic of the Directed Energy Deposition method, specifically and Electron Beam Gun [20]

Material Extrusion

Material extrusion is an AM process in which material is selectively dispensed through a nozzle or orifice, an example of this technology is Fused Deposition Modelling (FDM). The FDM process is slightly different from the other processes, as it generates items by extruding its raw material through a nozzle. The nozzle then moves both horizontally and vertically to create each 2D layer of the final product [3]. Figure 1.10 is a schematic of the FDM process and how the build material and support material are used together to create the finished part.

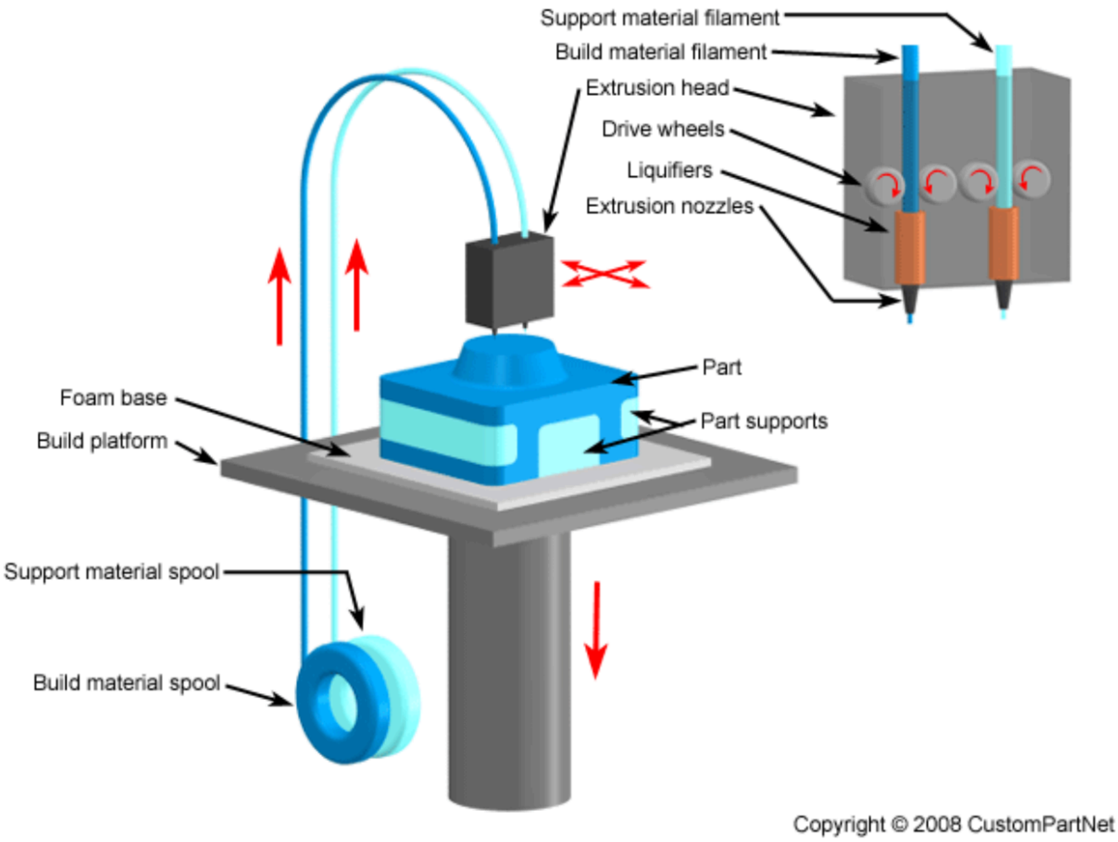


Figure 1.10 - Diagram showing the FDM process [21]

Material Jetting

This is an AM process in which droplets of build material are selectively deposited. The material jetting process uses an arrangement of printing heads to concurrently selectively deposit an acrylate-based photopolymer as shown in Figure 1.11.

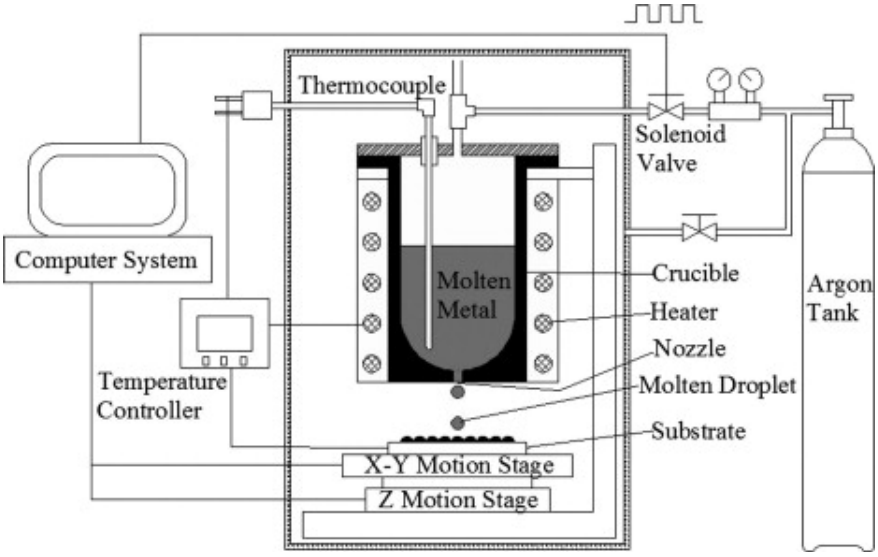


Figure 1.11 - Schematic of a jetting droplet system [22]

The layers are then cured using a UV lamp that passes over the accumulated material. In some cases (InVision process from 3D Systems), the layers are supported using jetting wax. These supports can then be removed in post processing. Jetting can also be a thermal phase change technique – this is where the material is squeezed out hot and then cools quickly to solidity.

Sheet Lamination

Sheet lamination is an AM process that uses stacked sheets of material (usually paper) that are bonded together as its raw material. Each sheet of paper then acts as a layer, which is cut separately by the laser [23], as shown in Figure 1.12. This creates a profile like the other methods that is built from the bottom up.

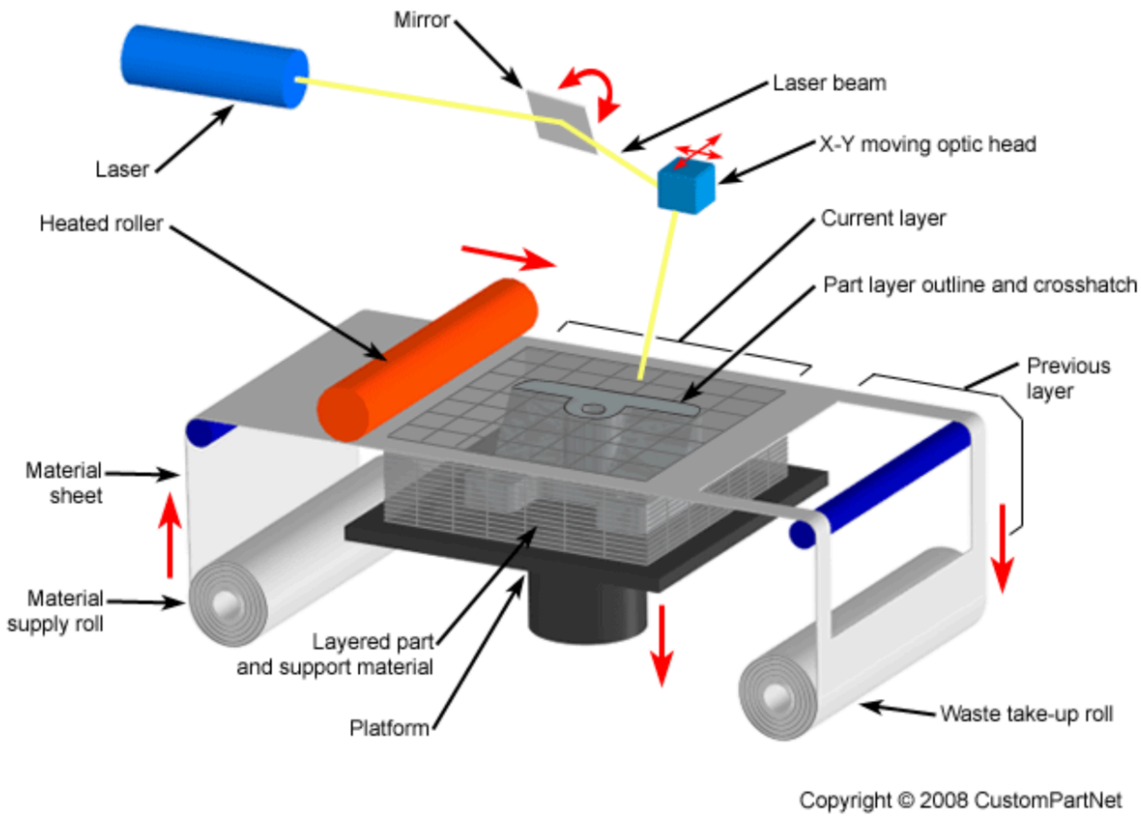


Figure 1.12 - Schematic of the LOM machine [24]

Once the product building is complete, it is usually post-processed with hand tools, which can be difficult to use on complicated and thin geometries due to the material properties in those states.

Vat Polymerisation

Vat polymerisation is an AM process in which liquid photopolymer in a vat is selectively cured by light-activated polymerisation, an example of this is Stereolithography (SL). This uses a method of inducing a curing response in a photocurable resin with an ultraviolet (UV) laser to build products one layer at a time. The products generated need support structures to attach the part to the build platform [25]. Figure 1.13 is a schematic of the SL process, which is a type of vat polymerisation. This shows the setup of the apparatus.

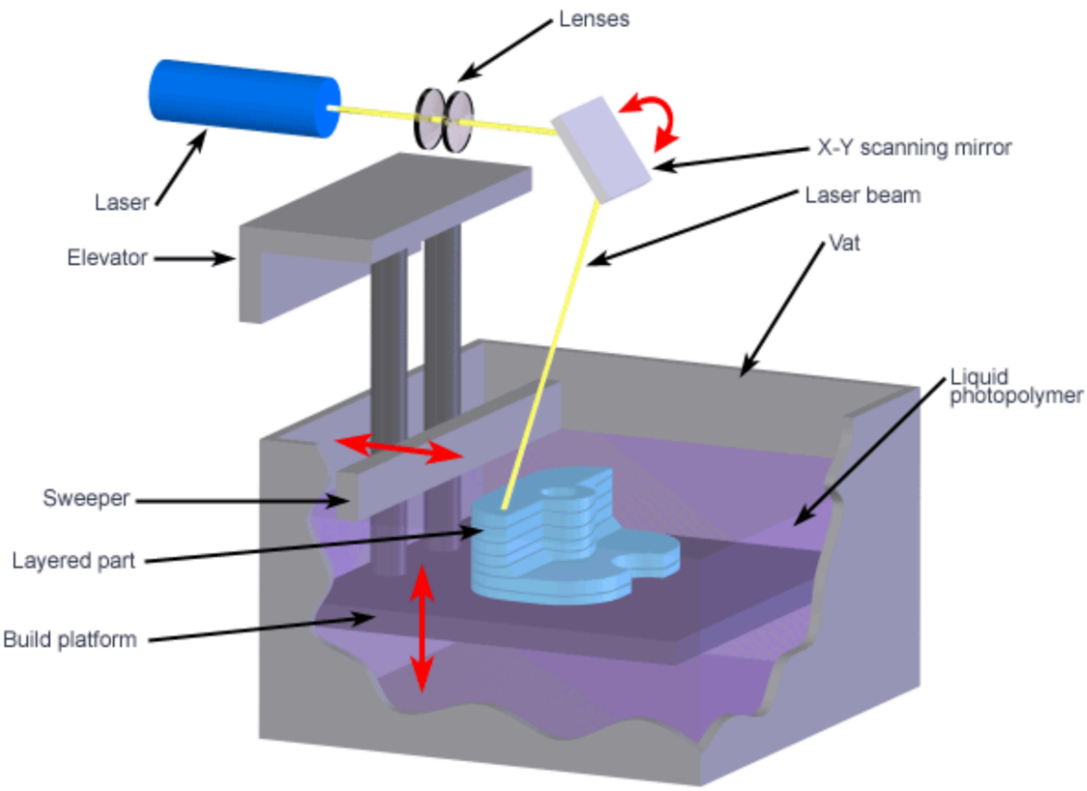


Figure 1.13 - Diagram depicting the SL process [26]

A CAD file is used to initiate the laser, and then the selected part is cured within the resin and solidified to create each layer separately before the platform is lowered for the next layer to be produced with a fresh layer of liquid resin. After the product is manufactured, the excess resin is drained and can be reused [27]. The part is then removed from the machine, the parts can then be removed from its supporting structures and post-processed if need be.

Powder Bed Fusion

Powder bed fusion is an AM process in which thermal energy selectively fuses regions of a powder bed, an example of this technology is Laser Sintering (LS). Consecutive layers of powdered, raw material are distributed to a plane surface, usually by a roller as shown in Figure 1.14 below, although the EOS systems use a blade to dispense the powder.

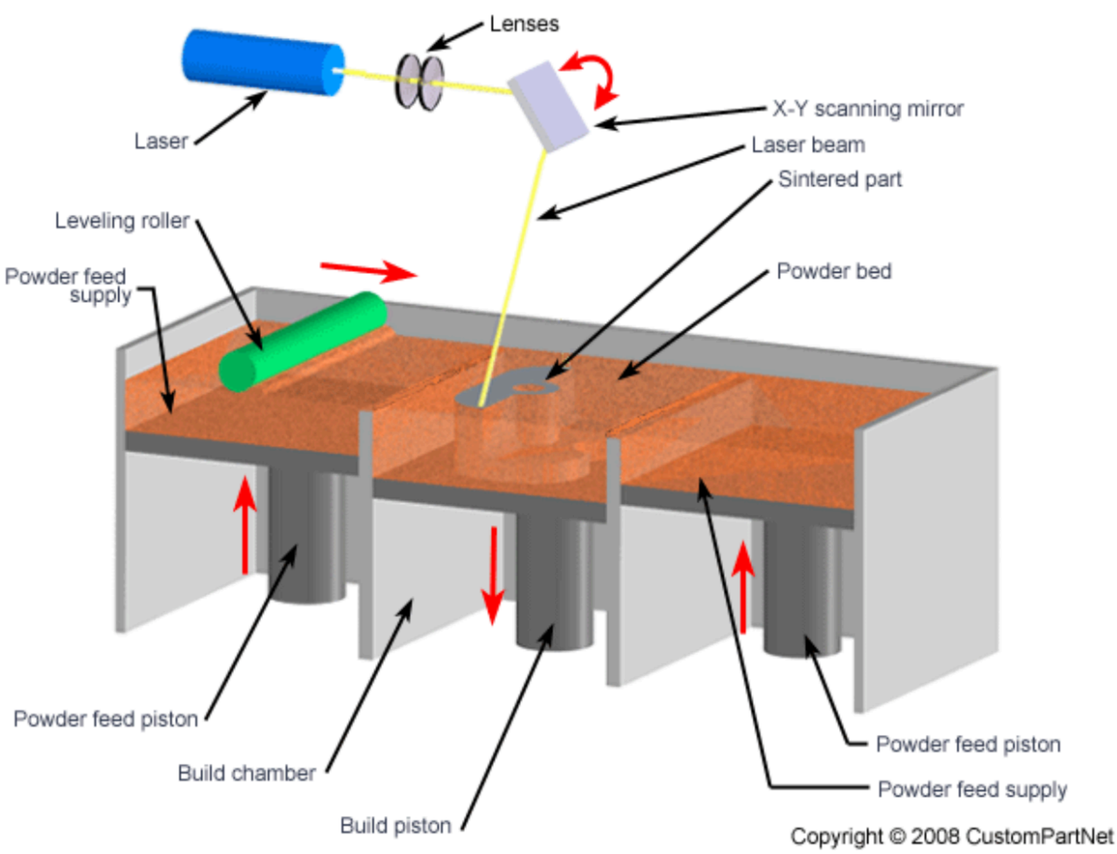


Figure 1.14 - Schematic arrangement of a conventional LS machine with roller placement of powder [28]

The powder is then held at a temperature just below its melting point in the build bed chamber. The laser then selectively scans the powdered area to tip the temperature of the powder in contact over its melting point to create a 2D shape that is supported by the surrounding powder once it solidifies.

1.3.3 Method Comparisons

Each of the methods can only use certain types of materials to build successful parts. Table 1.1 is adapted from Grenda [29] and shows the different materials that can be used for each process.

Table 1.1 - AM technologies and the materials used to make direct consumer products (adapted from [29])

Method	Plastic	Metal	Ceramic/other
Binder Jetting		✔	✔
Directed Energy Deposition		✔	✔
Material Extrusion	✔		✔
Material Jetting	✔	✔	
Sheet Lamination			✔
Vat Polymerisation	✔		✔
Powder Bed Fusion	✔	✔	

Each of the AM methods have their own benefits and limitations as stated in Table 1.2. LS was the chosen method to manufacture the parts for this project to focus on its main limitation of poor surface finish, also due to machine availability.

Table 1.2 - Table of benefits and limitations of AM methods

Method	Benefits	Limitations
Binder Jetting	- No support structures - Low materials cost - Colour output	- Poor surface finish - Limited material selection - Poor mechanical properties
Directed Energy Deposition	- Can be used on already existing parts for repairs or to add features - More control over grain structure	- Varying surface finishes depending on material - Limited material selection
Material Extrusion	- More affordable - More accessible - Good for conceptual models	- Poor surface finish - Poor mechanical properties - Not for accurate part generation
Material Jetting	- High accuracy of parts - Can print with multiple materials at once	- Needs support material - Materials are expensive to manufacture [15]
Sheet Lamination	- No support structures - Faster build times	- Poor surface finish - Inconsistent bonds between layers
Vat Polymerisation	- Good surface finishes - Thin layers [3] - Good detail [15]	- Must be post-processed in a UV or thermal oven for curing [3] - Poor thermal and mechanical properties [15] - Needs support structures
Powder Bed Fusion	- Surrounding powder acts as support structure - Large range of materials	- Size limitations - Poor surface finish

1.3.4 Applications

The current and potential applications of laser sintering span many different industries [3]:

Consumer Goods

AM has an impressive potential market in the consumer goods sector. This is due the increased design freedom available through the CAD design process as shown in Figure 1.15.

Figure 1.15 - Examples of consumer goods manufactured using AM. A complex geometry part [30]] (left) and printed trainer soles [31]] (right)

The shoes shown in Figure 1.15, demonstrate the wide personalisation and optimisation that is achievable through this technology. The consumer would have had a consultation to determine the best shoe soles for them and then the parts would have been printed on demand for them.

Fashion Industry

The combination of the fashion industry and AM give designers the freedom to make items of clothes or jewellery that would have been difficult or impossible to make before. Figure 1.16 shows an AM dress that has been designed using links similar to chain-mail (left). Due to the dress being made out of a polymer material, the dress is much more light-weight than its traditional metal copy would have been.

Figure 1.16 - Examples of items from the fashion industry. A printed dress [32]] (left) and a printed designer necklace [33]

Industrial (civil/automotive)

Industry is slowly adopting AM to some of its sectors. This is due to the parts' surface finishes and tolerances not being as consistent as is needed for the application. However, AM is gradually being integrated into the sector and with Figure 1.17 depicting a concrete printed house [34] and an engine AM component by Ford [35].

Figure 1.17 - Two examples of items made using AM from the engineering industry. A concrete printed house [34]] (left) and a printed car engine part by Ford [35]

Medical

The medical industry is greatly benefitting from the customisable aspect of AM. The lead times of many procedures is being cut dramatically due to the 3D scanning and AM abilities of the process. This means that there is not a long wait for injection moulded parts to be cast and then set. One example of this is a cranial implant as shown in Figure 1.18

Figure 1.18 - An example of an item made using AM from the medical sector. A cranial implant [5].

1.4 Sintering

1.4.1 Background

Sintering is a technique that has been practiced for centuries; some examples of early sintering pieces were bricks heated in open fires and firing porcelain. Sintering is usually apparent at temperatures above half of the absolute melting temperature of a material [36]. The verb to sinter from the Oxford English Dictionary is “*to coalesce from powder into solid by heating (and usually also compression)*” [12], which reduces the surface area of a mass of powder by melting, to create a solid final product. The main aim of sintering is to reduce the amount of porosity in a material to generate a part with increased density. This creates a porous medium of two phases: a phase of substance and a phase of voids [37]. The voids in this case are not desirable. There are three possible driving forces of sintering: surface free energy, applied pressure and chemical reactions, as shown in Figure 1.19.

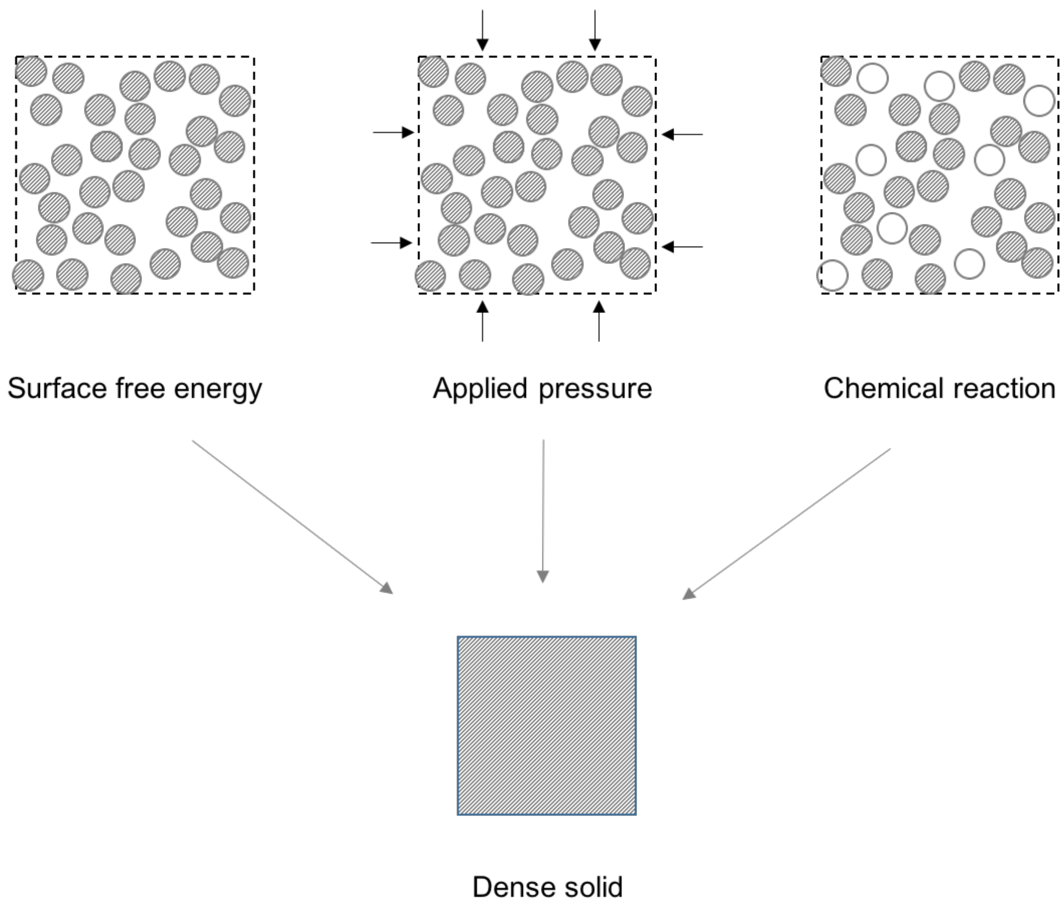


Figure 1.19 – The three main driving forces of solid densification [38] Adapted from [39].

Apart from controlling the density, sintering can also be used to eliminate any irregular curvatures on the surface of a part [36]. Any concave or convex shapes on the surfaces will naturally flatten out during the sintering process due to the transport of mass around the irregularities. It is the surface tension and surface free energy that induces this mass flow [40]. The sintering process can be placed into four stages as shown in Figure 1.20.

1. Powder before sintering
2. Formation of grain necks
3. Evolution of necks and Grain Boundaries (GBs) and the elimination of pores
4. Isolation of pores.

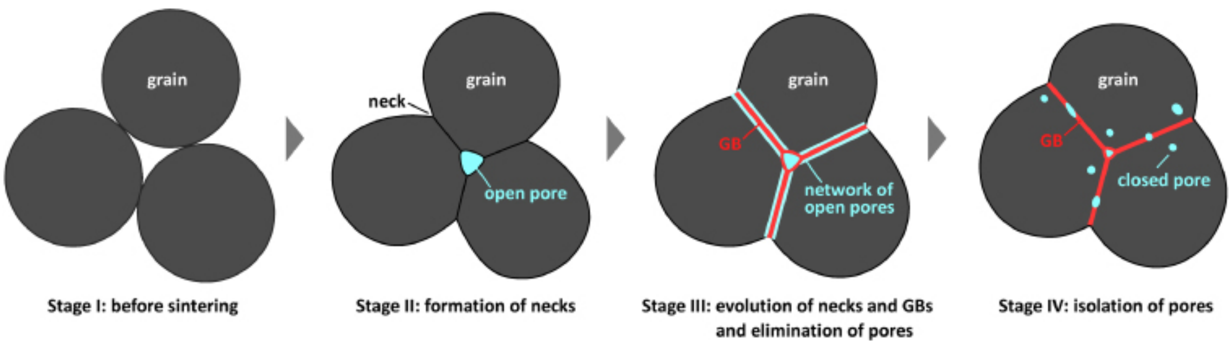


Figure 1.20 - The four stages of sintering [41]

To increase the density of a part, it is vital that the pore count and size is minimal so as to create fully dense parts with good mechanical and structural properties.

For years, sintering was defined as a technological process of obtaining sintered materials from powdered systems [42], but Frenkel developed the first theory of sintering in his two-particle system [43]. He deduced that solid materials at high temperatures have similar flow to the flow of viscous liquids, which is the basis of his theory.

1.4.2 Combining two particles theory

The theory of combining the particles is incredibly simplified, as the combining of the particles in the sintering process is shown in Figure 1.21.

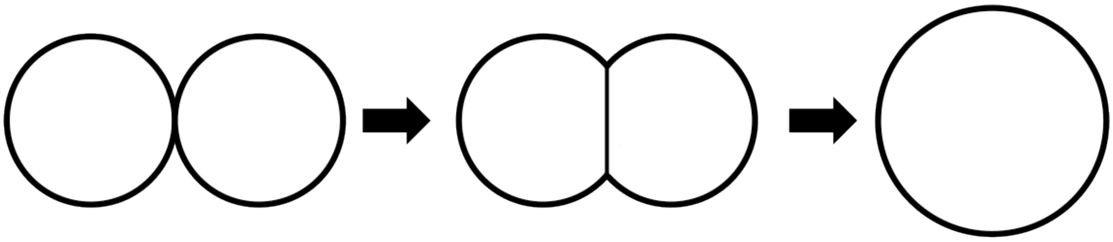


Figure 1.21 - The particles fusing together in the sintering process

The spheres in Figure 1.21 each represent a spherical particle. This is where two particles are initially in contact at a point. After a certain amount of time, the drops will be in contact along a circular cross-section with a radius of *y* as shown in Figure 1.22, and also that the remaining parts of both particles keep their spherical shape:

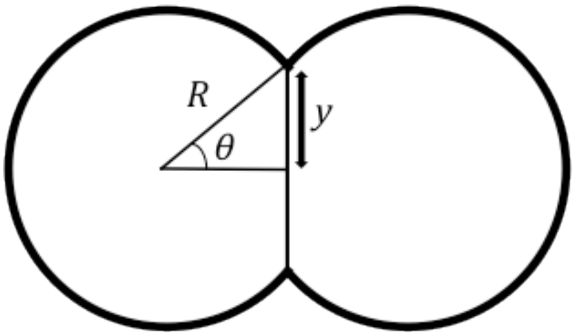


Figure 1.22 - An adaption diagram of Frenkel's two-particle model [43]

The rate of neck growth in the two-particle system is based upon Frenkel's initial theory in Equation 1.1 [43]

Equation 1.1 – Rate of neck growth

$$\dot{y} = \frac{2}{3}\frac{\gamma R}{\eta y}$$

Where $\dot{y}$ is the rate of neck growth, γ is the surface tension, R is the particle radius, η is the viscosity and y is the cross-sectional neck radius. This is a highly simplified description of what happens theoretically during the sintering process and has been modified many times by other authors [40, 43, 44]

Sintering has a driving force, which is the reduction of the total interfacial energy γA, which in turn is comprised of the change in interfacial energy, γ, and the change in the areas between the particles, A. The reduction of total energy can be shown as in Equation 1.2 [44].

Equation 1.2 – Reduction of total energy

$$\Delta(\gamma A) = \Delta\gamma A + \gamma\Delta A$$

The change in interfacial energy is due to the densification and the change in interfacial area is due to coarsening as shown in Figure 1.23.

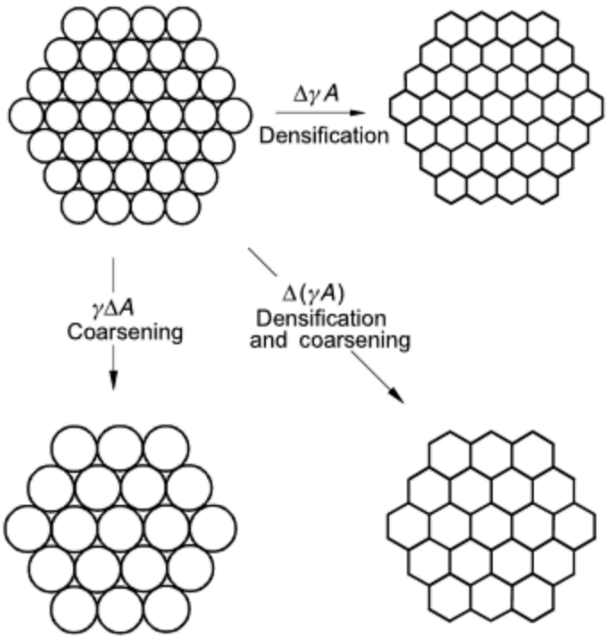


Figure 1.23 - Diagram showing the basic phenomena that happens during sintering [44]

Figure 1.23 is a useful way of visualising how the particles become sintered in slightly different ways.

The main factors that affect the rate of neck growth are taken from process variables and material variables:

- Temperature
- Pressure
- Atmosphere
- Heating rate
- Cooling rate

} Process Variables

- Powder particle size
- Powder particle shape

} Material Variables

The above can all affect the rate at which the particles will sinter and by controlling these, it is much easier to predict what will happen. The way in which the sintering theory will be described gives a simplified idea of the theory, but simulations can provide more accuracy.

1.4.3 Types of sintering

There are two main types of sintering: liquid phase sintering and solid state sintering (with some in between stages).

Solid state sintering

Solid state sintering happens when a powder is densified entirely in a solid state at the sintering temperature, which is below the material's melt temperature. This gives very strong mechanical properties to the material.

Liquid-phase sintering

Liquid phase sintering occurs when there is a liquid phase existent during the sintering of the powder. This allows an easier control of the microstructure, but does not give as strong mechanical properties as the solid state sintering does.

1.4.4 Laser sintering (LS)

Laser sintering with polymers uses the liquid state sintering technique, the basic principle of which is to fuse layers together using a CO_2 laser. A powdered raw material is used to build parts layer by layer, typically 0.1mm thick. Each layer is then scanned and sintered by the laser to create a 2D solid shape that is supported by the surrounding powder. Another layer of powder is then deposited on top of the layer below and the process is repeated until a 3D object is created in a cake of powder. The powder and/or part bed is usually preheated before this process. Figure 1.24 shows an example of the LS process.

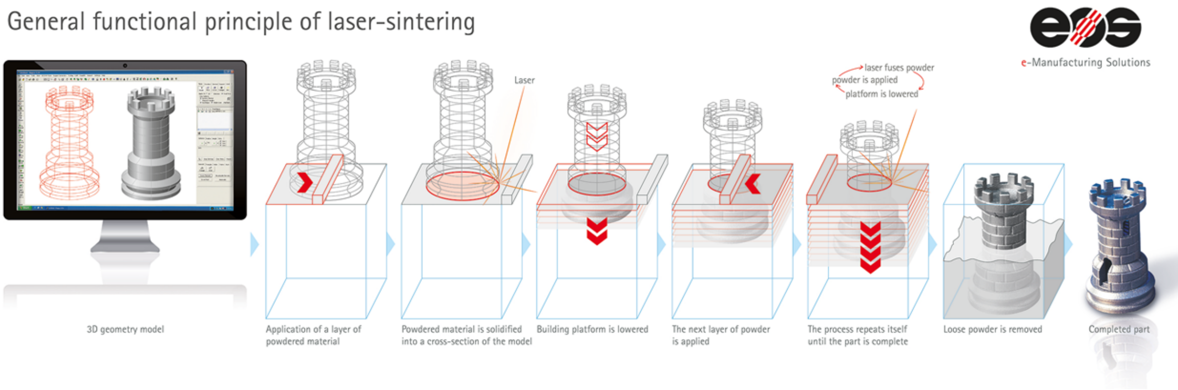


Figure 1.24 - Schematic arrangement of a conventional LS machine with roller placement of powder [45]

There are a few manufacturers of laser sintering machines, two of the larger manufacturers are: EOS and 3D Systems. EOS uses a blade for powder deposition and preheats the powder bed, whereas 3D Systems uses a roller for the powder deposition and preheats the powder instead of the build bed. For this thesis, the P100 EOS system will be used for the building of any laser sintered parts.

Laser sintering is a precise method of manufacture, giving the designer almost complete design freedom dependent on their CAD drawing skills.

Factors affecting the LS process

During the laser sintering process, the following factors must be considered when planning a build:

Powder

There are a range of polymers and filled polymers available. For this project, the standard unfilled, Nylon-12 powder was used. This is a standard material used in this process and can be utilised for a wide range of application parts and therefore is a good material in which to base investigations on surface finish about. There are five different states that the powder can be in as explained in the EOS manual [46]:

1. **New powder** – virgin powder that has not yet been used.
2. **Used powder** – plastic powder that must be sieved and regenerated prior to further use.
3. **Recycled powder** – sieved used powder that can be used for regeneration.
4. **Regenerated powder** – a mixture of recycled powder and new powder.
5. **Waste powder** – residue from the sieve or plastic powder that has already been removed from unpacking the parts.

These should all be separated from each other to ensure that they are not contaminated. There can be some problems when handling the powder, one of them being electrostatic charging of the powder during sieving, mixing or transferring the powder into bins. To avoid this problem, the powder should be stored after mixing to allow it to settle.

For this project, new, used and regenerated powder was investigated to see the effect on surface finish. The storage and maintenance of the powder is important to allow the best possible results when trying to improve the surface finish of laser sintered parts.

Building Temperature

The building temperature is the temperature of the process chamber. The suggested building temperature was dependent on the material that is being used. The polymer material used in this project is a nylon-12 polymer and the recommended building temperature for this is just below the melt temperature, so the laser only has to input a small amount of energy [46].

If the building temperatures are too low, this will cause the outer areas of the layers to roll upwards (known as curling). If the building temperatures are too high, this may cause all of the plastic to melt, which can be very problematic, not only for the build, but for the machine too. It can also cause the re-coater blade to be soiled in melted plastic, which will then cause irregular recoating of each layer and tearing out of parts from the powder bed. Another reason for not overheating the bed is that it prevents the powder from being recyclable as the particles become damaged from the excessive heat. By changing the temperatures of the bed temperature, this also effects the properties of the parts being built.

Process related effects

To improve the part quality of the piece that is being built, it is useful to take into account the positioning and orientation of the parts in the building chamber to make a constructive influence to improving the part properties. For example, the most successful area to place the part is in the middle of the build bed and away from other parts being built to ensure the following problems do not affect the part [46].

Shrinkage

Once the part has been made it contracts during cooling due to physical processes. If the build bed cools at an uneven rate, this can lead to the part shrinking in different magnitudes in different directions [46]. By ensuring the parts are well spread out within the build can create less of a chance of a “hot spot” developing and will give a more even cooling rate. The laser sintering machine software usually scales the part up by the magnitude of shrinkage for that material to compensate for this, but it should still be considered in the design process, especially for parts that need exact geometry and tolerances.

Distortion

Distortion occurs when there are large thermal differences during the building process or during cooling process afterwards, which results in warped parts. It is equally dependent on the material used and the geometry of the part. The optimal setting of the process chamber temperature and the removal chamber temperature within the Formiga P100 system can positively influence the distortion behaviour.

The following types of distortion can occur during [46]:

- **Building Phase** – due to excessively quick cooling of the individual layers in the process chamber there can be fluctuations in the application of the powder.
- **Cooling Phase** – failure to comply with the recommended cooling time, removing the exchangeable frame too soon or premature opening of the chamber door will result in the overall job cooling down too quickly. For physical reasons, the part cools down unevenly from the bottom to the top and from the outside inwards, which can result in the distortion of the part in the layers at the bottom.

For parts that are critical in relation to distortion, powder generously regenerated with new powder should be used. There is a general rule of thumb: the higher the portion of new powder, the less distortion on the parts.

Build orientation and placement

The literature also suggests that the orientation and placement of LS parts can affect the parts' performance properties and surface finish [47, 48]. Ellis et al. found that parts build at 0° and 90° to the bottom of the build bed created the smoothest surface finish results without post-processing techniques [49]. Parts built at 15° and 30° to the build bed had rougher surface finishes with visibly apparent "stair-stepping". This was investigated with the parts created for this project to confirm whether this was true for the EOS P100 machine in Chapter 4.

1.4.5 EOS Formiga P100 Laser Sintering System

This is the LS system that will be used for the making of the test pieces later on in the research.

Machine and accessories

The P100 Machine has some accessories that are used in conjunction with it to create the polymer parts.

Machine

Below in Figure 1.25, is the P100 Machine. This is where the sliced CAD files are made into actual 3D parts.

Figure 1.25 - The P100 Laser Sintering Machine

The screen to the right of the machine is the monitor where all of the main controls are, including where to find the process window giving a live update of the build.

Unpacking and Processing Station

Once the part has been built and cooled down, the building bin can then be exported from the P100 machine and placed in the unpacking and processing station, as seen in Figure 1.26, for post-processing.

Figure 1.26 - The Unpacking and Processing Station with building bins to the right of the station

Mixing Station

The mixing station, as shown in Figure 1.27, is where the new and recycled powders are mixed before building to ensure a regenerated powder to be used in the build.

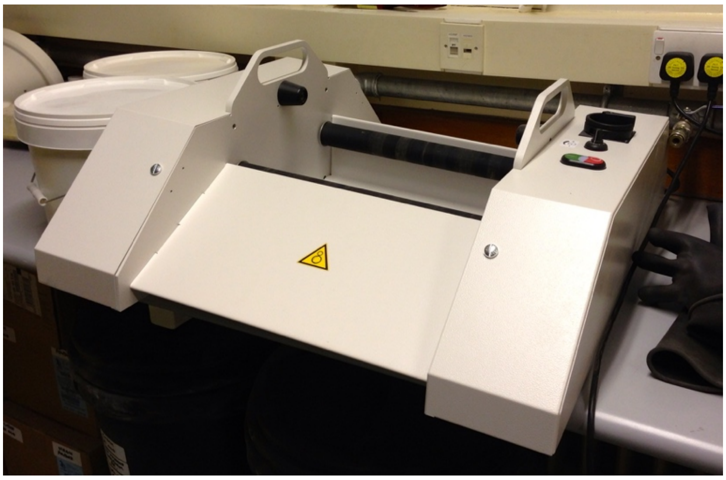


Figure 1.27 - The Mixing Station

The powder bin is placed on the mixing station and then rotated continuously for a pre-set time. Once this time has elapsed, the regenerated powder of new and recycled powders is then ready for building. This process may cause electrostatic charging of the powder, which is undesirable and will cause the plastic powder to become lumpy. Therefore, the powder must be stored in the bins after mixing to settle before use.

Shot-blasting cabinet

The shot-blasting cabinet, as shown in Figure 1.28, is where the finished products are cleaned after being removed from the powder cake at the unpacking and processing station.

Figure 1.28 - The shot blasting cabinet

The shot-blasting medium is mixed with pressurised air and is applied at adjustable high pressure to the part that is to be cleaned and is operated by a pedal at the bottom of the cabinet. The medium is usually made out of glass beads with a size of 70-110µm [46]. Any excess shot-blasting medium and powder that is blasted from the part fall through the grid in the bottom of the cabinet into a sieve where the shot-peening medium can then be reused.

From Section 2.2, the technique of sintering can be affected by five main factors explained above. Therefore, all of the build parameters will be kept the same standard settings for PA2200 (a Nylon-12 based polymer provided by EOS). The standard build parameters for this machine and material combination can be found in Table 1.3 [46, 50].

Table 1.3 – Standard build parameters for PA2200 in the EOS Formiga P100 LS machine

Parameters	
Layer thickness	0.1mm
Part bed temperature	170°C
Removal chamber temperature	150°C
Laser power (contour)	16W
Scan speed (contour)	1500mm/s
Laser power (hatching)	21W
Scan speed (hatching)	2500mm/s
Scan spacing	0.25mm
Heat up time from cold	1°C per minute ~ 2.5hours
Cooling time after build	~ build time

1.5 Surface Roughness

As mentioned before, the surface finish of AM parts can be described as a limitation of the technology, therefore this section outlines the theory and literature to link in with this.

1.5.1 Theory

Background

The surface roughness of a part is defined by the British Standards Institute (BSI) as [51]:

"*surface irregularities with relatively small spacings, which usually include irregularities resulting from the method of manufacture being used and/or other influences*".

No matter how much a surface is post processed, a surface cannot be completely perfect. As Williams describes in his work [52]:

"*No real engineering surface, no matter how carefully or indeed expensively, prepared can possess perfect geometry*".

This is due to the fact that even though there may be errors in the form or shape of a part, the surface finish is the characteristics of a surface, which has three main components. The high frequency or short wavelength components are known as the roughness and the larger wavelengths are referred to as the surface's waviness [53]. When combined together, these create the surface profile as shown in Figure 1.29.

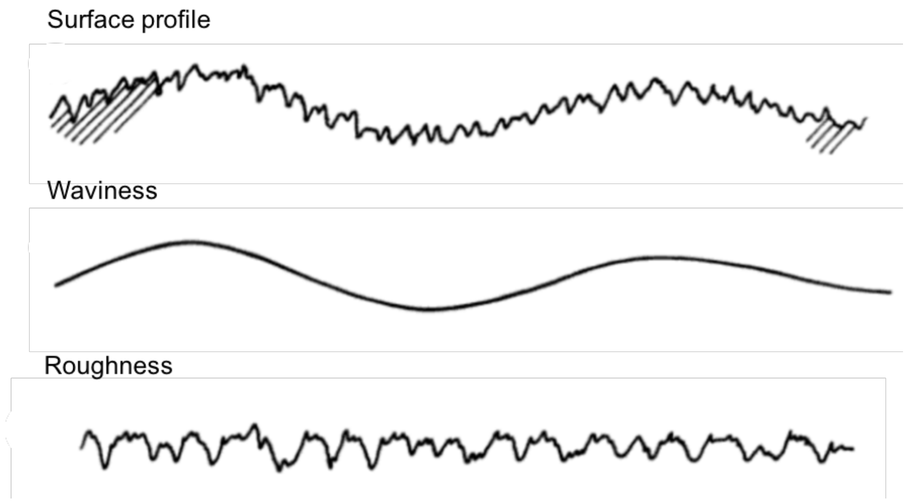


Figure 1.29 - The components of surface topography. Adapted from [52]

The manner in which these components integrate with a manufactured surface is as shown in Figure 1.30.

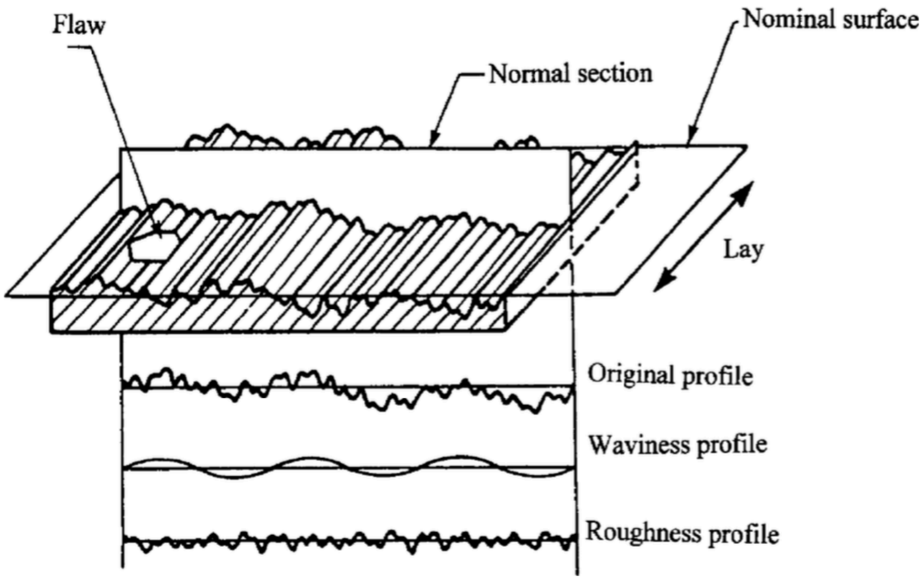


Figure 1.30 - Roughness and waviness of a surface shown in comparison to the surface of a part [53]

As shown in both Figure 1.29 and Figure 1.30, the roughness and waviness combine to create the surface profile. The lay (as shown in Figure 1.30 is the direction of the prevailing texture of the surface, usually determined by the method of manufacture being used or by other influences [51].

To simplify the amount of factors investigated in this project, the waviness of surfaces was not analysed as the hand held mobile phone cases were assumed to have flat surfaces.

Surface examination techniques

Surface examination techniques are mostly split into either non-contact or contact methods [52].

1. *Non-contact (microscopy)* – The non-contact method of examining surfaces and gives qualitative data. Usually carried out visually using beams of light. This however, can be magnified depending on what piece of apparatus is being used.
2. *Contact (profilometry)* – The contact method is mostly conducted using a stylus that is dragged across the surface of the part and gives quantitative data. This measures the displacements of the surface profile to often give an average of the roughness measurement over the sample.

For this research, the method of surface profilometry was used to gather quantitative data over the other option of qualitative microscopy. This was due to equipment availability and time constraints.

Surface Profilometry

Surface profilometry uses a diamond stylus that is dragged across the surface profile. It measures the displacement of the peaks and valleys found on a material's surface as shown in Figure 1.31.

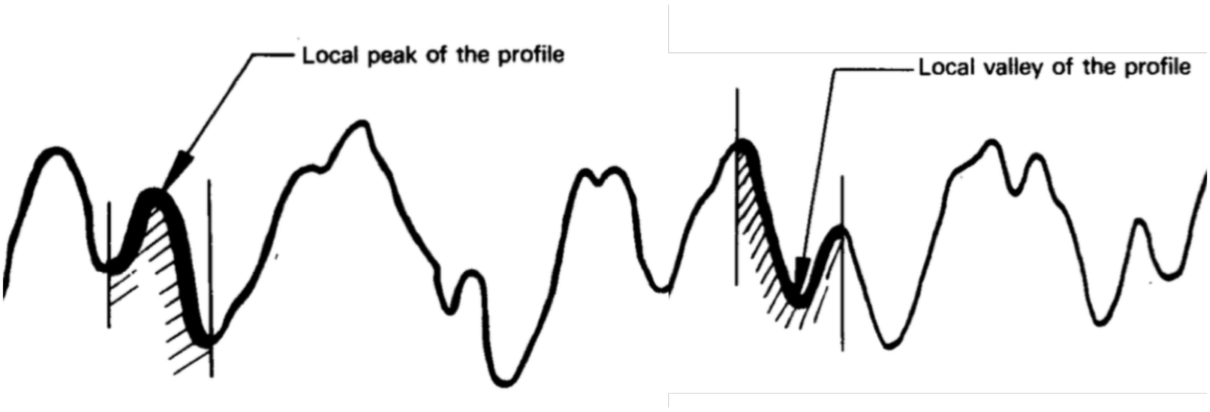


Figure 1.31 - Diagram of the peaks and valleys found on the topography of a surface [51]

Once the stylus has measured across the sample, it calculates some roughness parameters as described in Table 1.4.

Table 1.4 - Table showing the different surface roughness parameters. Adapted from [52]

Symbol	Name
R_a	Average roughness
R_{max}	Maximum peak to valley
R_q	Root Mean Squared roughness
R_z	Ten point height average

The two most common parameters used are R_a and R_z, and R_a was the main value used when measuring LS samples in this work to easily distinguish the average differences between surfaces.

R_a is the arithmetical mean deviation of the profile [51], which is the average roughness measured during the test and the standard value used. This value can be measured by using a height function, which is adding all of the peak and valley profiles and then dividing them by the overall sum of displacements as shown in Equation 1.3.

Equation 1.3 – Overall sum of displacements

$$R_a = \frac{1}{l}\int_0^l |y(x)|\, dx$$

Where l is the sample length and $y(x)$ is the profile height function. Another way of showing how R_a is obtained is in the illustration in Figure 1.32, with m being the median value.

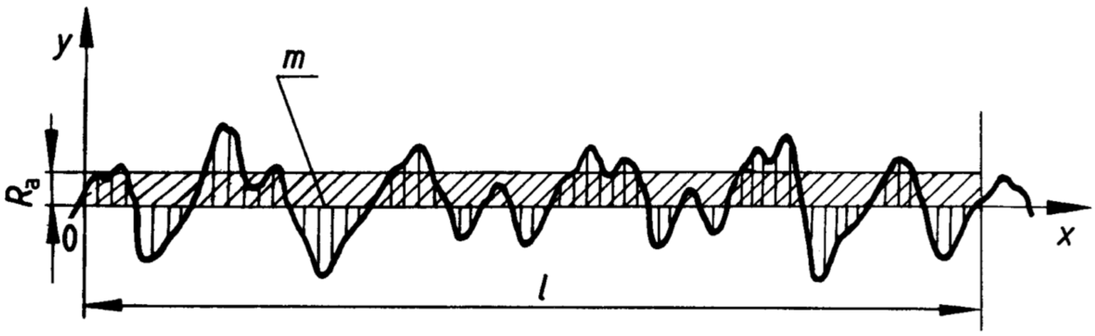


Figure 1.32 - Diagram illustrating Ra [51]

R_z is the ten-point height of irregularities [51], which uses the five highest peaks and five lowest valleys of the profile to determine the average irregular displacement. This can be defined as shown in Equation 1.4.

Equation 1.4 – Ten point height of irregularities

$$R_z = \frac{\sum_{i=1}^{5}|y_{pi}| + \sum_{i=1}^{5}|y_{vi}|}{5}$$

Where y_{pi} is the height of the *i*th highest peak profile and y_{vi} is the depth of the *i*th deepest profile valley. A way to illustrate how to obtain the highest and lowest values of the peaks and valleys is shown in Figure 1.33.

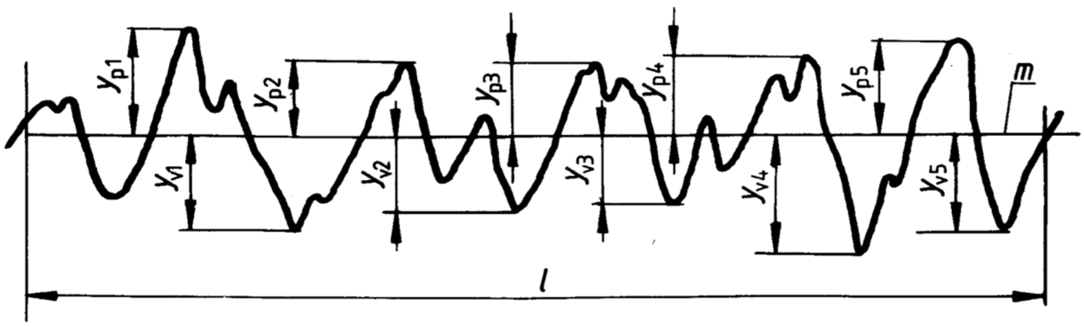


Figure 1.33 - Diagram illustrating Rz [51]

1.6 Surface roughness of Laser Sintering (LS)

1.6.1 Technology and Process

The natural surface finish achieved by LS parts is often portrayed as an issue. There are two ways in which to address this; through changing build and material parameters or through post-processing. Some of these methods are mentioned here.

Changing build parameters

Changing the build parameters gives more control over the following parts of the machine:

- **Laser Power** – the diode current or amount of energy emitted from the laser.
- **Laser Scan Speed** – the rate at which the laser passes over the powder bed to scan out the desired geometries for each layer.
- **Laser Fill Scan Spacing** – the spacing between each laser diode.
- **Laser Energy Density** – this compares the laser scan speed and the laser as explained in Equation 1.5 [54, 55]:

Equation 1.5 – Laser energy density

$$Laser\ Energy\ Density = \frac{P}{vd}$$

Where *P* is the laser power, *v* is the scan speed and *d* is the laser fill scan spacing. The laser energy density is the overall input applied to the powder bed during sintering.

From previous research, it has been deduced that controlling these parameters in a certain way can help to reduce the surface roughness. When the laser scan speed is reduced, the extra time spent travelling over the powder bed allows the particles to fully fuse and will lead to a smoother surface finish with much better inter-particle neck growth [54, 55]. However, speeding the scan speed up will not give enough heat exposure to the particles and the surface finish will therefore resemble the initial surface finish of the powder. By increasing the laser power, this will also give a similar effect to increasing the scan speed, but increasing it too much can cause a “balling effect” to take place. This is when the molten material breaks up into small spheres due to the high surface tension differences generated as a result of changes in thermal properties within the molten material [56, 57], as seen in Figure 1.34.

Figure 1.34 - Examples of increasing balling effect from left to right [56]

The strip to the furthest right of Figure 1.34 is the most severe case of balling with the strip furthest to the left having the opposite effect where there is a lack of melting. The two middle strips are examples of sufficient sintering of the powder. Balling can be a large problem when looking at the inter-layer connections – it decreases the density of the part being made and increases the overall surface roughness of the finished part. It has been proven that using a medium laser power and low scan speed can increase the surface finish up to around 90%, but higher laser fill scan spacing would create a worse surface finish due to too little energy being input to the material which would not be sufficient to sinter the powder completely [44]. Also, by having a higher laser energy density will allow for lower porosity and better mechanical properties, but may cause high shrinkage effects when the energy is too high [54].

Laser re-melting (LRM)

LRM is a method used in laser sintering, to not only improve the surface finish of a part, but also to improve the product's density and eliminate as much porosity in the material as possible. LRM is when the same layer of powder is scanned twice before placing a fresh layer of powder on top of it [58]. This process increases the production time if LRM is applied to every layer; however, this method can also just be applied to the surface once built which would not really affect the overall production time.

A problem with LRM is the increased chance of creating an “edge effect” which is when elevated edges are created in the finished product when the molten material is heated for an extended amount of time – this is not desired. The edge effect largely occurs as the first layer is scanned – this is the point when the layer is surrounded at both sides and underneath by powder particles with very low thermal conductivity. Particles are dragged into the molten volume of the scan, which increases the size of the melt pool and affects the solidification rate, giving a less than desired surface shape and finish to the part. With the addition of the dragged in particles to the melt pool, this leaves a lack of powder around the part to support it or for the next layer.

It was decided not to change the build parameters from the machine as the standard set-up is to achieve the correct balance of parameters to generate the best parts already.

Changing material parameters

As the properties of LS are directly dependent on machine parameters and initial material properties, any change in these creates a change in the sintering process, material molecular structure and mechanical properties [54]. Therefore, it may be a possible route to go down when looking into creating a lower surface roughness of LS parts. This could be, changing the particle size or even the particle shape to create an easier powder bed to sinter.

However, for this thesis, the emphasis will be on post-processing of LS parts instead of changing build or material parameters. This encourages a more practical outcome of improving the current post-processing that could be suggested to industry when creating LS parts for market.

Post-processing

Some of the more common post-processing techniques are described here [59-61].

Shot-blasting (or Bead-blasting)

This post-processing technique is the standard method used on LS parts once they have been taken out of the machine. More information can be found in Section 2.2.5.

Sanding

Sanding is a frequently used post-processing technique for LS. Varying sizes of grit are used to erode higher peaks of surface particles from the natural surface of and LS part to reduce the overall roughness. Sand paper comes in many different grades; ranging from 180 grade (similar to that of a natural laser sintered finish) to anything up to 25000 grade (where it is so smooth, that paint does not easily stick to the finished parts).

Tumbling

Tumbling is another smoothing method that can be used as a post-processing method of LS parts. The products are placed in a barrel with water and media (like ceramic or plastic particles) and then the parts are rotated at a predetermined speed, for a set amount of time, anything up to three hours [62]. More work has also been carried out by Schmid, Simon and Levy on Vibratory grinding [63] which has a similar principle and This type of post-processing technique was not used in this project due to machine availability.

Painting

Although this may seem like a basic post-processing technique, this is one of the simplest methods of creating a smoother surface on an LS part. By placing the paint on top of the surface that needs to be altered, the paint fills in all of the “valleys” as depicted in Figure 1.31. This creates a surface with a smoother finish overall as the troughs of the surface roughness are no longer apparent. However, this method was not taken forward due to material availability.

The PUSh™ Process

The PUSh™ process is a new and promising chemical post-processing technique developed at the University of Sheffield. It acts to reduce surface roughness and improve aesthetic appeal leaving no chemical residue on the part. It has been shown that at all build orientations, the PUSh™ process significantly reduces surface roughness and mildly increases part density [64]. Due to a pending patent, the process is confidential.

The surface finishing techniques to be taken forward for this thesis were a mixture of standard and new processes dependent on available equipment as well. The processes chosen were:

- **Shot-blasting** – This is the standard post-processing procedure for LS and should definitely be included.
- **Sanding** – This technique is a common post-processing method for many materials, not just LS.
- **PUSh™ Process** – This is a new chemical treatment developed at the University of Sheffield. This was a good opportunity to trial the new process and see how participants reacted to the surface finish.

1.6.2 Consumer input

Lagrosen believed that the more users are involved in the product development process, the more likely they will be satisfied with the manufactured products [65]. It is becoming more and more apparent that for AM technologies to be fully integrated by industry and other sectors, a more central role is needed for customers in the process of creating products, as Hoyer et al. explained in their work [66].

Customer introduction to CAD

A lot of the literature on consumer input for AM processes is focussed on the interaction between the consumer and CAD software to generate personalised designs that the customer wants. This is often in the form of free, easy-to-use software designed by CAD developers (for example SketchUp [67], 3DVIA Shape [68] and Sculptris [69]), which often come with video tutorials. While this software is a good introduction to the CAD process, it is very limited in its design freedom and ultimately, the consumer will still need to contact a company for a high-quality product.

Consumer manufacturing

Another method to engage the consumer to produce their own personalised product is through the use of 3D scanners with a turnaround time of four-six weeks with Pinla3D [70]. The scanning cameras capture 3D data that can be used to print what the consumer scans as explained by Kopf et al. [71].

AM was not easily accessible to the general public until 2007 when the first 3D printer was released for just under £1000, namely both the RepRap Darwin [72] and the Fab@Home Model 1 [73]. Now it is possible to buy hand-held AM machines to print as though using a pen like the 3Doodler [74] for just £99 as shown in Figure 1.35.

Figure 1.35 - Image of the 3Doodler pen [74]

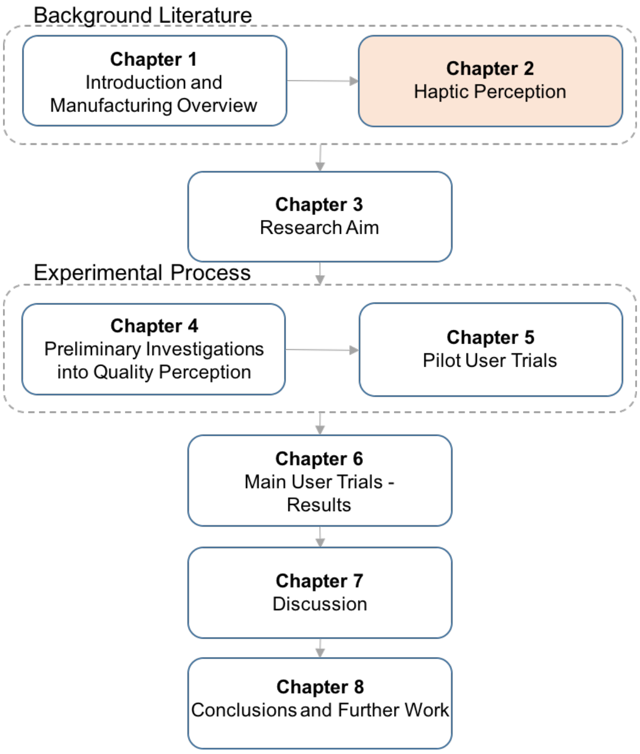
While desktop AM machines are good at creating consumer input of lower-end products, the more important focus for this project is how the consumer inputs with higher-end AM.

Consumer perception of AM parts

There is little literature on the subject of the perception of surface finish of AM parts, other than the surface finish is not deemed to be up to standard [75]. Ariadi [76, 77] carried out work on how to encourage consumers to design their own products with a small part of the work dedicated to whether the participants preferred AM (in particular LS) surface finishes to injection moulded surface finishes of hand-held pens. The outcome was that 53% of the participants would like to use products made by AM, but that they wanted the surface finish of the injection moulded process. This suggests that there is a gap in the literature to better understand the consumers' perception of AM parts in more depth. Barnes, Childs and Lillford have carried out a large collection of work [78-82] on an engineering principle that incorporates the consumer in the product decision making process called affective engineering. This is covered in Chapter 2.

Therefore, this project incorporated the AM need for surface improvement with the new and upcoming methodology of affective engineering.

2 Haptic Perception



This chapter explores the sense of touch, haptic perception and how perceptions can be collected and quantified. Delving into the areas of skin tribology, affective engineering and methods of opinion assessment to produce a broad background to better inform the surface roughness experiments later on in this thesis.

The definition of haptic is "*an information processing perceptual system that uses inputs from receptors embedded in the skin, as well as muscles, tendons and joints to produce a sense of touch*" [8]. This thesis will focus on people's responses to surfaces, therefore introducing how people perceive things and objects through touch. In this chapter, the sense of touch will be explained and analysed to produce a broad background knowledge to better inform the surface roughness experiments later on in this thesis.

2.1 Skin

2.1.1 Overview

Skin is the largest organ in the human body and acts as a sensory port of external stimuli having several kinds of sensors [83]. It is a multi-layer organ comprised of many different types of skin and sensitivity. Many different researchers have investigated this - the most prominent being early findings from Penfield and Boldrey [84]. The most sensitive parts of the human body were found to be glabrous (hairless) skin found mainly on the hands and face. This is shown in the homunculus map in Figure 2.1.

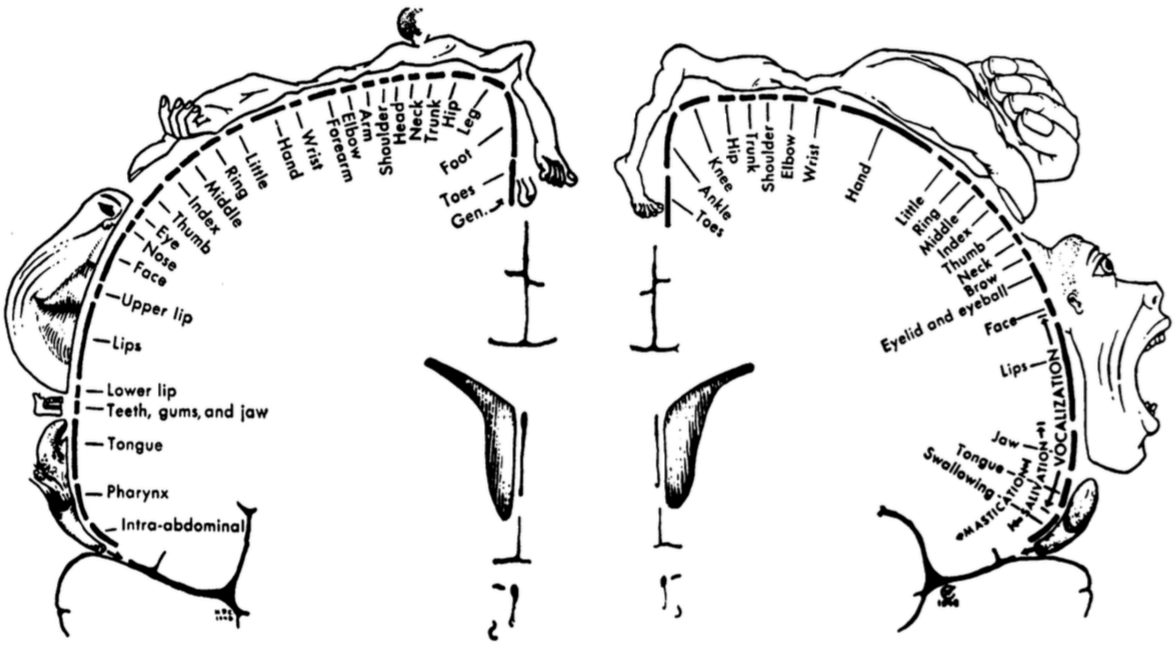


Figure 2.1 - The motor and sensory homunculus map [85]

A homunculus is a visualisation technique that illustrates a distorted scale model of the human body to show the connection between different body parts and areas in the brain hemispheres. Figure 2.1 is a prime example of this. The body on the left side of the illustration is the motor homunculus. The larger the body parts in this half show how much brainpower there is dedicated to controlling them. The right hand side of this illustration is very similar to the left, but it depicts how much brainpower is dedicated for sensing the different body parts, or how many nerve endings there are. This is known as the sensory homunculus. This side of the picture was then developed into a scale model by Breedlove et al; as shown in Figure 2.2.

Figure 2.2 - The homunculus man [64][86]

Figure 2.2 pictures a homunculus model of a man with greatly enlarged hands and facial features, piecing together the information developed by Penfield and Boldrey [84] to create the distorted figure above. This shows that the larger body parts have more nerve endings and therefore a greater sensitivity when they are used for exploring objects.

Fingers will be the main exploratory tools for the testing in this project due to their increased nerve endings and sensory advantages. Hand held objects will be the focus of the applications.

2.1.2 Biology

The human skin is an incredibly complex, layered organ and is mainly made up of two distinct layers: the epidermis and the dermis with the subcutaneous tissue lying underneath as shown in Figure 2.3.

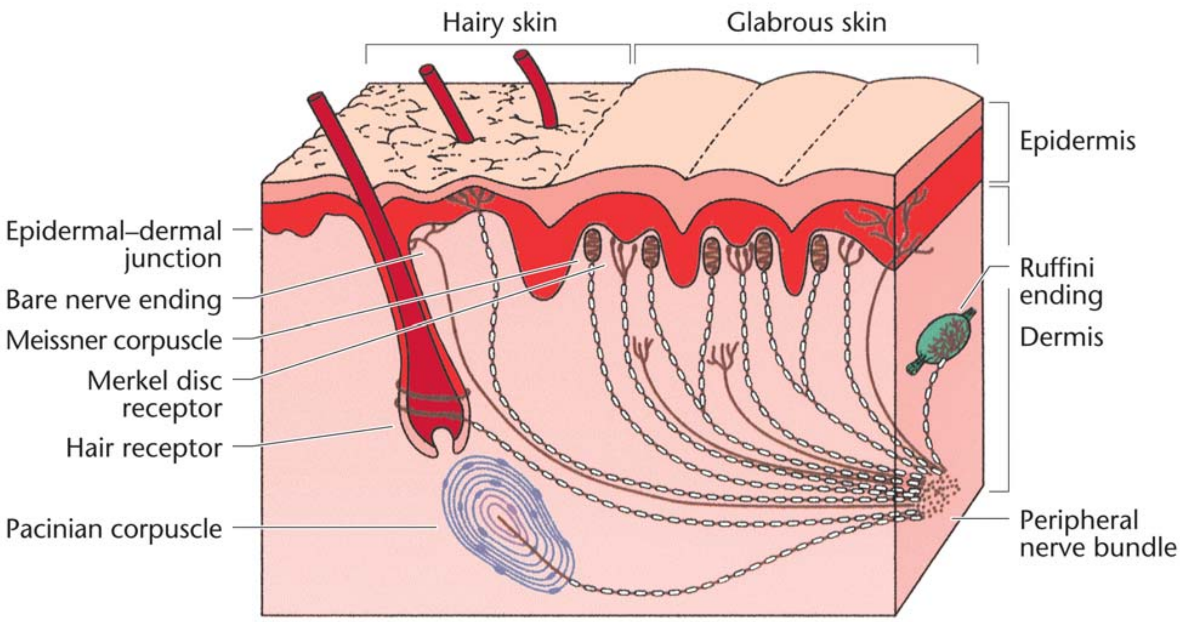


Figure 2.3 - Diagram of the human skin [87]

When exploring an object for the first time the human body experiences sensory information detected through the skin, which is often aided by vision. Glabrous (hairless) skin has four different types of mechanoreceptors that can detect certain features to help identify and perceive common traits for identification. The four sensory mechanoreceptors are also shown in Figure 2.3 and are namely: Merkel Discs, Meissner Corpuscles, Ruffini Endings and Pacinian Corpuscles. These can be found in Table 2.1 [88].

Table 2.1 – The four sensory mechanoreceptors

Mechanoreceptor	**Feature Sensitivity**	**Primary Functions**
Merkel Disc *(SAI)* *Slow adapting* *Small*	Sustained pressure. Maximally sensitive to very low frequencies. Spatial deformation.	Very low frequency detection. Coarse texture perception. Pattern/form detection. Stable precision grasp and manipulation.
Meissner Corpuscle *(FAI)* *Fast adapting* *Small*	Temporal changes in skin deformation. Spatial deformation.	Low-frequency vibration detection. Stable precision grasp and manipulation.

Ruffini Ending (SAII) *Slow adapting* *Large*	Temporal changes in skin deformation.	High frequency vibration detection. Fine texture perception. Stable precision grasp and manipulation.
Pacinian Corpuscle (FAII) *Fast adapting* *Large*	Sustained downward pressure. Lateral skin stretch. Low dynamic sensitivity.	Direction of object motion and force due to skin stretch. Stable precision grasp and manipulation. Finger position.

Merkel Discs are placed near the skin's surface and are mainly responsible for detecting surface texture, they are also activated by static contact. Meissner Corpuscles are placed close to the surface of the skin and are mainly responsible for detecting the sensations of stroking and are activated by dynamic contact. Ruffini Endings lie deeper in the skin and are responsible for the interpretation of shape. Pacinian Corpuscles are placed lower in the skin and are responsible for the interpretation of vibration. All of these sensory mechanoreceptors work together with the help of vision to interpret new surfaces and compare them with other surfaces that have been experienced before.

Katz [89] observed that roughness is only perceived accurately when the finger is in motion and in contact with a textured surface. Johnson et al [90] have proved this in that the perception of roughness depends on the activity of one of the rapidly adapting mechanoreceptors, in which otherwise they would be redundant.

This suggests that when planning tests, the participants' fingers should be active in their movements to perceive roughness.

2.2 Haptic exploration

2.2.1 Movements

When exploring an object for the first time there are two different types of movements that can be observed: prehensile and non-prehensile movements. Prehensile movement is when the object is held in the centre of the hand and non-prehensile movement is where no grasping happens at all – the movement is mostly pushing or lifting the object as a whole [91]. When using prehensile movements, there are two types of grip that are usually used: the power grip and the precision grip. The power grip is a clamp-like positioning formed by the fingers and palm of the hand, giving the holder a strong, stable positioning around the object. An example of the power grip can be seen in Figure 2.4.

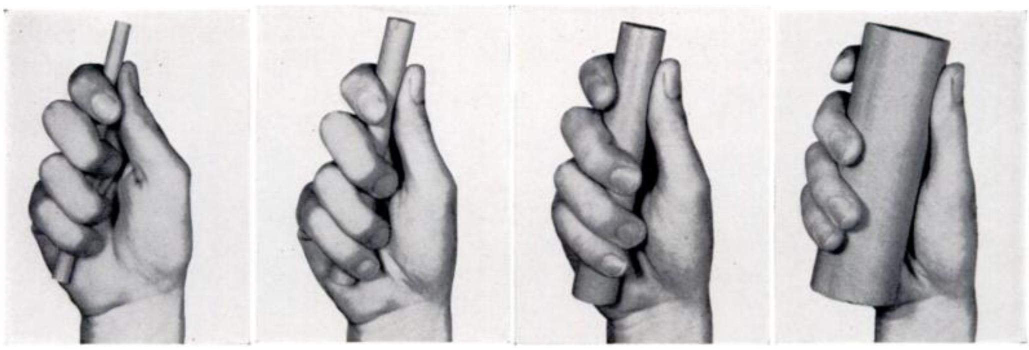


Figure 2.4 - Different examples of a power grip [91]

A precision grip is when the object is held in place by the ends of the fingers and thumb without the need for the palm to stabilise the positioning, an example of the precision grip can be seen in Figure 2.5.

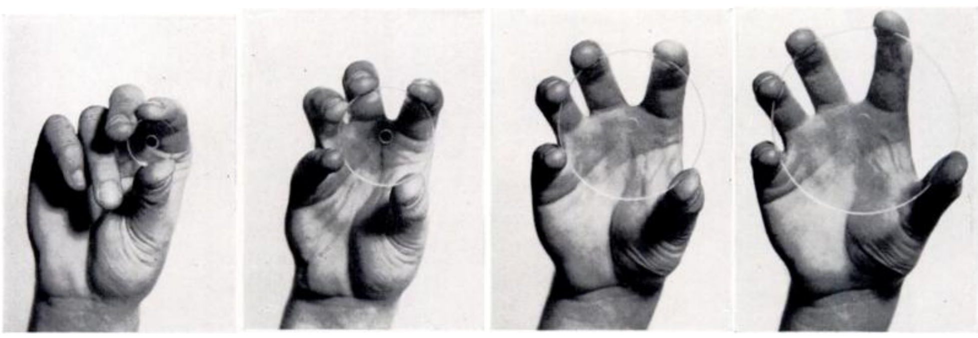


Figure 2.5 - Different examples of a precision grip [91]

When choosing which type of grip to use for a new object, there are usually two main influencing factors:

1. *The size of the object* – the extremity of object sizes, both large and small are usually handled using the precision grip.
2. *Influence of the intended activity* – the precision and power grips are named due to their intended activity. If the subject wishes to be careful and precise with the object

There are also further significant miscellaneous factors that also strongly influence the grip choice, yet are difficult to define as a single factor. These could be many different physical factors such as weight, texture, temperature, wetness or dryness of an object that could affect which grip is chosen and used to hold the item. Other more emotional factors such as fear and hunger can also influence this.

These grips can be used in conjunction with each other – for example when opening a plastic bottle of water. The power grip is used to establish a strong hold of the bottle whilst the precision grip is used to twist open the bottle lid.

For hand held objects, especially phone cases, the type of grip used is a mixture of both the power and precision grips depending on the particular movement and usage. For example, a precision grip would be used to pick up the object, yet a power grip would be used during a phone call. The main experimentation of this project, did not incorporate differing grips, but for further work or case studies, this would be imperative to include.

2.2.2 Exploratory Procedures (EPs)

Extensive research has been completed in the subject of haptic perception by Lederman and Klatzky [8-10, 92-97], especially with their work investigating Exploratory Procedures (EPs). When a new object is explored for the first time, it has been shown that there are particular reoccurring subconscious motions that hands use to identify different characteristics of an object. These EPs can be seen in Figure 2.6.

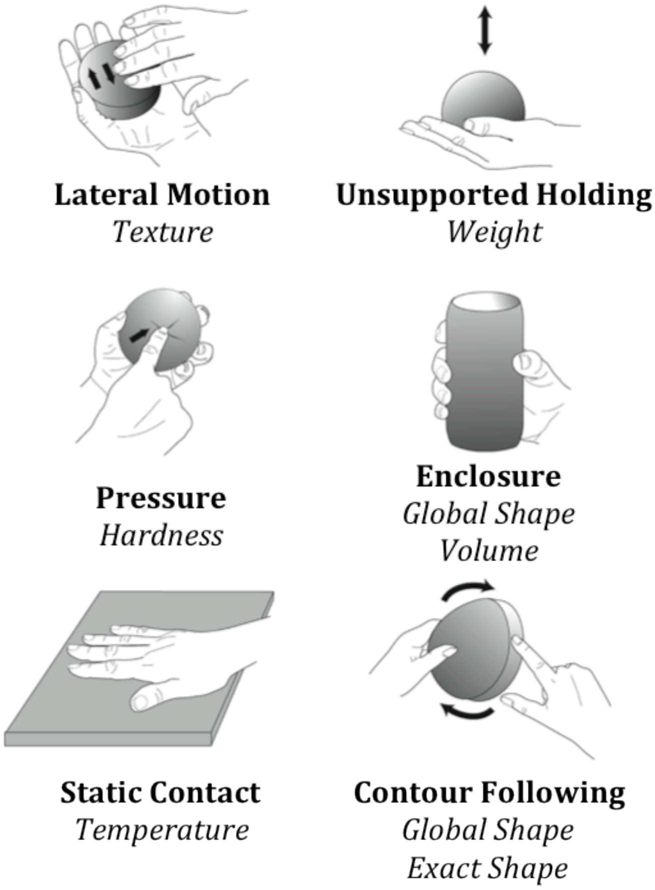


Figure 2.6 - Diagram showing the different exploratory procedures [10]

The EPs were largely noted when the participants were asked to comment on a particular characteristic. For example, the lateral movement was mostly observed when the subjects were asked to comment on the texture of an object. Below is a list of the different EPs and which procedures they determine.

- **Lateral Motion** – uses sideways motion between skin and the other surface. Typically, the fingers rub back and forth across a small surface area. Is used to determine the texture of an object.
- **Pressure** – produced by applying torque or normal forces to one part of the object, while another part of the object is stabilised or an opposing force is applied. This can be seen by obvious movement as in poking, or by signs of force evident in the fingers and hand. This is used to determine the hardness of an object.

- **Static Contact** – the object is supported externally, by an external surface or the other hand, while one hand passively rests on it without moulding. This can be used to determine the surface roughness of an object, but is not as accurate as lateral motion. It is mainly used to determine the temperature of an object.
- **Unsupported Holding** – the object is lifted away from any supporting surface and maintained in the hand without any effort to mould the hand to the object. Typically, there is a hefting of the arm or wrist. This is used to determine the weight of an object.
- **Enclosure** – the hand maintains simultaneous contact with as much of the envelope of the object as possible. Often one can see an effort to mould the hand more precisely to object contours. Periods of static enclosure may alternate with shifts of the object in the hand(s). This is used to determine the shape or volume of an object.
- **Contour Following** – the hand maintains a dynamic contact with a contour of the object. The movement is smooth and non-repetitive within a segment of object contour, stopping or shifting direction when a contour segment ends and it does not occur on a homogeneous surface. This is used to determine a detailed shape outline of an object.

As mentioned earlier, the texture of an object is more accurately observed when there is movement present in the examination between skin and the surface of the test piece. Therefore, there should be a greater chance of gathering correct and precise perceived roughness when the subjects use movement in their examinations of each surface.

2.2.3 Finger choice

As to the correct number of fingers used in the examination or which digits to use, there are conflicting results in the research studied [78, 98, 99]. The ring finger is naturally motorically awkward [78]. This means that its use could weaken any recognition of shape, therefore giving a truer perception of roughness. Although for the purposes of this thesis, it is important to identify the perception of texture without other factors aiding the final outcome, whilst maintaining as close to real-life situations as possible.

2.2.4 Vision

Vision is another factor to consider when designing experiments for haptic exploration. There has been a lot of research into the human perception of surfaces focussing on the use of sight. Many researchers have worked with [100, 101] and without [102, 103] the use of sight in their work, yet Lederman et al. found that in the perception of roughness; touch dominated vision [104]. Katz also beautifully stated *"the tactual properties of our surroundings do not chatter at us like their colours; they remain mute until we make them speak."* [89], which suggests that the sense of touch adds so much more to the understanding of a product. Sight can also encourage preconceptions of different new materials and it is important that it is used for the correct reasons.

In this thesis the main focus is on touch, but sight will be investigated slightly in individual interviews.

2.3 Affective Engineering

Affective engineering is a study that measures consumers' emotional responses to products, identifying the properties of the products to which they are responding, and then using the information to design better products [105]. It is uses adapted quantitative methods and techniques to gather qualitative data for analysis. Therefore, this technique is very useful to understand the perceived quality of any product.

"*Emotions are inseparable from and a necessary part of cognition. Everything we do, everything we think is tinged with emotion, much of it subconscious. In turn, our emotions change the way we think and serve as constant guides to appropriate behaviour, steering us away from the bad, guiding us toward the good.*" [106].

As explained by Norman [106], emotion is apparent in everyday thinking and decision making. He argues that the emotional side of design may be more critical to a product's success than its practical elements. These emotions help to form a person's perceptions of a product and ultimately whether they would purchase it or not. It is these perceptions that are the driving interest for this project, specifically looking into quality and surface finishing.

2.3.1 Kansei beginnings

Affective engineering uses the Kansei approach to engineering, which was developed by Professor Nagamachi at the University of Hiroshima in Japan in the 1970s [107]. The word Kansei is a Japanese word not easily translated into the English language as it explores the psychology of a person's feelings, it can be loosely translated as emotionality, sensuality or sensitivity/sensibility [108]. According to Nagamachi, Kansei Engineering is defined as:

"*translating technology of a consumer's feeling and image for a product into design elements*." [107].

Schutte and Eklund developed a process to evaluate a product's emotional quality by Kansei engineering using these steps [43]:

1. Identify words and phrases describing the emotional bond between the users and the product in question
2. Identify important product elements and a selection of the products concept that best represents those elements
3. Collect the users' impression of the chosen product concept with regards to the words identified in step 1
4. Analyse the collected data comparing the strength of the users' emotional responses for each of the concepts and words used
5. Define the new product development strategy from the results

These steps were used to build the affective engineering process.

2.3.2 Affective engineering process

Affective engineering is the technique followed in this thesis that captures the personal elements of Kansei engineering to achieve a design process that is tailored to the consumer. It is a qualitative research method that incorporates quantitative data collection to verify its methods using opinion assessments. It follows a very similar step process; gathering adjectives to help describe the product qualities.

2.4 Methods of opinion assessment

There are many different types of opinion assessment that can be used in affective engineering, a few of which are mentioned below.

2.4.1 Individual Interviews

Individual interviews can be structured or unstructured depending on what the qualitative outcome objective is. Unstructured interviews allow the interviewee to go off topic and often leads to other areas of interest being highlighted [109]. It is important that there is a plan in place regardless of the style of interview. The planning of any of these opinion assessment methods can follow the methodology set out in Section 3.4.3.

2.4.2 Group Interviews

Group interviews are similar to individual interviews, but involve more than one participant at a time [109]. These can be deliberate or accidental, if a participant attends a session with a family member or friend. When other participants are involved, this can often lead to increased opinions as their ideas develop and build together.

2.4.3 Focus groups

A focus group is a special case of group interviewing. It is a small group discussion guided by a trained leader or facilitator [110]. It is used to learn about opinions on a specific topic and to control future action. The main difference between a focus group and group interview is that a focus group is more structured.

Krueger and Casey have carried out extensive research on developing and planning successful focus groups [111-113]. They state that a good focus group has the following characteristics [112]:

- Carefully recruited participants
- Interacting in a comfortable environment
- Led by a skillful moderator
- Followed by systematic analysis and reporting

Before the planning for the focus group can begin, it is imperative that the focus group is carried out for the right reasons. Krueger and Casey [111] produced a set of questions that aid the initial stages of the planning process:

- Why should this study be conducted?
- What kind of information will be produced?
- What types of information are particularly important?
- How will all this information be used?

These would not only help with the decision of whether to carry out a focus group, but also would help to propose the initial structure for the focus group.

As suggested by Krueger and Casey [111], the methodology for creating a focus group plan was split into five main sections: planning, participants, location, resource management, and post focus group work – with planning being the most important. However, Freeman discusses that each focus group is different, should be tackled independently and that there is no “definitive” set of rules when conducting one [114]. This suggests that while there are many different guidelines available to help with planning a focus group, they should not be followed blindly.

Planning

Planning a focus group is the most important part of the methodology as this includes the planning and development of the questions to be used in coordination with the aims of the focus group to achieve a successful outcome. As Krueger and Casey stated, “Quality answers are directly related to quality questions.” [111]. Meaning, if time and effort are put into creating the questions for the focus group, that the information will be of a better quality because of it. These questions are usually split into five categories [111]:

1. **Opening** – ice breaker
2. **Introductory** – general topic and fosters conversation
3. **Transition** – helps to paint bigger picture
4. **Key** – important topics
5. **Ending** – summary

By splitting the questions into these categories, this allows the facilitator to easily guide the conversation in the direction needed to collect the right information and not to waste time. It also creates a focused and logical sequence for the participants to help them to fully develop their ideas and for the facilitator to see the participants' understanding and thought processes.

Moderator

Having a skilful moderator can be incredibly useful to a successful focus group. Krueger and Casey suggest that the moderator should establish an open environment for the participants to feel comfortable in [112]. They also state one of the most influential factors of a good quality focus group, is that the moderator must show respect the participants [111]. Not only must they fully understand the purpose of the study, but should also show empathy and belief that the participants' answers are valued. This creates the open environment that is desired for the participants to feel comfortable sharing their opinions.

Participants

The literature is divided as to whether participants should know each other or not. This is because some authors, such as Single and Powell imply that participants tend to be more honest in front of strangers [115]. Others, such as Kitzinger, suggest that knowing the other people in the room encourages more free-flowing conversation and these groups show how people might naturally discuss topics [116].

There is no ideal number of participants and the range can be anything from 4 participants [117], to 25 participants [118]. Most focus group guidelines encourage the group size to be between 6-10 people, however any set more than 12 people has the tendency for the group to fragment into individual conversations [111]. There needs to be a good balance between giving the group enough opportunity to share insights, and to have a diverse enough group in numbers.

Location

The location of the focus group is also an important part of the methodology as the environment created by the location can be the difference between the participants openly contributing and the participants feeling interrogated. The location should create a relaxed and open environment that invites the focus group members to participate in the discussion. The room should also be free from distractions and quiet enough to record [111].

Krueger and Casey [111] suggested a checklist for setting up the room in advance:

- The room should have chairs facing each other.
- Tables enable participants to lean forwards and be less self-conscious about their bodies. If there are tables available, use them to create a central place to sit.
- Eye contact is vital for the participants to engage.
- Chairs must be evenly spaced.

Therefore an ideal set up of a focus group developed from the checklist above would be similar to that found in Figure 2.7.

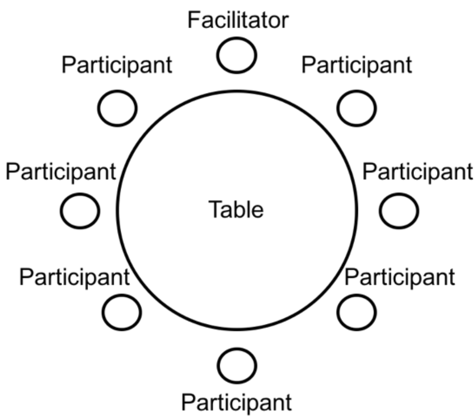


Figure 2.7 - Ideal seating plan for equal participant contribution in a focus group.

Resource management

Once the questions and location are decided upon, the technicalities of the focus group need to be addressed. If the focus group is to be recorded, it is vital that the recording equipment is of a good enough standard to document the conversation clearly for transcription. In this case, two separate devices should be used in case of one failing.

Food and refreshments have been proven to improve participants' moods and counter against unconscious bias due to the increased serotonin levels experienced in the brain [119]. Eating together also "tends to promote conversation and communication within the group" [111]. Therefore, by providing this, participants should be more open to new ideas and be less prejudiced towards the questions asked during focus groups.

Analysis and results

Once the focus groups are complete, the data can be captured in different forms as explained by Krueger and Casey [111]. Below are summaries of each of the different methods.

- **Transcript based** – this is where complete transcripts are typed for analysis, usually from a recording of the discussion taken at the time of the focus group. This captures every detail of the conversation, but can be very time consuming.
- **Abridged based** – this is similar to transcripts, yet less time consuming. This method relies on listening to an audio recording of the focus group and picking out which parts are the most relevant and useful to be transcribed.
- **Note based** – unlike the previous techniques, this relies mostly on notes taken during the focus groups and audio recordings are used as back up. Notes based analysis tends to be for focus group aims that do not require as much details, such as pilot-testing.
- **Memory based** – this requires a lot of skill from the facilitator and is mostly used when a focus group is conducted in a room with one-way mirrors for the facilitator to have external observers.

The analysis for this project requires detailed results from the focus groups, therefore a transcript based method will be used to analyse the conversations.

2.4.4 Forced choice tests

Whereas focus groups collect qualitative data, quantitative data is also needed. One method to gather quantitative data for affective engineering is by using a forced choice technique. The most common type of forced choice test is the Two Alternative Forced Choice (2AFC) test. The 2AFC test is a historical test that simplifies naturally occurring situations tracing back to a model from nature, where animals either avoid or approach a new object or situation [120]. Translating this to an experimental situation, a participant is given two products for example and asked to choose which has the highest “strength” between the two [121], where strength is deemed as the focus of the test. For example, quality, roughness, hardness, etc. The 2AFC test has been widely studied and used in psychological tests, which is a “common performance validity assessment methodology” in this field [122].

Bogacz et al. state that there are three fundamental assumptions made during the 2AFC test [120] as shown below, which should be taken into consideration when conducting tests using this technique.

1. Evidence favouring each alternative is integrated over time
2. The process is subject to random fluctuations
3. The decision is made when sufficient evidence has accumulated favouring one alternative over the other

When planning the 2AFC tests, it is important to be prepared beforehand. The order in which the pairings are to be shown to the participant can be a particular downfall. It is important that the facilitator is organised so that the participant concentrates solely on the task at hand, rather than what the facilitator should be doing. The testing process for the 2AFC method would be useful to assess the participants’ reliability and to generate a snapshot of their first impressions of AM in the main experiments.

2.4.5 Semantic differentials

Osgood et al. describe semantic differentials as “*a combination of association and scaling procedures designed to give an object measure of the connotative meaning of concepts*”

[123]. Semantic differential tests are used in psychological analysis, but also commonly in affective engineering with the use of adjective analysis such as in the work of Barnes, Childs and Lillford [78-82]. This where the participant would test each of the products separately, hidden behind a screen, then rate it against opposite adjectives on scales as determined from a focus group. This has been prominent in product packaging tests of moisturiser bottles [124]. In particular, this study looked into the quality of luxury product packaging. This is where semantic differential tests were actively used in affective engineering to translate the consumers' feelings for a product into design elements.

The semantic differential method is a technique that collects large lists of words to describe a product from as many sources as possible, for example from shops that sell the product through to magazines that advertise it and focus groups. These are then refined to a small group of adjectives that are used in surveys for experiments of different objects, usually on a scale between two opposites. By using scales of an odd number, this allows the participants to rate objects neutrally [78]. The opposites help to form a clear picture of the subject's perceived scaling of texture with regards to different parameters.

This usually leads to a six-step methodology system [124]:

1. Identify product context
2. Adjective generation and reduction
3. Create test stimuli
4. Perform semantic differential experiments
5. Analyse and interpret results
6. New product evaluation

The main aim of the semantic differential test is always to find ways to improve a product, which is similar to that of Kansei engineering. Figure 2.8 shows an example of a semantic differential scale.

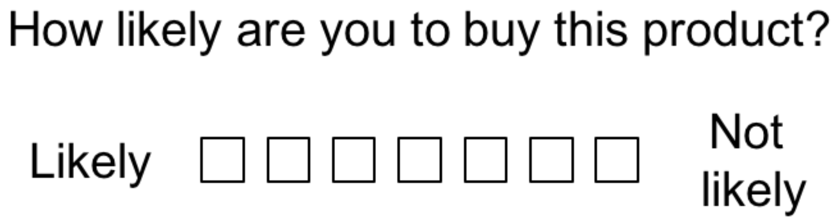


Figure 2.8 - Example of a sematic differential scale

This allows the participant to use a scale to define the strength of which they answer the question.

Adjective generation for scales

Adjectives for semantic scales can be collected from a variety of sources, one lucrative method is using focus groups. Once the audio recordings have been transcribed, adjective collection can begin. Lillford and Barnes have been at the forefront of developing linguistic support to aid the adjective selection for the semantic differential scales [79, 81, 82]. They developed guidelines for researchers to which have been adapted for this thesis below:

1. Only adjectives are allowed
2. Remove adjectives that are not plausibly related to objects
3. Remove adjectives that describe purely evaluative reactions
4. Remove ambiguous adjectives
5. Remove adjectives that describe feelings
6. Remove adjectives relating to prolonged experience with the sample rather than a brief experimental encounter
7. Remove adjectives requiring additional context to be understood
8. Remove comparative adjectives
9. Remove any adjectives that are not purely to do with touch.

Many researchers have explored the possibilities of specific adjective scales. Chen et al. [105] investigated different dimensions used especially in touch perception and determined that it consisted of three main opposites:

1. Roughness-smoothness
2. Hardness-softness
3. Sticky-slippery

Therefore, they used these opposites plus a few others to fully investigate tactile textures in their methodology as shown in Figure 2.9. The other opposites help to understand not only the roughness of a material, but the quality as well.

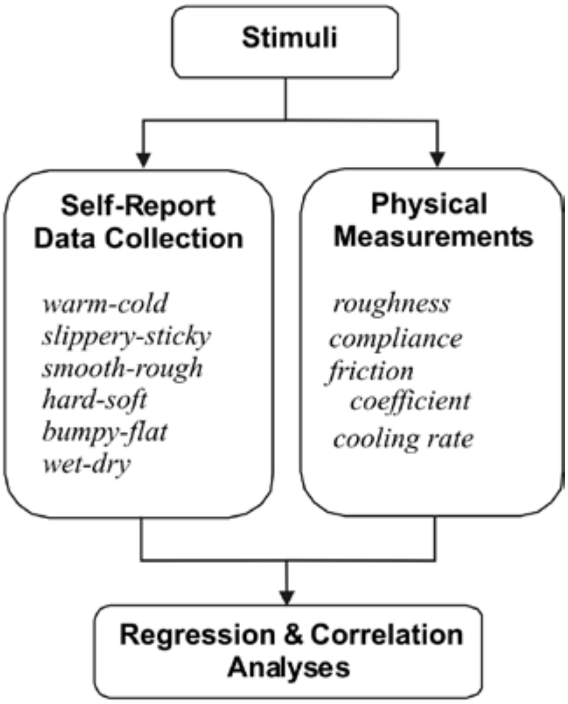


Figure 2.9 - Methodology of the sematic differentials technique [105]

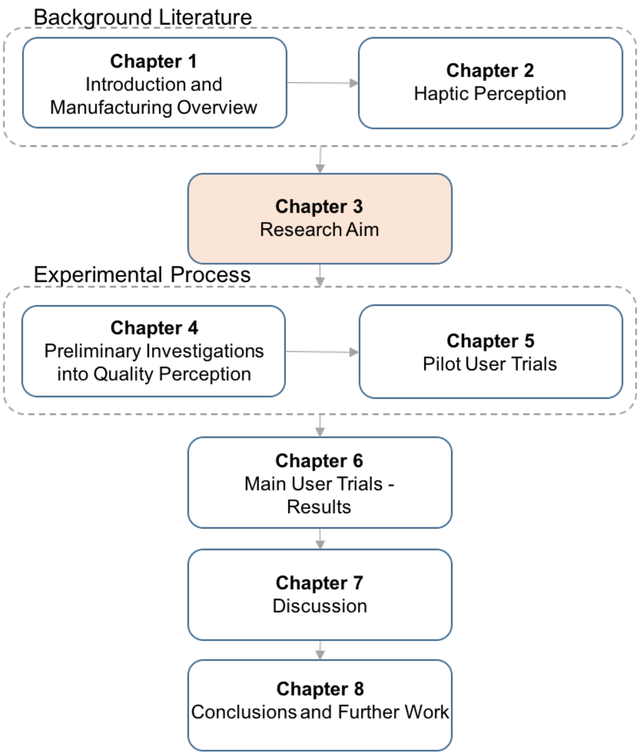
This methodology allows for the separate investigations of both the self-reports and the physical measurements to be used together when analysing the data to predict an accurate picture of the subject's object perception. Once the results are collected, they can then be analysed for correlations between adjective scales to find improvements to be made to the products.

The adjective pairs in Figure 2.9 will be taken into consideration for the adjective pairing generation in later experiments.

2.4.6 Summary

There are a variety of ways in which reactions can be tested to products, some of which will be used later in this thesis, for example, focus groups, 2AFC tests and semantic differential tests. These were the main successful opinion assessments chosen to help analyse qualitative data in the recent literature of affective engineering [79-82, 124]. These will combine to create a testing process to investigate, gather and analyse the perceptions of quality.

3 Research Aim



3.1 Problem definition

As established in the introduction, there are many proven benefits to AM, including increased design freedom, personalisation and optimisation [3]. However, the surface finish of AM parts is still thought to be a problem area [125] and there is currently limited input from consumers in its research advances. This project utilises techniques for human factors research, to provide a novel understanding of the way in which surface finish affects users' perceptions of the quality of a LS part.

3.1.1 Specific Objectives

1. Identify range of roughness achievable with "standard" LS finishing techniques
2. Identify relevant human interactions techniques to assess quality perceptions of the different surface finished LS parts
3. Design and conduct experimental work to quantify these
4. Identify how the findings from this research can be applied to industry

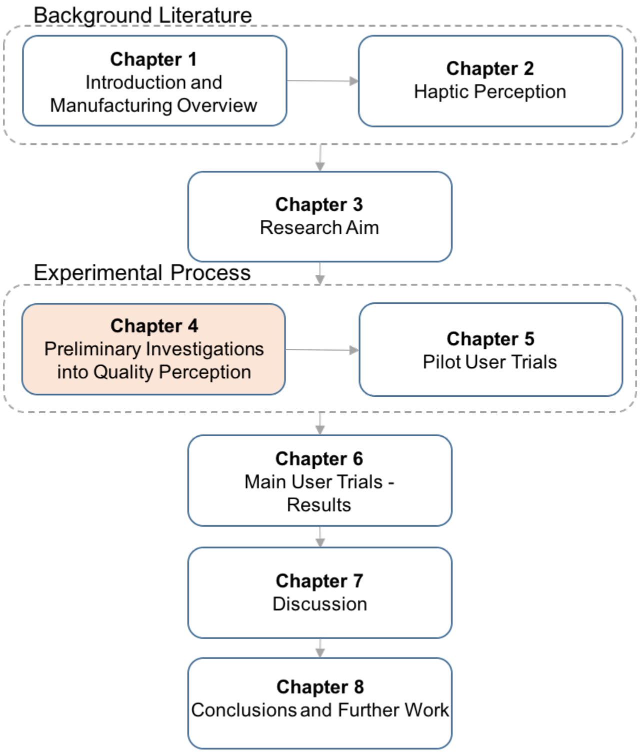
3.2 Approach

After a review of literature on LS, roughness and human perceptions, a series of parts were then produced to test the range of roughness available from the machine. Using these parts, focus groups were then utilised to identify the correct language to use for further experiments. A range of human interactions techniques were combined into one experimental procedure. A small pilot test and iteration were conducted before the main experiment. Statistical analysis was then used to understand the results and finally future recommendations were suggested for research routes following this project.

3.3 Ethics Approval

Before any work could commence, it was imperative that ethics approval was obtained from the University Ethics Committee. This then enabled the work to be carried out in a regulated manner and meant that all data obtained would not be identifiable with the participants. For more information on the ethics approval for this project, see Appendix A.

4 Preliminary Investigations into Quality Perception



This chapter begins by exploring the range of LS surface finishes achievable using standard techniques, before testing the opinions and perceptions of these parts to generate focussed vocabulary for later experiments.

4.1 Surface roughness testing

An important starting point was to explore if there were any noticeable surface quality differences by changing parameters within the current build technique. This included investigating different powder qualities, build orientations and positioning of the parts. Each part used for this initial testing was built using the default parameters on the EOS P100 Laser Sintering machine.

4.1.1 Objective

As discussed in Section 2.3.2, the following parameters of build bed positioning, orientation of the parts and material quality all have an effect on surface finish of LS parts. These parameters are discussed further throughout Chapter 4.

4.1.2 Methodology

Material Choice

Injection moulded parts are the most prominent rival to the LS process as it has smoother surface finishes and therefore many believe to be a higher quality process. It was decided to only include LS parts for this project to justify the development of surface finish of LS parts before further expansion into the market. Further work could look into how LS parts could potentially rival injection moulded parts in the consumer market.

Build preparation

To prepare for the build, a plan was put in place to design the layout of the build and to ensure the correct build parameters were used.

Layout

The test sample geometry was a 70mm x 20mm x 2mm tile; these dimensions were to guarantee a finger-width area for the participants to explore when used in later participant testing. The layout of the build focussed mainly on two areas:

1. **Build bed positioning** – Half of the tiles were positioned in the centre of the build bed and the other half built around the edge. This was to identify if the quality of parts changed depending on the build bed position of the part.
2. **Part orientation** – The tiles were also split into three different orientations, with a third of the tiles each built at 0°, at 45° and 90° to the build bed surface. This was to identify if the orientation of the part affected the surface finish quality of the parts. From the literature, it was expected that the parts built at 45° to the build bed surface would have the roughest surface finish [126].

The part layout positions are summarised in Table 4.1.

Table 4.1 – Layout of the test sample parts in the build bed.

Tile Orientation	**Tile Position**	
	Centre	*Edge*
0°	3	3
45°	3	3
90°	3	3

This build was to be carried out three times in three different powder types of the same material. The material used was PA2200, which is a nylon-12 based polymer provided by EOS. The three varieties of powder were:

1. **Used** – This was an old powder, that had been used in a previous build that had then been cleaned and recycled ready for another build.
2. **50-50** – This was a mixture of both the virgin and used powders. This is the standard powder that is used for most LS builds, as recommended by the machine manufacturer.
3. **Virgin** – This was a new, pure powder that had not been used before.

These three types of powder were chosen to demonstrate the variety of powder combinations available for use in LS [52]. From these areas of interest, the part names were generated with the first number representing the orientation, letter representing whether the part was in the centre of the build or the edge, and the last number representing the part number. For example, part "*45 E 3*" was positioned at 45° to the surface of the build bed at the edge of the build area and was part number three.

Build parameters

The build parameters were kept to the standard settings for the EOS Formiga P100 LS machine for the PA2200 powdered polymer as described in Chapter 1 to ensure the best possible quality build. The build parameters used are shown in Table 4.2.

Table 4.2 - Standard build parameters for PA2200 built in the EOS Formiga P100 LS Machine. Adapted from [46].

Parameters	
Layer thickness	0.1mm
Part bed temperature	170°C
Removal chamber temperature	150°C
Laser power (contour)	16W
Scan speed (contour)	1500mm/s
Laser power (hatching)	21W
Scan speed (hatching)	2500mm/s
Scan spacing	0.25mm
Heat up time from cold	1°C per minute ~ 2.5hours
Cooling time after build	~ build time

Once the build was completed in the three different grades of powder (virgin, 50-50 and used), then the parts were cleaned and prepared for surface testing.

Part clean-up

Once built, the parts were taken out of the machine in a powder cake, extracted and cleaned. The parts were cleaned using compressed air and then washed with water and dried thoroughly to try to eliminate any loose powder left on the tiles.

Profilometry testing

Profilometry was the chosen method of measuring the surface roughness of the test sample parts as explained in Chapter 1. This process uses a diamond stylus to trace a profile across a specimen to gauge the average roughness of the surface.

Measurements were taken at 0.5mm/s for a sample length of 20mm to ensure a practical speed so that the stylus could detect all surface displacements (as advised by the machine manual [127]). Each tile was tested six times; three tests were each performed on the top bottom and then averaged. This was to gather a more general picture of the roughness across the whole surface, rather than just the one area. The literature had suggested that there may be differences in the top and bottom surface roughness measurements [7]. The path of the stylus on each side of the part is depicted in Figure 4.1.

Figure 4.1 - Guideline of where the profilometry measurements took place on each part

Data was accumulated for all three types of powder in different positions and orientations within the build bed. As explained in Chapter 1, the arithmetical mean deviation (R_a) value was identified to be the measurement of most benefit from this testing. R_a values show the average displacement from the surface plane set at 0, which is the standard value to identify [7, 52]. The collected surface roughness data can be found in Appendix B.

4.1.3 Results

Used powder

Top and bottom surfaces

As shown in Figure 4.2, the used powder results indicate that the top surface of the parts generally had a rougher surface finish in comparison to the bottom surface with error bars indicating the range of values measured for each surface.

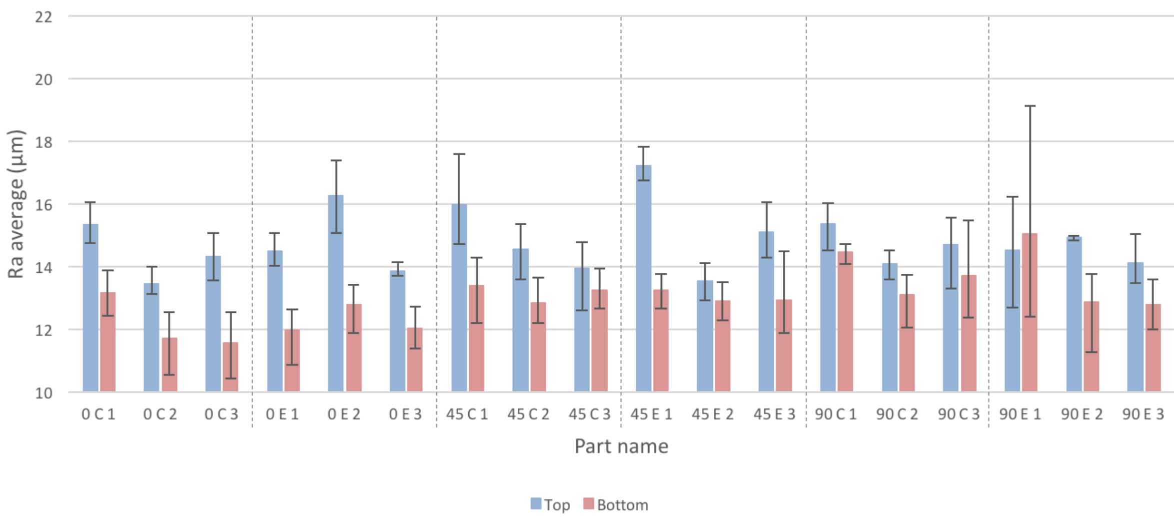


Figure 4.2 - Difference of the Ra average values between the top and bottom of the used parts

Figure 4.2 shows that the top average values (blue bars) are predominantly higher than the bottom average for all three orientations and build bed positions, apart from part 90 E 1 – although that part did have a very large range of measurements.

Build position

Parts built at the edge of the build bed had slightly more varied measurements than those built in the centre, however this factor did not result in a great difference in terms of average surface roughness. This lack of difference suggests that as long as the parts are centred in the build bed as advised [46], then parts nearer the edge of the build bed would not be greatly affected.

Orientation

The different orientations of the parts again did not have a large effect on surface roughness measurements. The parts built at 45° had more varied results, but this result was expected according to the system manual [46].

50-50 powder

Top and bottom surfaces

The top surface was found to mostly have higher roughness values than the bottom surface, with much higher values found on the 45° parts as shown in Figure 4.3.

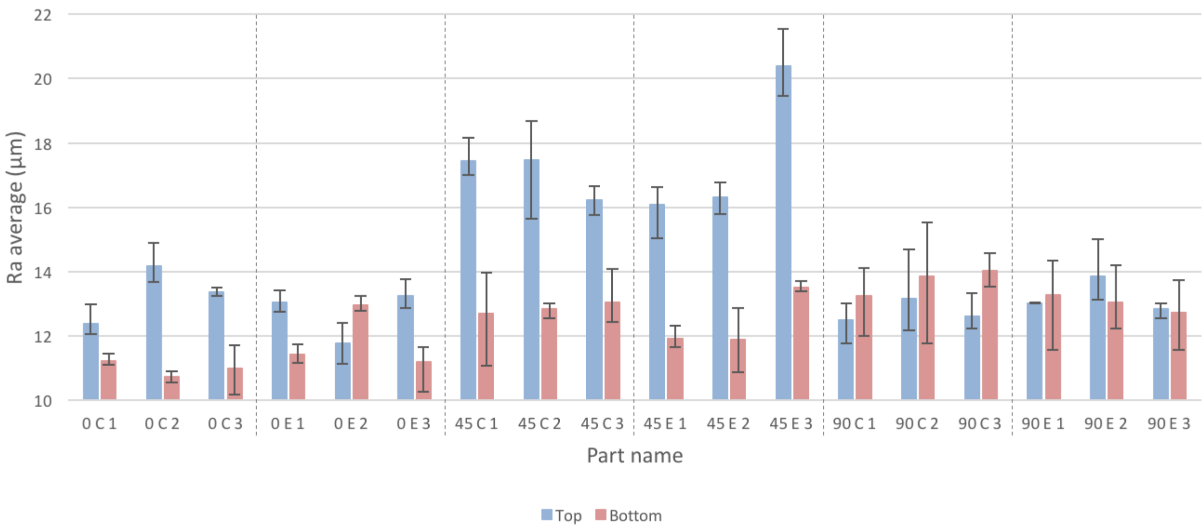


Figure 4.3 - Difference of the Ra average values between the top and bottom of the 50-50 parts

Compared to the 45° parts, the 0° and 90° parts seemed to have closer values of roughness for the top and bottom readings. This could be due to the reduced "stair-stepping" effect from the horizontal and vertical build lines compared to the slanted build line from the 45° built parts.

Build position

For the 50-50 powder, there was not much difference in the build position values found between the parts built in the centre and the parts built on the edge of the build bed.

Orientation

As shown in Figure 4.3, all of the parts that were placed at a 45° to the build bed surface had a larger top surface roughness than all of the other part orientations. This result suggests that the top of parts built at 45° had a rougher surface finish, and if a smoother finish was desired, 45° would not be the best orientation to use.

Virgin powder

Top and bottom surfaces

The 0° and 90° parts were far closer in roughness value between the top and bottom surfaces in comparison to the 45° parts, as shown in Figure 4.4.

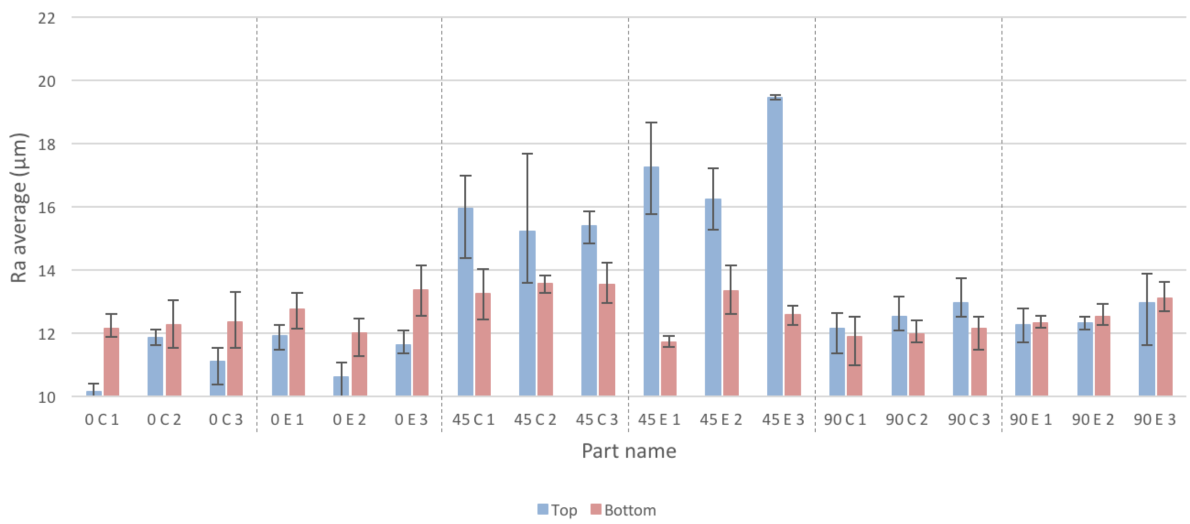


Figure 4.4 - Difference of the Ra average values between the top and bottom of the virgin parts

This result suggests far more consistent roughness between the top and bottom surfaces of each part, implying this may be a useful powder to build in for consistent and smoother surface finishes.

Build position

The build positioning of these virgin sample parts do not show much difference between the centre and edge built parts except the 45° edge parts, which are notably rougher. This result suggests that the 45° edge parts are not as consistent as other parts built centrally in the build bed.

Orientation

The virgin powder parts followed a similar pattern to the 50-50 powder parts, with the 45° parts having a rougher top surface finish than the other orientations. The bottom of the 0° and 90° parts were mostly slightly smoother than the top, as shown in Figure 4.4.

Summary

It was found that, overall, the bottom surface of the parts was measured to have a lower roughness value than the top surface. The used parts had rougher surface finishes with a trend that mostly followed with the 50-50 and then virgin powders, respectively. However, the average surface finish of the 50-50 parts' bottom surface was slightly smoother on average than the bottom of the virgin parts.

From all three data sets of the different powders, it was clear that the virgin powder gave a lower average of surface roughness. Virgin powder tile 0 C 1, was measured as the lowest roughness achievable (10.15μm) and the 50-50 powder tile 45 E 3 had the highest roughness (20.40μm). These two test plates were taken forward for use in the focus groups.

The orientations of the parts also showed some variations. The top of the parts built at 45° to the build bed were considerably rougher in both the 50-50 and virgin powders. This supports the findings by Ellis et al. [49] of parts built at 0° and 90° to the build bed giving smoother surface finishes. The used powder parts built at 45° to the build bed were not as outstanding, but gave more varied results in comparison to the other orientations in that powder.

The parts built at the edge of the build bed were more varying in range than the parts built in the centre.

For future builds, it was decided to use virgin powder in the centre of the build bed at either 0° or 90° as these orientations produced the most consistent and smooth parts.

4.2 Focus groups

In order to identify whether the participants could distinguish between the roughest and smoothest parts from the LS machine, focus groups were held and were also used to determine vocabulary for use in subsequent testing.

A focus group is defined as “bringing together representative users to discuss their issues and concerns about the features of the system being evaluated” [128] It was decided to use the focus groups to gather qualitative information over individual interviews, as focus groups produce a more natural environment – “the participants are influencing and influenced by others as they are in real life” [111]. It was important to allow participants to “stimulate and encourage each other” [129] and to simulate a real life atmosphere to allow relaxed participants to share their views and generate as many words as possible.

4.2.1 Objective

Aim

There were two main aims for this focus group:

1. To identify whether the consumer has the ability to distinguish between the roughest and smoothest natural surfaces created during LS.
2. To identify the vocabulary used to describe quality for later experiments.

4.2.2 Methodology

Krueger and Casey advised to use five main sections to structure a focus group: planning, participants, location, resource management, and post focus group work [111].

Planning

The planning section is the most important part of the methodology as explained in Section 3.4.1. It was decided to carry out two focus groups in order to maximise the collection of vocabulary, whilst maintaining an acceptable size of group.

In order to test the stated objectives, participants were each provided with the roughest and smoothest samples from Section 5.1, and asked to describe them. This was to confirm any noticeable difference. Three phone cases were then handed out and the participants were asked about the quality of each.

The LS parts that were used in this study were two test parts from the surface roughness testing – the smoothest and roughest natural surface finishes from the EOS Formiga P100 machine, Virgin 0 C 1 and 50-50 45 E 3 respectively. These parts were used to determine whether there was a noticeable difference between the surface finishes to the average consumer. Three phone cases were also used from an earlier study conducted by a Masters student, each of which was finished to a different surface roughness using sand paper; these cases were used to give the participants a real life application for the technology and also to stimulate the generation of descriptive “quality” words upon interaction with the parts.

The questions were split into five categories as advised from the literature [111]:

1. *Opening* – ice breaker
2. *Introductory* – general topic and fosters conversation
3. *Transition* – helps to paint bigger picture
4. *Key* – important topics
5. *Ending* – summary

These five categories created the main structure of the group interview. This structure was not only useful to the participants, but to the facilitator as well, building the sequence in a focussed and logical configuration. The questions formulated for these focus groups can be found in the Focus Group Agenda, shown in Figure 4.5.

Focus Group Agenda

Ice breaker to encourage participants to speak freely

Opening
Please say your name and what your favourite subject was in school.

Topic
The point of this study is to see what your perceptions of different things are and what you perceive quality to be. We will be focussing this on 3D printed parts.

Guidelines
- There are no right or wrong answers, only differing points of view.
- We are tape recording; please make sure that only one person speaks at a time.
- You do not need to agree with others, but you must listen respectfully as others share their views.
- We ask that you turn your mobile phones off or put them on silent. If you cannot, and if you must respond to a call, please do so as quietly as possible and re-join us as quickly as you can.
- My role as the facilitator will be to guide the discussion.
- Please talk to each other.

Introductory section

Introduction
Has anyone heard of Additive Manufacturing before? 3D Printing?
What do you think of the technology?
The purpose of this focus group is to see what perceptions you have of laser sintered parts (type of AM)

Open-ended questions encourage discussion rather than one-word answers

Transition
When you hear the word "quality", what springs to mind?
How do you define "quality"?

Key
(Give out the two test plates)
How would you describe these two plates?

(Give out the three phone cases)
If I were to give you these phone cases, how would you describe them?
Are there any noticeable differences between these phone cases?
How would you improve the phone cases to make them a higher quality?

Most important. This is where the useful vocabulary will come from.

Ending
Summarise the overall consensus of the group and then ask…
Is there anything I have missed?

Figure 4.5 - Focus group agenda

The order of the questions was formed to encourage the participants to progress their ideas and answers throughout the focus group. The AM questions in the introduction start off by engaging the participants in order to explore what they already know about the technology, so that from then on, they were building on their base of knowledge. By asking the participants to talk about quality in the transition section, this allowed them to link the first two sections (AM introduction and quality of AM parts) when answering the key questions later on, and hopefully creating more useful and efficient answers. By having a group of people answering the questions together, this also allowed them to use each other's viewpoints to generate more ideas and create a wider choice of vocabulary.

Participants

As explained in Section 2.4.3, there is contrasting literature views on whether the participants should already know each other or not. As the focus group was designed to encourage word generation, it was decided to work with groups of participants who knew each other in advance to encourage a more relaxed and free-flowing environment as suggested by Kitzinger [116] rather than a group of strangers who might have been as confident in front of a group of people they did not know.

It was decided to choose the group sizes between 6 and 10 so as not to have a fragmented group [111], but to still have enough participants to generate a worthwhile debate. The participants were all students or alumni from the University of Sheffield.

Location

As explained in Section 3.4.1, the location of the focus group is important so as not to have any distractions and to create a relaxed environment to encourage conversation.

Therefore, during both sessions, the focus groups took place in quiet rooms that were free from distraction. The participants were allowed to choose their own seats around a central table ensuring that seats were placed as evenly as possible and the recording equipment was placed centrally on the table.

Resource management

These focus groups were to be recorded for transcription afterwards to ensure all of the vocabulary was collected.

Food and refreshments were provided as suggested from the literature [111, 119]. This was to improve the participants' moods and to again encourage a relaxed and open atmosphere.

Post-focus group work

Following each focus group, the discussions were transcribed and then analysed, with any themes, interpretations or ideas taken into account.

4.2.3 Combined tiles focus group

Background

This focus group consisted of seven participants who already knew each other with a male-female gender split of 3:4 and age range of 19-27. Participants were allowed to choose their own seats, with the final seating order shown in Figure 4.6.

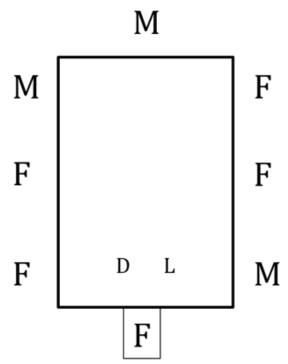


Figure 4.6 – Focus group 1 seating plan

M was used for a male participant, F used for a female participant, F inside a box for the facilitator and D and L used for the dictaphone and laptop respectively. The laptop and dictaphone were used to ensure the discussion was recorded and they were placed near the facilitator for ease of access and testing.

Each participant was given an information sheet including details about the project and what would be entailed in taking part. Each person then freely signed a consent form after they were invited to ask any questions about the focus group.

Each of the participants were asked, as an ice-breaker, what their favourite subject was at school. The group age range was between 18 and 27, giving a good spread across the target audience [130], from undergraduates to final year PhD students.

The agenda, shown previously in Figure 4.5, was followed and the focus groups were transcribed. The main findings are summarised in the following paragraphs.

Sensitivity of LS

The participants had very limited knowledge about AM, which mainly came from word-of-mouth or the media. This was useful as the parts that were shown to them were the first AM parts they had come into contact with. This meant that the participants had restricted preconceptions of what the parts would be like and therefore were open to more truthful observations.

Both of the test parts were given out to each participant for them to explore and describe. Unfortunately, one of the participants asked if the plates were different – which was not expected. The answer given was that if the participants could feel a difference then they should let the facilitator know, which may have given the impression that the plates should feel different. All but one of the participants claimed that they felt a very subtle difference. This part of the focus group was analysed and re-evaluated before the next focus group was carried out.

Haptic exploration techniques were noted down by the facilitator if the exploration procedure stood out as different, however word generation and perceived surface differences were the main priority of the focus groups.

Quality perception

The group came to a consensus that the materials used to make the product were most influential when deciding upon whether something has good or bad quality. Other ideas that were discussed were weight, finish and durability, but the participants agreed that it depended on what the object was as to what defined its quality. This suggests that an application may be needed in the later experiments.

The phone cases were given out separately. All but one of the participants stated that they preferred the phone cases from smoothest to roughest. The other participant claimed they preferred the cases from roughest to smoothest as they were worried the smooth cases would cause them to drop the phone. An interesting comparison was that the smoothest case was deemed as "*luxurious*" and "*your M&S brand of phone case*" signifying that it was of a better quality than the others, as it would come from that store.

Summary

Overall, the combined tiles focus group was successful and addressed both of the aims set out at the beginning. However, there were a few changes made to the protocol for the next focus group:

1. *Tiles to be handed out separately* – In the combined tiles focus group, the roughest and smoothest tiles were handed out together. The overall perception of the test plates was that a slight difference in roughness could be felt. For the next focus group, the plates were to be handed out separately to see if there was a noticeable difference between the roughest and smoothest LS tiles.
2. *The moderator to not lead vocabulary* – This was not ideal in the combined tiles focus group, as it may have hindered the thought process of some of the participants. Words were given by the moderator if the participants were struggling. However, the participants should be left to generate their own vocabulary. The key to a successful focus group is a facilitator that takes a "peripheral, rather than a centre-stage role for the simple reason that it is the inter-relational dynamics of the participants that are important, not the relationship between researcher and researched" [111].
3. *Recording devices more evenly distributed* – Not all of the conversation could be picked up by both recording devices, therefore their positions were re-evaluated and spread out between the participants.

4.2.4 Separate tiles focus group

Background

The separate tiles focus group was conducted as before, however the points from the previous focus group were also addressed. It consisted of 8 participants with a male-female gender split of 6:2, and the age range was between 18 and 28 years. The seating plan can be seen in Figure 4.7.

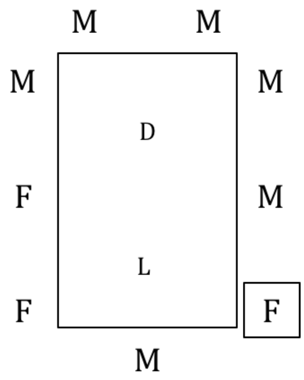


Figure 4.7 – Focus group 2 seating plan

Sensitivity of LS

Again, the participants' knowledge about AM was very limited. The media played a more prominent part in their feedback about what they already knew, but most of the participants had little to no experience with the subject matter. The interpretation of this was that the participants would have restricted preconceptions. As the subject knowledge was limited it was decided to add an explanation of AM, specifically LS, into the agenda. Therefore, the participants would hopefully have a better understanding of the technique before handling the parts for better engagement with the task.

Unlike the combined tiles focus group, the two test plates were handed out separately. Even though the group was told that the plates were not necessarily the same, all of the participants did not mention that they could notice a difference between them.

Quality perception

The group decided that to define quality the object would be well made and expensive. There was not as much discussion at this point of the separate tiles focus group, maybe due to it being in the early stages and the group was acclimatising.

The phone cases were also given out separately. The group came to the same consensus as focus group 1; they all preferred the phone cases from the smoothest to the roughest. However most of the group thought that the phone cases were not substantial enough to protect the phone if it was dropped.

Summary

The protocol changes made after focus group 1 lead to a successful and more free flowing focus group. Each of the earlier points were addressed and it was apparent that most of the participants did not find a noticeable difference in the two extreme tiles when handed out separately.

4.2.5 Focus group results

Sensitivity of LS

The first part of each focus group was to investigate if the participants could notice a significant difference in the smoothest and roughest natural surface finishes of LS parts. Table 4.3 shows whether each participant distinguished between the roughest and smoothest tiles, as taken from the surface roughness testing.

Table 4.3 - Table depicting if participants noticed a difference between tiles

	Tiles given together							**Tiles given separately**							
Participant	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Difference	✔	✔		✔	✔	✔	✔								
No Difference			✔					✔	✔	✔	✔	✔	✔	✔	✔

It can be seen that when handed the parts together, most participants noticed a very small difference, and when handed the tiles separately, no difference was noted.

Those participants who did notice a difference in surface roughness mostly claimed that it was only slight and would not have necessarily observed it if they did not directly compare the two at the same time. One participant in particular said:

"If I didn't have them both in my hands at the same time, I definitely wouldn't have noticed it."

None of the participants who were handed the tiles separately stated they could feel a difference between the samples. The only time the participants felt a slight difference was when they were actively seeking it.

The main findings from the two focus groups on the sensitivity of LS are negligible with respect to the difference in the surface roughness. It was therefore decided that further post-processing would be investigated in the main experiments.

Vocabulary

Once the focus groups were transcribed, the language used by all of the participants was then analysed. The participants from both focus groups generated 88 different words to describe quality of the plates during the group interviews. The words were then collected and ranked in order of frequency and placed in a word cloud for representation, as shown in Figure 4.8. The most frequent words used were rough, smooth and different.

Figure 4.8 - Word cloud created from adjectives collected in both focus groups

The word cloud as portrayed in Figure 4.8 was created in a piece of software called Wordle. A word cloud is a visual representation for text data that gives greater prominence to words that appear more frequently. It shows a brief overview of the important words used by the participants in the focus group. As shown, many words like "*rough*", "*smooth*" and "*velvety*" are larger as they appeared more frequently in the transcriptions than others. However, this does not mean that the less frequent words are not as important.

Table 4.4 shows the adjective generation breakdown for each focus group.

Table 4.4 - Word generation from both focus groups

Focus Group	**Tiles given together**							**Tiles given separately**							
Participant	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
No. of adjectives	41	14	14	10	25	28	22	30	4	6	30	16	17	7	31
Different adjectives	26	10	10	8	18	15	13	16	4	6	23	12	12	7	20
% of adjectives that are different	63	71	71	80	72	54	59	53	100	100	77	75	71	100	65
Total different adjectives	54							60							

When analysing the descriptions given by each participant, the numbers varied greatly. Some participants generated over 40 words each whereas others only generated as little as 4 words. There was a large amount of overlap between the number of different adjectives used and the number of repeated adjectives, with the participants producing the most number of adjectives, not necessarily producing a larger percentage of different words. The separate tiles focus group generated a larger amount of different adjectives, but that was expected due to the increased number of participants and there was an overall overlap of 26 words between each focus group. These adjectives were then analysed to be used in later experimentation.

4.3 Adjective development

4.3.1 Word reduction

As described in Section 2.4.5, the semantic differential test is one of the main qualitative data experiments used in affective engineering. This testing method is based on qualitative adjective pairing scales that allow the participant to rank whatever they are testing on this scale.

As there were 88 different adjectives used to describe the quality of the plates in the focus groups, these had to be reduced to a more focussed and targeted set of words. One of the methods suggested from the literature is to use specific rules to eliminate words that do not fit the test. The linguistic guidelines that were adapted for this work were [79, 81, 82]:

1. Only adjectives are allowed
2. Remove adjectives that are not plausibly related to objects
3. Remove adjectives that describe purely evaluative reactions
4. Remove ambiguous adjectives
5. Remove adjectives that describe feelings
6. Remove adjectives relating to prolonged experience with the sample rather than a brief experimental encounter
7. Remove adjectives requiring additional context to be understood
8. Remove comparative adjectives
9. Remove any adjectives that are not purely to do with touch.

Once all of the words that were not adjectives had been removed, the pool of words to reduce were:

"limited good durable usable easy bad high well different rough smooth low sturdy cheap expensive best worst chalky sharp weird noticeable similar nice grippy fluffy velvety wobbly flimsy greasy soft comfortable stable better light substantial strong tough thick brittle cool luxurious huge identical difficult clean hard secure promising industrial interesting poor pliable robust comparable powdery fine furry thin strange unusual neat see-through worn normal rigid consistent pleasant complex successful weak flexible”

From this, the words were then systematically compared to the list of rules to eliminate any words that would not fit the focussed set needed. Taking into account the frequency of the words as well, the pool of words that were then selected were:

“rough smooth strong weak velvety soft hard cool”

One issue with these words was that although velvety was used frequently, it was thought it may emit a sense of luxury as a word. This was in conflict with both guidelines four and five. Therefore, the word *furry* was substituted in place of velvet so as not to include a word that could suggest a feeling.

5.1.1 Word pairings

For the words to be prepared for implementation into the semantic differential questionnaire, they had to be paired with their opposite in meaning. For example, rough and smooth would be placed together as a pair. This reduced the list, which then must be decreased further to accommodate the questions each with an odd numbered scale of two opposites [124].

The literature suggests the following pairings for surface roughness perceptions [105]:

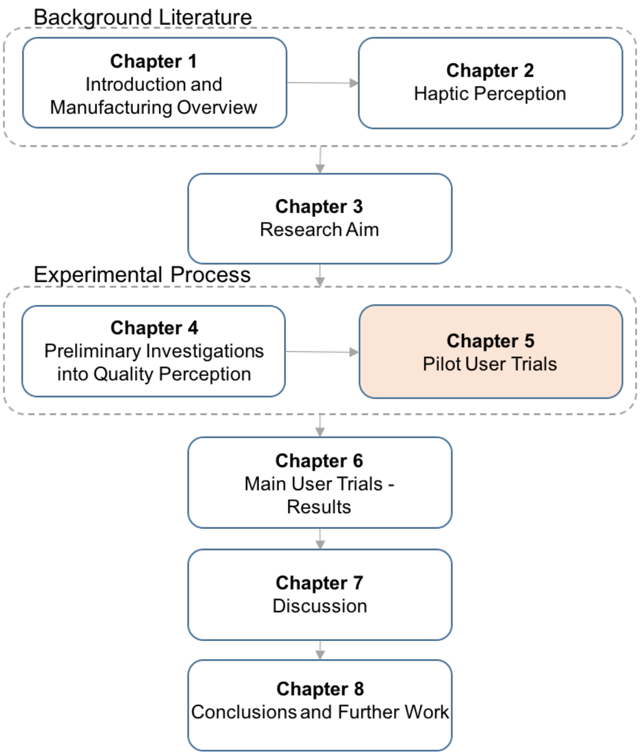
1. Warm – cold
2. Slippery – sticky
3. Smooth – rough
4. Hard – soft
5. Bumpy – flat
6. Wet – dry

Using the adjectives collected and advice from the literature, the following word pairings were produced to investigate the surface quality of LS parts:

1. Rough – not rough
2. Smooth – not smooth
3. High quality – low quality
4. Hard – soft
5. Cool – warm
6. Furry – not furry

The decision to split up rough and smooth came from a combination of the literature [79, 81, 82] and the fact that they were both the most frequently occurring adjectives from the focus groups. It was important that even though they are usually deemed as polar opposites to each other, that for this work, no word ambiguity was apparent. Therefore, it was decided to split them into rough – not rough and smooth – not smooth as they were deemed to be the most important adjectives relating to quality in both the literature and from the focus groups. This would also test the consistency of the participants' answers in the main experimentation and to better understand the relationship between perceived quality and measured surface roughness. The temperature pairing came from some of the words gathered from the focus groups and hardness is from the literature [105]. These adjective pairs were then used in the trial and main testing explained in Chapter 5.

5 Pilot User Trials



This chapter discusses the design and development of the next major stage of experimental work. Prior to beginning large-scale testing, a small trial was conducted in order to assess the suitability of this approach and to generate improvements. The details of the preliminary methodology, testing and results can be found in this section.

5.1 Initial experimentation

5.1.1 Aim

The main aim of the testing process was to determine user perceptions of quality through Two Alternative Forced Choice (2AFC), semantic differential and interviewing testing methods. An experimental design was determined and tested on five participants, then refined.

There were several objectives that were established before carrying out this testing:

1. *Design* preliminary methodology.
2. *Test* the logistics of the experimental process.
3. *Observe* the participants' behaviour.
4. *Gather* the participants' opinions of the investigation process.
5. *Refine* methodology ready for larger-scale methodology.

To be able to achieve these objectives, this chapter will be split into three main sections as shown in the flowchart in Figure 5.1.

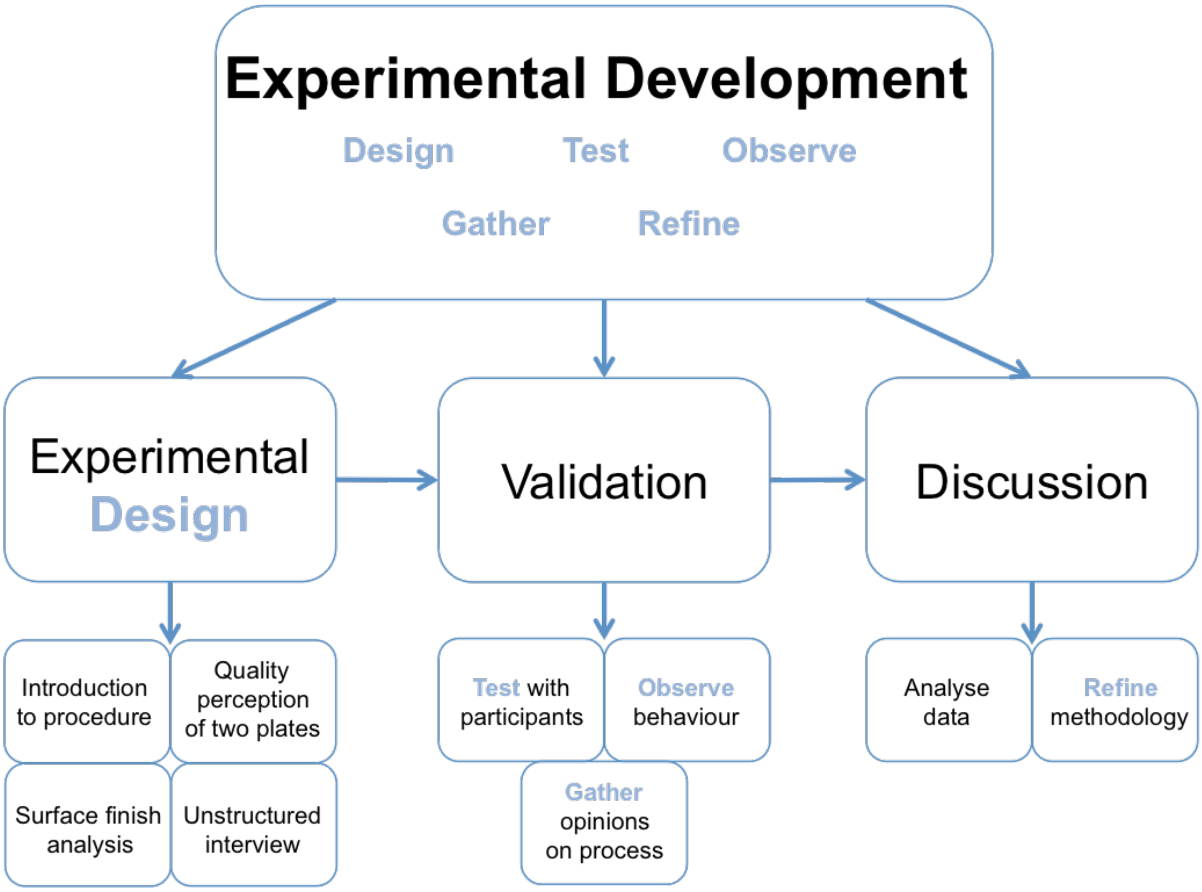


Figure 5.1 - Chapter structure flowchart

5.1.2 Experimental design

Using information from the earlier focus groups and literature, the following sections overview the initial methodology proposed for large-scale testing. This experiment contained four sections:

1. *Introduction to procedure* – Participants were introduced to the testing process and asked to fill out a couple of questions about themselves (age, dominant hand, etc.).
2. *2AFC test* – Participants assessed sets of two different plates at a time and decided which one was of a higher quality each time.
3. *Semantic differential test* – Participants ranked each plate on set scales developed from the language gathered in Chapter 4.
4. *Unstructured interview* – Participants were asked about their experience of the tests and gave feedback.

These four sections were proposed to be developed for the experimental process to incorporate both types of haptic perception testing methods (2AFC and semantic differential) and to explore consistency. More detail of the development process can be found in the following sections.

Sample preparation

For the experimental development, six LS were produced. The plates were increased in size compared to the previous plates used for the machine testing, to give the participants a larger surface area (80mm×40mm×2mm) to explore during the tests, as suggested from the focus groups in Chapter 5.

To address the initial aim of the thesis, the parts were produced with a range of common LS surface finishes, as discussed in the following sections.

Natural Finish

The six plates were all post-processed in the same way initially, by being blasted with air and then washed with water to remove as much excess powder as possible. This generated the natural surface finish given from the machine to all the parts. One of the plates retained this as its final surface finish and the other five were processed further using other post-processing techniques.

Shot-blasting

One of the remaining test plates was post processed using shot-blasting, the standard laboratory protocol used to finish LS parts. This is used to remove any excess, unsintered powder from the surface of the part. The media used were glass beads, which were blasted at the parts for 30 seconds each, at around 80mm away and at a pressure of 3 bar. During this process the parts were rotated, so as to have an even finish.

Sanding

Sanding is a commonly used post-processing technique that uses different variations of gritted paper to erode larger surface particles from parts to create a smoother finished surface.

Three of the testing plates were sanded using 240, 400 and 800 grades of sand paper to give a spread of sandpaper roughness that can be detected by the human finger as stated by Skedung [131].

PUSh™ Process

The PUSh™ Process is a newly developed chemical surface treatment that significantly reduces surface roughness without the need for sanding [132]. One of the test plates was post processed using this technique to provide the smoothest finish currently available.

The parts were post processed to give differing surface roughness for the experimental design procedure as shown in Table 5.1.

Table 5.1 – Summary of post processed parts used for the trial tests

Part	Post Process	Surface roughness (µm)
1	Natural finish (control)	13.25
2	Glass bead-blasted	15.49
3	Sanded with 240 grade sandpaper	12.92
4	Sanded with 400 grade sandpaper	11.98
5	Sanded with 800 grade sandpaper	12.60
6	PUSh™ Process	6.90

Experiment preparation

In order to achieve the objectives as stated in Section 6.1.1, four sections to the experiment were created, listed as follows:

A. Introduction to the experiment
B. Quality perception between two plates (2AFC test)
C. Surface finish analysis (Semantic differential test)
D. Unstructured interview

The sections were designed to break up the experiment, not only for the participant, but also for the facilitator, so that each section was focussed on the original aims and builds on the engagement of the previous section.

A: Introduction to procedure

The aim of this section was to introduce the participant into the experiment without overwhelming them and give them an overview of the testing process.

Section A was designed to introduce the participant to the experiment, giving an overview of the whole process, as well as to present consent forms. In Krueger and Casey's research on opening questions in focus groups [111], they suggested that the opening questions should be easy to answer and factual to encourage engagement in the activity. This was translated to the introduction so as to put the participant at ease before the main section of testing. The participant was given a consent form, information sheet and questionnaire booklet which contained all of the paperwork needed to complete the experimental process. When the experimental paperwork was given to the participant, the facilitator stated:

"The point of this study is to test out an experimental procedure and to gather opinions on it. Please read through the information sheet and consent form carefully. If you are happy with them, please feel free to sign."

The personal details from each participant did not contain any data that would make them recognisable to the facilitator during the analysis and to ensure anonymity. The introduction allowed the participant to be slowly introduced and taken through the next steps.

Quality perception between two plates (2AFC test)

The aim of this section was to familiarise the participant with the plates and to test their choice reliability.

Section B tested the participant's quality perception between two plates by using a 2AFC method. This method is largely used in psychological tests [122] and forces the participant to choose between two plates that are hidden from view, as shown in Figure 5.2.

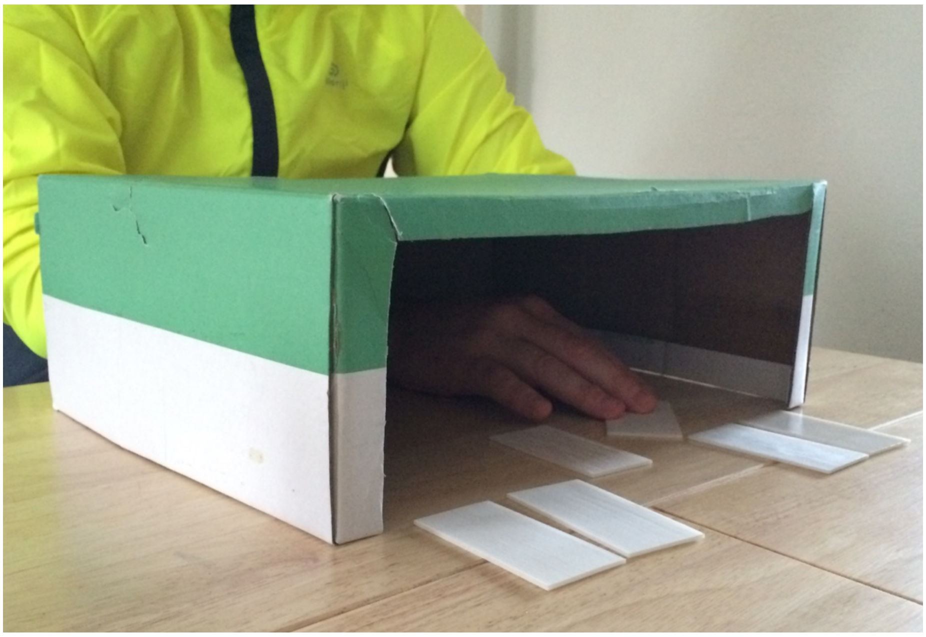


Figure 5.2 - Customised box used in the test procedure

As explained in Chapter 3, there has been a lot of research into the human perception of surfaces focussing on the use of sight. Many researchers have worked with [100, 101] and without [102, 103] the use of sight in their work, yet Lederman et al. found that in the perception of roughness; touch dominated vision [104]. It was decided not to use sight in the 2AFC experiments so that any input from visual memories from participants' past experiences were not used to influence decisions. Also as this thesis largely looked into the perception of roughness, the decision to only use the sense of touch was in line with the work of Lederman et al. [104].

In the questionnaire booklet, there was a statement informing the participants of what was happening in this section:

"You will be asked to choose between two parts at a time in a two alternative forced choice experiment, led by the facilitator".

The participant was informed that they could only use one hand for analysis, but no finger would be specified unlike in Barnes and Childs' work where they only use the motorically awkward ring finger [78]. This was to create a more life-like situation and to ensure that the participants' concentration was on the experiment and not trying to interpret the reason for finger choice.

The participant was told by the facilitator:

"Please choose which plate feels higher in quality."

With the six tiles, there would be 15 pairing combinations that would be carried out three times to make 45 tests. This was to test the repeatability of the experiment and the consistency of the participants. It would be important to observe the finger movements similarly to Lederman and Klatzky [9] and participant engagement to assess the effectiveness of the experiment.

Each pairing was already listed for the facilitator and the order was randomly generated to make the testing process completely fair. This guaranteed a more easily flowing section for both the participant and the facilitator. As the pairs were tested, the facilitator would note down the tile that was chosen as the higher in quality.

Surface finish analysis

The aim of this section was to generate a more quantifiable understanding of the participants' perceptions through the semantic differential test method.

Section C tested the participant's impression of surface finish by using a semantic differential technique. Semantic differential tests are used in psychological analysis, but also more commonly in affective engineering with the use of adjective analysis such as in the work of Barnes, Childs and Lillford [78-80, 105, 133]. This where the participant would test each plate separately, hidden behind a screen. They would then rate it against words on semantic differential scales as determined in Chapter 4.

In the questionnaire booklet, the participants were told to turn the page if they had not already done so. An example of the page that was presented is shown in Figure 5.3.

Please rate the feel of each part on the semantic scales below:

Part ________________

Rough	1	2	3	4	5	6	7	Not Rough
Soft	1	2	3	4	5	6	7	Hard
Warm	1	2	3	4	5	6	7	Cool
Not Smooth	1	2	3	4	5	6	7	Smooth
High Quality	1	2	3	4	5	6	7	Low Quality
Furry	1	2	3	4	5	6	7	Not Furry

Any further comments:

Figure 5.3 - Semantic differential scales used in section C

The participants were told to rate each tile against all of the scales presented in the booklet. The key words given for each scale were those that were chosen from the focus groups in Chapter 4 and literature [105]. The scales were an odd number so as not to force the participant into a decision, but to allow them to decide that the parts are neither soft nor hard [78]. The order in which the plates were given was randomly generated to prevent any detection of plate order patterns and the facilitator was given a list of these beforehand.

As the participants rated the parts, the facilitator could take observational notes of the exploratory techniques used by each participant.

Unstructured interview

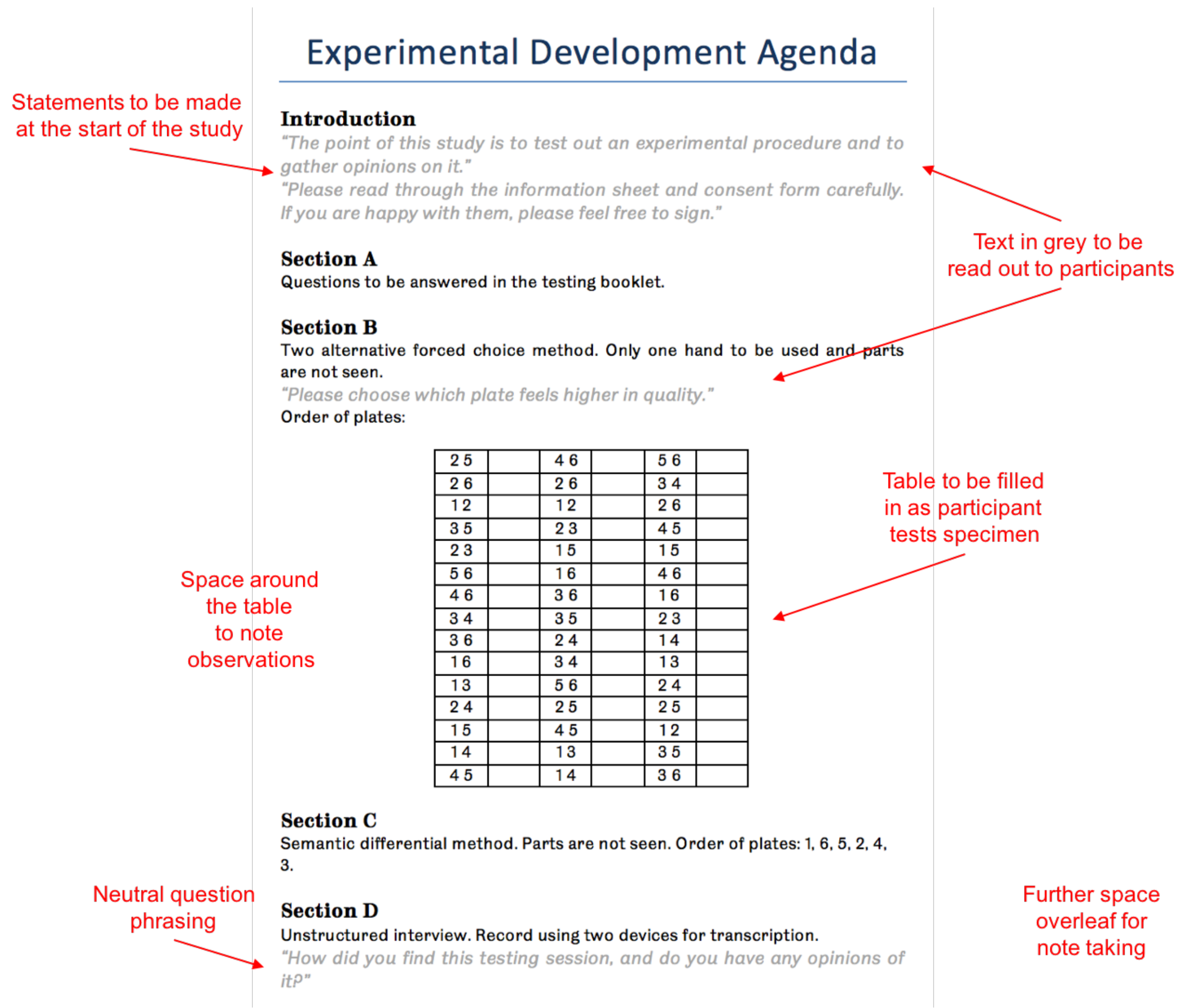
The aim of this section was to gather feedback from the participants about the experimental procedure to then take forward to improve it for further testing.

Section D gathered the participants' opinions and observations from the testing process in the form of an unstructured, recorded interview. The initial question to be asked was:

"How did you find this testing session, and do you have any opinions of it?"

This was designed to be a very simple question deliberately to leave open for any comments; a technique used by Krueger and Casey [111] in their focus group work. It is very important that the question for this section was phrased so that it did not lead any vocabulary or cause any opinions to be changed. Other questions were also asked if the facilitator felt that it would be useful as the conversation developed. The recorded interview was then transcribed for further analysis.

By using these four sections during the testing process, the aims could be approached and documented in a clear and concise manner, which enabled a practical refinement of the methodology. To guide the facilitator through the process, an agenda was drafted as shown in Figure 5.4.



Experimental Development Agenda

Introduction

"The point of this study is to test out an experimental procedure and to gather opinions on it."

"Please read through the information sheet and consent form carefully. If you are happy with them, please feel free to sign."

Section A

Questions to be answered in the testing booklet.

Section B

Two alternative forced choice method. Only one hand to be used and parts are not seen.

"Please choose which plate feels higher in quality."

Order of plates:

2 5		4 6		5 6	
2 6		2 6		3 4	
1 2		1 2		2 6	
3 5		2 3		4 5	
2 3		1 5		1 5	
5 6		1 6		4 6	
4 6		3 6		1 6	
3 4		3 5		2 3	
3 6		2 4		1 4	
1 6		3 4		1 3	
1 3		5 6		2 4	
2 4		2 5		2 5	
1 5		4 5		1 2	
1 4		1 3		3 5	
4 5		1 4		3 6	

Section C

Semantic differential method. Parts are not seen. Order of plates: 1, 6, 5, 2, 4, 3.

Section D

Unstructured interview. Record using two devices for transcription.

"How did you find this testing session, and do you have any opinions of it?"

Figure 5.4 – Experimental Development Agenda for the facilitator

The agenda allowed the facilitator to have a concise, easy-to-read document at hand to help with the structure and flow of the experiment. It contained all of the essential statements that must be read out to each participant, along with part orders and combinations. This was also used as a way to quickly record observations made during each section of the test. All of the documents used in this section can be found in Appendix .

5.1.3 Validation

In order to validate the experimental design methods, five trial participants were selected to take part in the testing process described in Section 6.1.2. These were participants who had shown particular engagement during the focus groups and who had freely given feedback during the session. This was to ensure that the feedback obtained for the trial experiments was detailed and relevant. The following results and observations were obtained:

Section A – Introduction to procedure

Section A did not pose any problems. Each of the participants read through the information sheets, freely signed the consent forms and provided their details.

Section B – Quality perception between two plates (2AFC test)

Test set up

The box used to conceal the parts was large, however, it was not large enough to obstruct everything from view. One of the participants mentioned that they could see the facilitator's agenda with the box of pairings. This gave them an indication as to how many pairing tests there would be, which was undesirable. The participant stated "*not that I was, looking at your sheet, but I could see the boxes and maybe that distracted me slightly*". It was important that the participants were focussed on the task at hand and not about how many pairing tests they were carrying out. Therefore, an even larger structure was needed to fully conceal the parts and possibly even the facilitator. There would then be less apparent distractions, enabling the participant to give the experiment their full attention.

Participant instructions

It was apparent that each participant needed to be given more information before the testing. Each participant was told not to pick up the samples during the testing process, with a couple of the participants asking if they should wash their hands. This extra information was incorporated into the introduction for the main set of experiments.

Length

There were a few deep breaths and breaks recorded in the testing of Section B. This could have suggested that some of the participants were becoming bored or tired of the testing, however in the interviews, only two mentioned anything about that section being long, with one of them only stating that they were "not expecting it to be that long", but when questioned further on the length, they did not feel it was too lengthy. Again, by giving the participants a bit more information when introducing each test, this may counteract the problem and give them a better understanding as to why they are conducting each test.

Section C – Surface finish analysis (Semantic differential test)

In this section, each participant was asked to rate each part behind the customised box, on a semantic scale in the questionnaire booklet, as shown in Figure 5.3.

Questionnaire booklet

Most of the questionnaire booklet was acceptable for the experiments, however there were a few alterations that needed to be made. One of which was to omit the part name at the top of each of the semantic differential scale pages. This caused some confusion among the participants, which could be avoided if the names were deleted. Another small change that needed to be made was to give the participants more informative instructions in the questionnaire. For example, at the end of each section, there should be a statement to inform the participant not to proceed until instructed to do so.

Plate comparison

A couple of the participants stated that they would have liked to be able to compare the plates in the semantic differential test, explaining that they thought their scoring may not have been as accurate without the comparison. This is unlikely to change in the next stage of tests because it is important that each sample is examined as a new plate each time.

After the testing was complete, one of the participants asked if they could have the plates placed back in the box for them to rank in order of quality. Whilst this was only one participant, it was felt this might give useful additional information and was included in the final design.

From Sections B and C there were some interesting behavioural observations noted during the testing process as shown in Table 5.2, with RH and LH being the notations used for each hand used.

Table 5.2 – Observation notes from the trial tests

	Testing notes	Exploration notes
1	- Parts moved around a lot. - Told not to pick up samples. - Took 3 voluntary mini breaks during section B.	- 3 middle fingers used to test plates with thumb as anchor. - Used RH for testing in B. - Changed hands if could not decide. - Used LH for testing and RH for writing in C.
2	- Told not to pick up samples. - No noticeable intakes of air. - Asked to go back and compare plates in C. - Only allowed to compare scores, not plates.	- Used lengthways stroking until unsure, then widthways. - Used index and middle fingers for testing with thumb as anchor. - Used RH for testing and for writing.
3	- Told not to pick up samples. - Wiped hands before testing. - Asked if hands should be washed. - Asked if there were "hundreds of plates". - Saw DP agenda sheet. - Three large intakes of breath. - Asked to compare plates in C. - Only allowed to compare scores, not plates.	- Used index and middle finger with thumb as anchor. - Thumb used for testing if unsure. - Used lengthways strokes, widthways if unsure. - Used RH for testing and writing.
4	- Told not to pick up samples. - Tried to have two informal chats in B. - Three deep breaths taken during testing in B. - Asked about washing hands. - Told to turn over each page.	- RH used for testing and writing. - Thumb used as anchor, index and middle used for testing – mostly middle. - Only used lengthways strokes.

5	- Told not to pick up samples. - Some deeper breaths noted during B.	- LH for testing, RH for writing. - Thumb as anchor, also used if unsure. - Three middle fingers used for testing. - Scratched plates if unsure. - Lengthways strokes mostly used, widthways if unsure. - Covered the whole of each plate. - Range of exploration: stroking, scratching, tapping and flat hand. - Moved fingers in all directions.

Haptic exploration

The haptic exploration from each participant was mostly based around the thumb being used as an anchor with the usage of the three mid fingers for exploring. A popular movement was lengthways strokes for the majority of the test with width ways strokes if the participant was unsure of a decision straight away. One of the participants was very thorough with their exploration, using tapping, scratching and static touching as well as strokes to study the samples. This did not alter or damage the plates in any way. With the thumbs being used as an anchor by all participants, a tile mount would be created to hold the parts in place during the testing process.

Section D – Unstructured interview

From the experimental development testing, it was apparent that the interviewing process in Section D needed more structure, in line with suggestions from Krueger and Casey [111]. It was made to be vague deliberately to encourage the participants to freely share and talk about whatever they chose to be important; but this seemed to give too much freedom that they did not know where to start. By giving the facilitator more carefully thought out neutral sub-questions, this would lower the chance of the facilitator subconsciously leading the vocabulary, but also still encourage the participants to openly express their views.

Most of the participants did not have many further opinions on the testing process. Again, the opinions ranged from a nostalgic "it felt like being at a museum using the feely-boxes" to "I felt very paranoid that I was being tested". This could be down to personality differences, but hopefully by giving the participants a larger amount of information in the next stage of testing, this should help all participants to feel more at ease.

Location

The locations for the experimental development testing were chosen for ease of access, which meant that three of the tests were carried out in a formal environment and two in a less formal one. Overall, it came across that the participants who were tested in less formal environments gave more varied views expressing both positive and negative opinions about different aspects of the experiment. Whereas those tested in a more formal environment seemed to be more quiet and less likely to expand on answers. Numerically, there were not enough people tested to give a clear decision as to which is best and this may have been down to each participant's individual personality; so for future experiments, the participants will all be tested in the same formal location to prevent bias from different locations.

5.1.4 Discussion

Whilst the main purpose of validation was to refine the test protocol, it was considered relevant to analyse the results obtained from the tests themselves, although there was a low number of participants.

Two alternative forced choice (2AFC) test

There were differing views found as to which plate "felt higher in quality". A useful visual aid to show how the plates were ranked for Section B is shown in Figure 5.5, with each participant represented by a different colour.

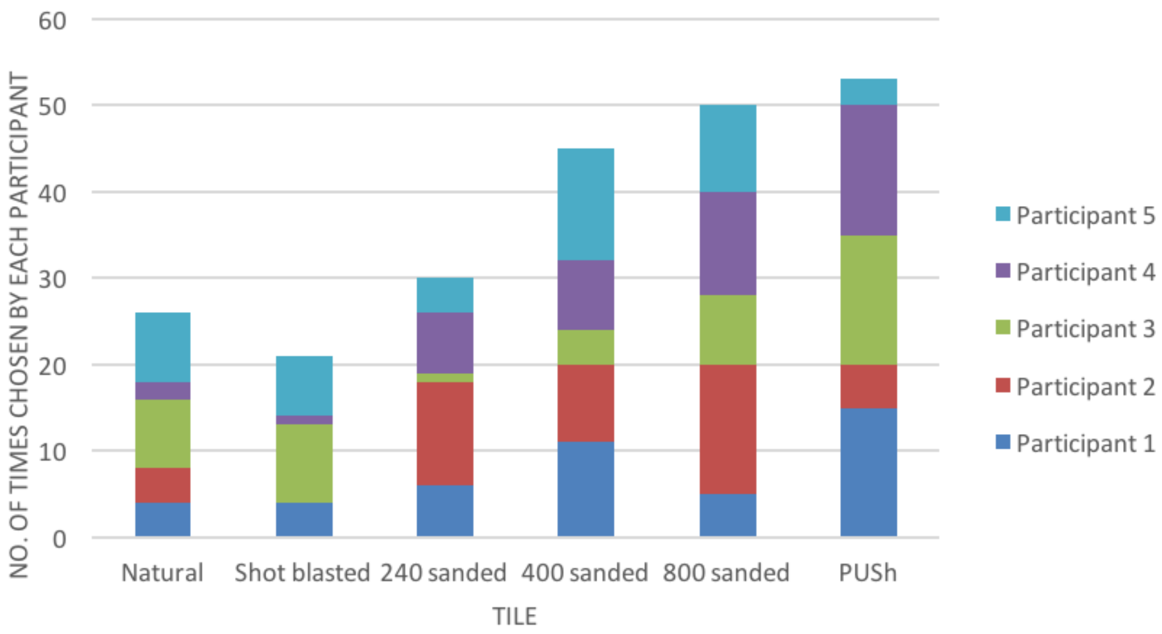


Figure 5.5 - Bar chart depicting the percentage of times each part was chosen by the participants in section B

The graph in Figure 5.5 shows not only the overall number of times that each plate was chosen as the higher in quality, but it also splits these overall numbers into participant choices. As is shown Figure 5.5, the PUSh processed tile was chosen to be the highest quality tile overall by the five participants, yet only three volunteers consistently chose this tile as the higher quality plate.

The same three participants stated that they preferred the surface of the PUSh processed tile, whereas the other two stated that they did not; this seemed to be the most conflicting view of all of the parts. One participant declared during the experiment that the PUSh part was not only the highest quality, but also the most preferred part, yet this opinion was over turned once they saw the part after the experimental development testing was completed. It was described as “tacky” and “like the fake fruit you would buy in a shop”, but also as the “most familiar” and “nice and smooth”. This suggests that the PUSh surface finish is familiar to the participants, but that it is associated with products that are not necessarily perceived as the highest of qualities. Therefore, the perception of quality of this surface may depend on the application that it is given.

Semantic differential test

With regards to the sematic differential ratings in Section C, each participant was able to rate the parts on six, seven-point, semantic differential scales. The frequency of the scores chosen by the participants overall is shown in Figure 5.6.

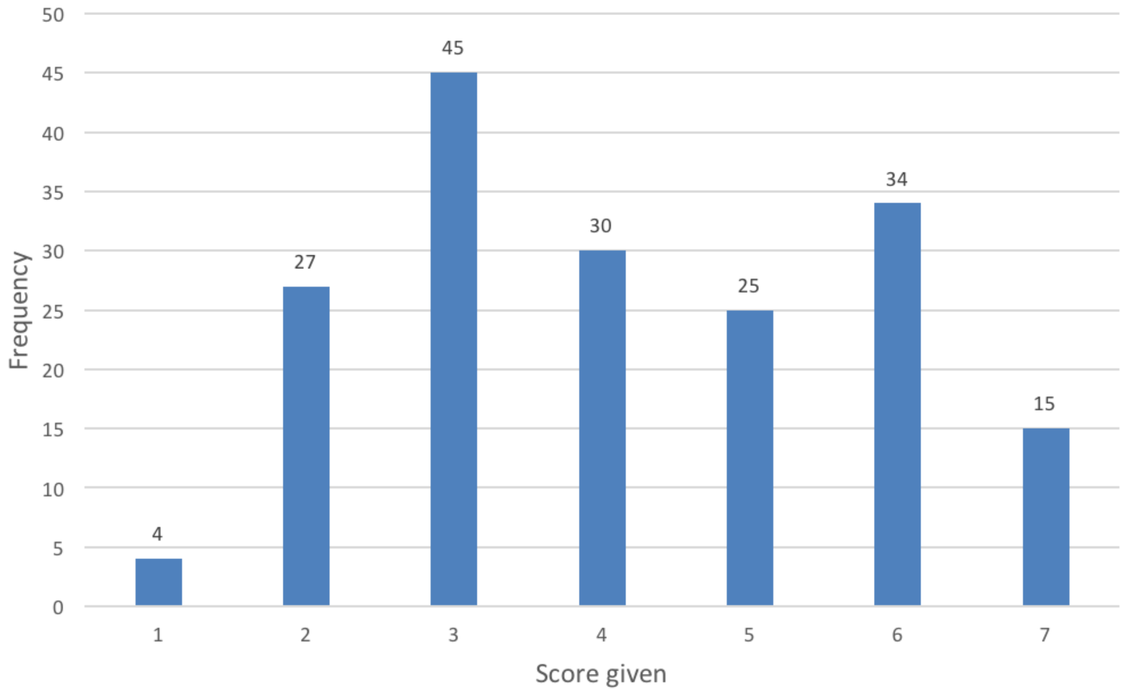


Figure 5.6 - Visualisation of the mean scores given by each participant

Figure 5.6 shows the frequency of each score being given by the participants on the six, seven-point, semantic differential scales. The large spread of data shows that all of the values were used to describe the plates with extreme values used less frequently, which is to be expected. This suggests that the use of the odd-point scale used was warranted, as observed by Barnes [78].

Refinements

From the validation and analysis of the data, the main refinements for the next major stage of testing can be placed into these sections:

1. *Information* – or lack of. The participants must be given more information to enable them to carry out the testing with minimal distractions. A demonstration of how they should interact with the parts would be useful.

2. *Customised box* – this needs to be larger so as to completely restrict the sight of each participant. The agenda used by the facilitator should not be seen.
3. *Tile mount* – this would be developed so that the tiles would not slide around as much when the participants explored them.
4. *Location* – the location of each experiment should be the same to avoid any distracting factors that cannot be controlled.
5. *Questionnaire* – needs to be updated so as to give clear instructions to the participants.
6. *Interview structure* – needs to be apparent. This way the participants can give relevant opinions without feeling lost.
7. *Semantic differential scale* – stays the same.

5.1.5 Conclusions

Overall the experimental methodology proved successful, with a few minor amendments required for the next stage.

The aims of these experimental development experiments were:

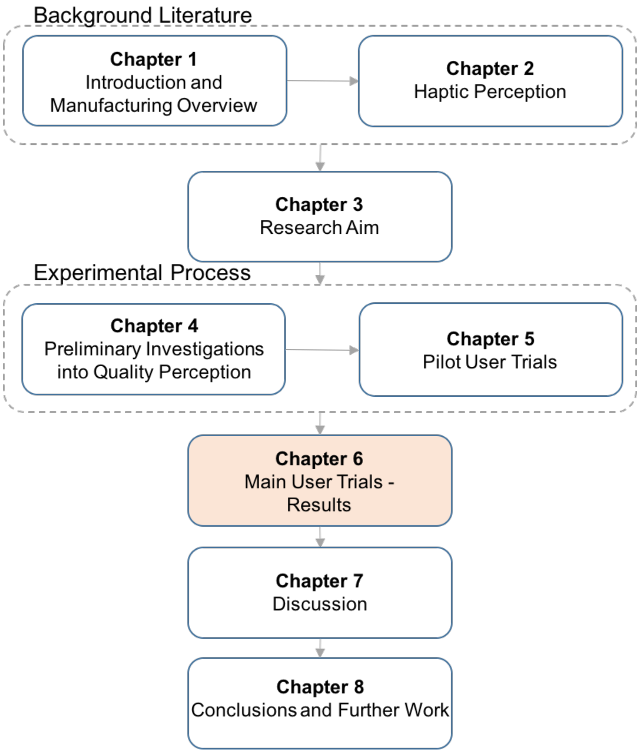
1. To develop experimental protocol.
2. To test the logistics of the experimental process.
3. To observe the participants' behaviour during the 2AFC and semantic differential tests.
4. To gain the participants' opinions of the investigation process.

These aims have all been addressed with many useful amendments highlighted to make the next stage of the experimental process more efficient and effective.

It was apparent from the behaviours and opinions of the participants that they need to be given more structure throughout the whole experimental process. This will help to engage them with the content more effectively whilst minimising the ambiguities they may have felt beforehand. By fixing the location to a central, formal place, this reduces any external factors and distractions that may occur in different locations.

Overall, the trial test was a very useful process to have that highlighted problem areas in the methodology that needed to be addressed. This procedure was built upon and refined to form a more comprehensive set of experiments to follow.

6 Main User Trials - Results



For the main set of experiments used in this project, a revised testing method was used. By introducing these changes, a far more structured testing method was developed and implemented.

6.1 Refinements

6.1.1 Tiles

The tiles were slightly changed from the previous experiment. The 240 grade sanded part was removed and two other sanded tiles (180 and 1200 sanded parts) were brought in. This was to provide a greater spread of roughness as the literature suggests that the human finger can feel a large range of surface roughness [131]. Table 6.1 shows the final list of post-processed parts that were used in the final experiments.

Table 6.1 – Summary of the post processed parts used for the main experimentation

Part	Post Process	Surface roughness (µm)
1	Natural finish (control)	11.09
2	Glass bead-blasted	8.64
3	Sanded with 180 grade sandpaper	3.42
4	Sanded with 400 grade sandpaper	3.10
5	Sanded with 800 grade sandpaper	3.70
6	Sanded with 1200 grade sandpaper	3.50
7	PUSh™ Process	1.74

The parts used for the main user trials were surface roughness tested using a profilometer and Figure 6.1 shows the surface roughness differences visually.

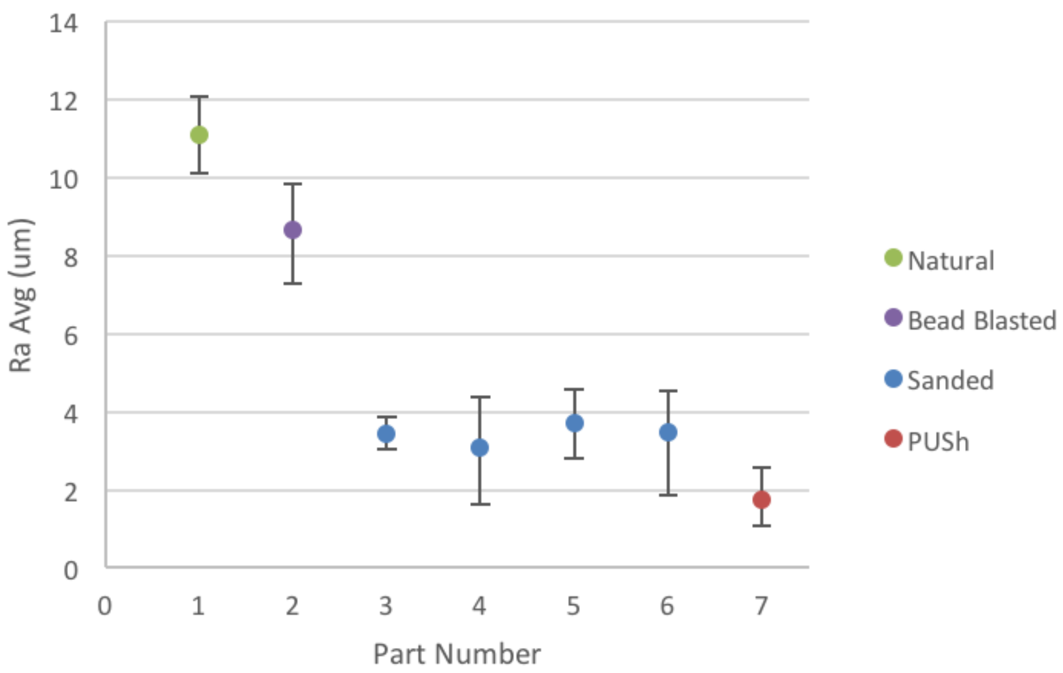


Figure 6.1 – Graph showing the differing surface roughness measurements of each test part

Each data point represents a different tile number as stated in Table 6.1 with the error bars representing the spread of surface roughness measurements obtained during profilometry. The differences in ranges could be due to the accuracy of the profilometer used. Figure 6.1 shows that the natural tile was measured to have the highest average surface roughness and the PUSh tile had the lowest. The sanded tiles had very similar averages and ranges measured, which suggests that the participants may have a slight difficulty in differentiating the between them when asked about roughness.

6.1.2 Information and questionnaire

The participants were given a far more detailed introduction to the experimental process. Each section reviewed the instructions given by the facilitator and there were also reminders to ask questions if need be. The set of instructions in the questionnaire booklet directed the participants not to act unless told to do so by the facilitator. Each of the pages had “please turn over” and “please wait for facilitator” signs to give step by step guidance.

Another section was added after the semantic differential tests where the participants were asked to rank the tiles behind the screen. This was included after a trial participant asked if they could rank the tiles after the trial was completed. This initial ranking could then be compared to a sight ranking that they would carry out during the interview, giving an insight as to whether vision has a differing impact to quality perception compared to touch.

The facilitator also took more detailed notes to ensure no part of the testing was overlooked or forgotten. More statements were included in the notes for the facilitator to read out and actions were also reworded. The new experimental documents can be found in Appendix D.

6.1.3 Customised box

A larger box was sourced and customised to create a fully obstructed view. The participants were now unable to see the facilitator apart from their head if they needed to ask questions. This was covered with a sheet to give a more finished look to the experiment.

6.1.4 Location

All of the participants were tested in the same location. It was noted that the facilitator was to be as welcoming as possible so as to encourage the participants to freely give any opinions and to feel comfortable in asking questions.

6.1.5 Interview structure

The interview structure became more detailed. The participants were reminded of the process that they had just been through. They were then asked if they thought they had favoured or not favoured any of the parts in the 2AFC test. The question was to see if they perceived to tell a difference between at least two of the tiles. They were then asked what the main factor was that they used when deciding what quality was. This was to gather vocabulary to better picture what people wanted from a high quality mobile phone case.

The tiles were then revealed to the participants in the order that they ranked them just before the interview. This offered a chance for the participants to change their ranking upon seeing the tiles.

The interview then moved onto personal experiences; asking if mobile phones were owned and what they as customers would look for when buying one. They were then asked if they would buy a mobile phone case with any of the surface finishes in front of them and why. This was to gather the participants' final overall perception of the surfaces.

By developing a new structure to the interview, it was intended to ensure the participants covered similar topics with their answers, whilst also to encourage them to expand on their answers.

6.1.6 Semantic differential scale

As discussed in section 5.1.4, there was no need for scale refinements.

6.1.7 Participant instructions

Overall, there were 44 volunteers who took part in this testing process. This did not include any of the participants from the experimental development assessments to avoid any pre-existing bias from previous tests.

All of the participants were students that were contacted through the University of Sheffield with a 57:43 percentage gender split between males and females, aiming to get a similar number of both. It is possible to argue that these students represent a section of the population that have easier access to disposable income due to mostly not being in a position to not have long-term monetary contracts and commitments [130]. Therefore, they would be in a more likely position to spend money on mobile phone cases.

The participants were all tested separately in the same room location. To encourage more participants to take part in the testing, the offers of a drink and a tour around an AM laboratory were given to all participants, but not all of the participants took these offers. It is very important that the contributors were not offered anything that could be interpreted as a bribe. Nothing of monetary value was exchanged or offered other than a beverage if they so desired. The participants must feel as neutral to the experiment as possible so as not to affect their perceptions or outcomes [119].

6.2 Types of data

Statistical data can be categorised into four standard groups that use different statistical methods during analysis as shown in Figure 6.2.

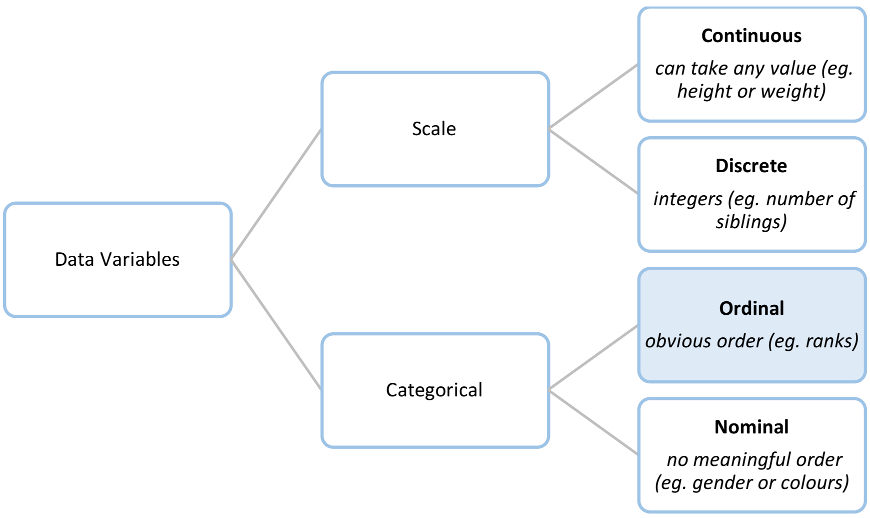


Figure 6.2 - Flowchart explaining different types of data variables [134]

The main difference between ordinal and nominal is that ordinal includes ranks, whereas nominal does not. For example, nominal includes colours and nouns which do not have a significant order. The data collected for this experiment is classed in the ordinal category because the participants were asked to choose ranks and orders. As the data fell into the ordinal category, standard parametric statistical tests cannot be used [135], and all further tests must be non-parametric.

6.3 Two Alternative Forced Choice (2AFC) Testing

6.3.1 Data Overview

In the 2AFC test, each participant was given a pair of tiles and asked to indicate which tile felt the highest in quality for a mobile phone case. The 2AFC test was designed to force the participant to make a decision as to which plate felt “higher in quality” between two that were hidden from view. Each tile was rated against all the other tiles in a completely randomised order and this process was repeated three times for each pair. As each tile was compared with all others, each tile had the potential to be chosen 6 times for each run through, and therefore a maximum of 18 times over the entire process.

By analysing the data from all of the participants, Figure 6.3 shows which tiles were chosen as the higher quality tile the most often overall. Profilometry results can be seen on external CD.

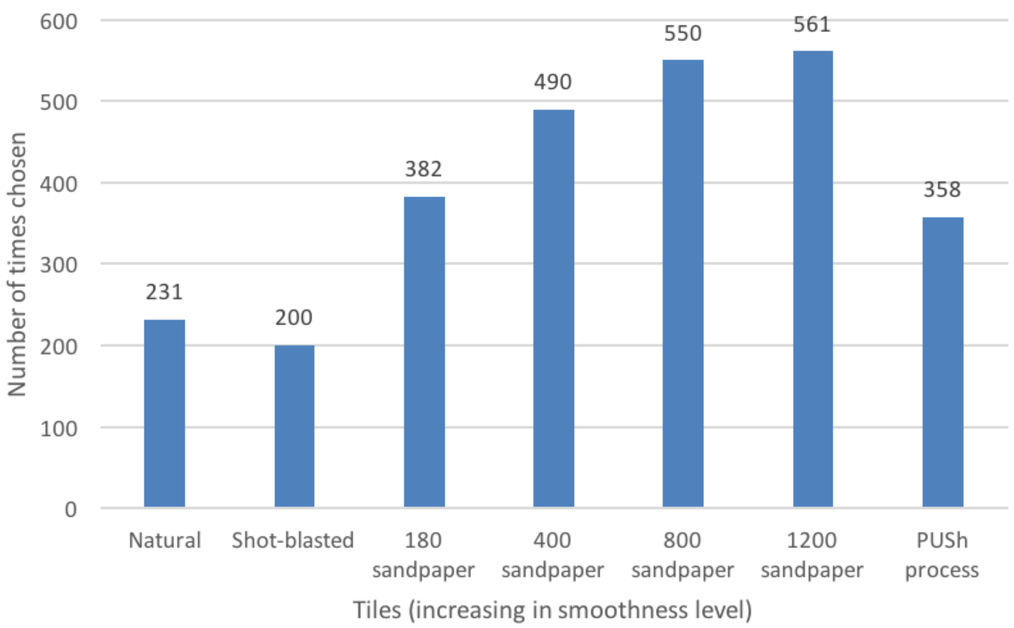


Figure 6.3 - Bar chart showing the number of times each tile was chosen to be of a higher quality over all participants' testing

Figure 6.3 shows how many times each tile was chosen by the participants, with the tiles placed in increasing smoothness level. It suggests that the participants perceived the surface finish of the 1200 grade sanded tile to be of the highest quality for a phone case, with the other sanded plates scoring the highest as well. However, there is a drop off in number of times chosen for the smoothest tile. This implies that most of the participants preferred a smoother surface for a phone case, but this did not include the smoothest, PUSh processed tile. In order to confirm whether any statistical significance can be attached to these results, a set of tests was carried out.

6.3.2 Consistency between participants

The next part was to calculate how consistent the participants were with each other in their decisions. This determined whether the sample size was appropriate and was carried out by analysing the inter-rater reliability of the participants for the 2AFC tests. If the value came back as a high agreement, then the sample size should be increased to better represent the population.

The inter-rater reliability compares all of the participant data from all of the participants together. This is a study to indicate whether the participants were in agreement of their decisions of quality.

This is measured using the Intra-class Correlation Coefficient (ICC), which is the percentage agreement of the participants. This examines the correlation of all of the data. An ICC is measured on a scale of 0 to 1; 0 represents no reliability and 1 indicates perfect reliability with no measurement error.

According to Cohen's effect sizes [136], as shown in
Table 6.2, these measure the size of association between sets of data. The higher the coefficient, the higher the consistency.

Table 6.2 – Cohen's effect sizes

	Effect size
Weak	0 – 0.3
Moderate	0.3 – 0.5
Strong	0.5 – 0.9
Very Strong	0.9 – 1

The ICC given was 0.477. This shows that 47.7% of participants were in agreement about their tile selection. This is considered a moderate size of coefficient, suggesting that people opinions differed somewhat, which implies that the large sample size tested was appropriate.

6.3.3 Consistency of individual participants

While the inter-rater reliability only indicates whether the participants' ratings are varied, a more useful analysis is to investigate whether the participants themselves are consistent in their own decisions. For the 2AFC, each participant had the choice of each pairing three separate times and by using an intra-rater reliability analysis, the repeatability could be analysed. This investigates each participant separately.

Table 6.3 shows the consistency of each participant across their own choices.

Table 6.3 – ICC results from the 2AFC tests

Participant	ICC	Participant	ICC
1	0.331	23	0.900
2	0.937	24	0.573
3	0.288	25	0.865
4	0.842	26	0.801
5	0.993	27	0.978
6	0.817	28	0.853
7	0.986	29	0.822
8	0.894	30	0.912
9	0.723	31	0.773
10	0.583	32	0.948
11	0.861	33	0.416
12	0.806	34	0.927
13	0.562	35	0.460
14	0.964	36	0.584
15	0.376	37	0.884
16	0.324	38	0.745
17	0.838	39	0.993
18	0.888	40	0.828
19	0.992	41	0.993
20	0.966	42	0.841
21	0.987	43	0.960
22	0.993	44	0.802

Table 6.3 has been colour coded to coincide with Cohen's effect sizes. As is evident in Table 6.3, 86.4% of the participants had an effect size greater than 0.5. This shows that 86% of the participants displayed a strong or very strong consistency. This implies that the participants

were actively taking part in the experiment, and provides confidence in the selected test method.

6.3.4 Friedman test

The next step was to analyse whether there was a significant statistical difference between the perception of quality of the tiles. As the data was ordinal, a non-parametric method was needed to investigate this. A Freidman test was used which compares the mean ranks between the related groups and indicates if there is a significant difference between these groups.

The Freidman test is the non-parametric alternative to the one-way Analysis of Variance (ANOVA) with repeated measures. It compares the differences between related, ordinal groups and indicates if there is a significant difference between them by calculating a statistical p-value. It can be used to test perceived differences.

To initiate this test, a null hypothesis (H_0) is generated as the starting statement to see if it can be disproved. An opposite, alternative hypothesis (H_1) is also produced as the substitute if the null hypothesis is found to be incorrect.

In the Friedman test, the null hypothesis states that the groups are the same and the alternative states that they are different. For example, if a jury has to decide whether a person is guilty or innocent based on evidence, the null and alternative hypotheses would be as shown in Equation 6.1. [137]

Equation 6.1 – Example of null and alternative hypotheses

$$H_0\!: The\ person\ is\ innocent$$
$$H_1\!: The\ person\ is\ not\ innocent$$

These hypotheses are then used to define the test, with the aim being to either prove or disprove the null hypothesis. This test uses the scores for each related group to give them a ranking, which is then used in turn to calculate a test statistic which is known as the p-value in a statistical computer programme known as the Statistical Package for the Social Sciences (SPSS).

The null hypothesis can only be rejected if there is enough evidence to disprove it; this is defined by the size of the calculated p-value. The standard practice is to accept 0.05 as the cut-off point [138]. If the p-value given is more than 0.05 (>5% of the data) then there would not be a significant difference between the groups and the null hypothesis would be accepted (person is innocent). If the test gives a p-value of less than 0.05 (<5% of the data), then it is said to be statistically significant the null hypothesis would be rejected for the alternative (the person is not innocent).

This was used as a non-parametric test to calculate if the participants perceived a difference in quality between all of the tiles. For further information and theory on the Friedman test, refer to Appendix E.

To initiate the Friedman test for the experimental data, null (H_0) and alternative (H_1) hypotheses were generated, as shown in Equation 6.2.

Equation 6.2 – The null and alternative hypotheses for the Friedman test

$$H_0\text{: The tiles are perceived to be of the same quality}$$
$$H_1\text{: At least one tile is perceived to be of a different quality to another}$$

The Friedman test gave a p-value of <0.001, showing there was a statistically significant difference between the perception of quality of at least some of the tiles. This indicates that the null hypothesis should be rejected in favour of the alternative. This did not indicate which tiles in particular were perceived to be of a different quality to the others. Post-analysis testing was therefore performed to specify which tiles were perceived to be significantly different.

6.3.5 Wilcoxon signed-rank test

The Friedman test can determine if the values were statistically different, but cannot identify the particular differences if there are more than two related groups, as there are in this thesis (seven different surface finishes). Therefore, a Wilcoxon signed rank test can be used as a further analysis.

The Wilcoxon signed-rank test is a non-parametric alternative to a paired t-test. It is used to compare two collections of ordinal data from the same participants. Like the Friedman test, it uses a p-value test statistic to determine whether there is a significant difference or not. For further information and theory on the Wilcoxon signed-rank test, please refer to Appendix F. The significance level was again placed at 5% ($p<0.05$) for this test. The results from this test are shown in Table 6.4.

Table 6.4 – Wilcoxon signed-rank results for the 2AFC test

Tiles	p-value	Perceived quality difference
Natural and shot blasted	1.000	No
Natural and 180 sanded	0.286	No
Natural and 400 sanded	0.001	Yes
Natural and 800 sanded	0.000	Yes
Natural and 1200 sanded	0.000	Yes
Natural and PUSh	1.000	No
Shot blasted and 180 sanded	0.022	Yes
Shot blasted and 400 sanded	0.000	Yes
Shot blasted and 800 sanded	0.000	Yes
Shot blasted and 1200 sanded	0.000	Yes
Shot blasted and PUSh	0.174	No
180 sanded and 400 sanded	1.000	No
180 sanded and 800 sanded	0.070	No
180 sanded and 1200 sanded	0.036	Yes
180 sanded and PUSh	1.000	No
400 sanded and 800 sanded	1.000	No
400 sanded and 1200 sanded	1.000	No
400 sanded and PUSh	0.628	No
800 sanded and 1200 sanded	1.000	No
800 sanded and PUSh	0.007	Yes
1200 sanded and PUSh	0.003	Yes

Table 6.4 is colour coded for any pairing where there was a statistical significance. Blue cells indicate any significance (p-values) found and imply that the participants found the tile pairings to be significantly different in quality.

Natural and shot blasted parts

The data suggest the natural and shot blasted tiles were not significantly different from each other, but were from all of the sanded tiles, which implies the participants generally agreed that the sanded parts were of a significantly different perceived quality to the natural and shot blasted parts.

Sanded parts

When the p-values for the sanded parts were compared, only the 180 and 1200 sanded parts were found to have a significant difference between each other. This implied the participants perceived the lowest and highest grades of sandpaper to be of a different quality from each other, but did not find a significant difference in quality between the other pairings. This suggests that there was not an apparent difference in the sanded parts other than the two extremes.

PUSh processed part

The PUSh processed part was found to be significantly different to the two highest grades of sandpaper parts, but not from any other pairings.

From the p-values calculated, it suggests that the tiles can be placed into groups of perceived quality. These consist of:

- *Group 1* – natural and shot blasted parts
- *Group 2* – 400, 800 and 1200 grade sanded parts
- The 180 sanded and PUSh parts would then be outliers.

This can be depicted more clearly using a diagram called a boxplot.

6.3.6 Boxplot

Boxplots give a more detailed picture of the spread of data by placing it into quartiles with the Inter-Quartile Range (IQR), the middle 50% of all the data, being placed in the “box”. The larger the size of the box shows a larger spread of the data and the median is depicted by the central line within the box. The lines to the top and bottom of the box represent the data that lies up to $1.5 \times IQR$ with points outside of these lines being noted as outliers. Starred outliers are more extreme, equating to over $3 \times IQR$. The overall spread of the participants’ choices can be seen in the boxplot in Figure 6.4 including groupings from the Wilcoxon signed-rank test and annotations in red.

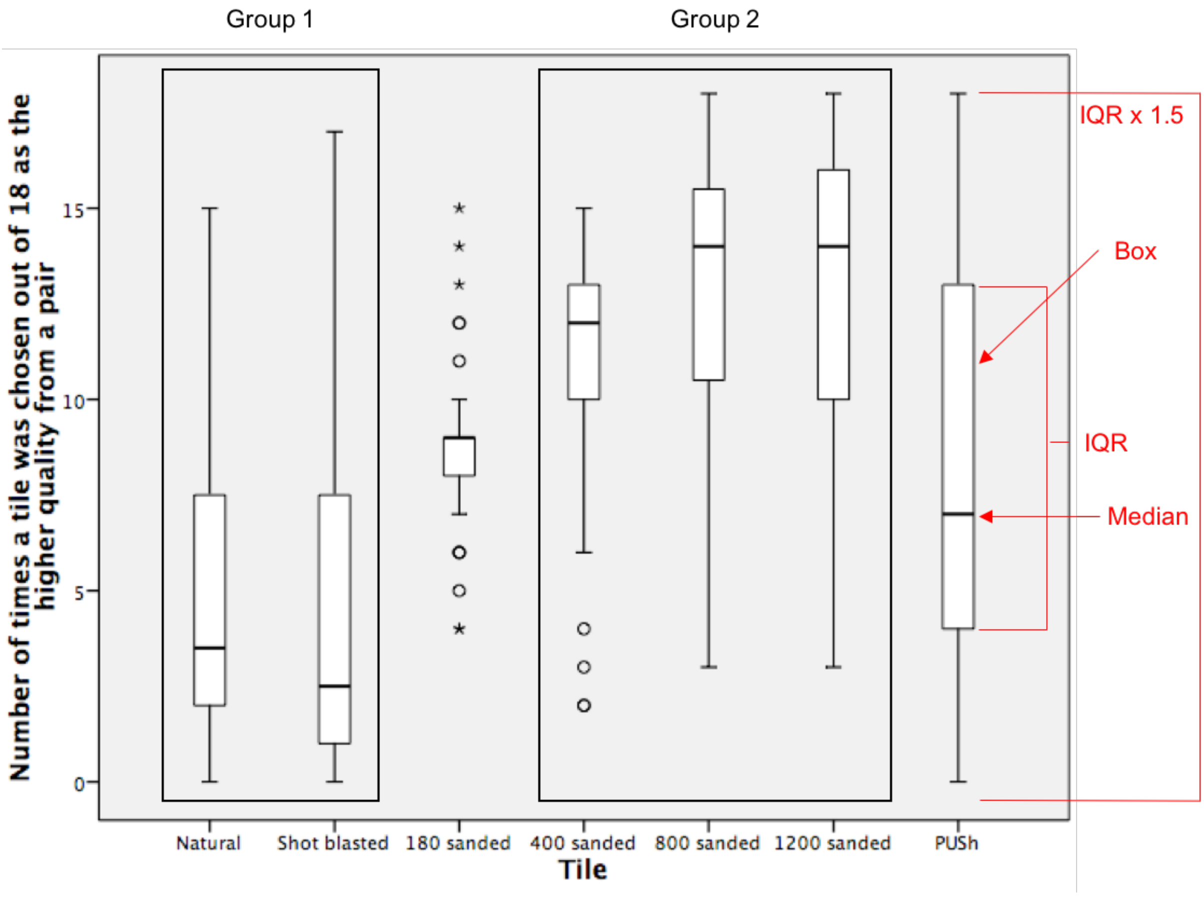


Figure 6.4 - Boxplot depicting the number of times each tile was chosen out of a possible 18 pairings, to be of a higher quality by all participants during the 2AFC tests

Figure 6.4 shows the data distribution from the 2AFC test from all of the participants for each tile. The x-axis shows all of the tiles in ascending smoothness level and the y-axis is a scale of the number of times a tile was chosen as the highest quality tile of a pairing, out of a possibility of 18.

Medians

The placings of the medians and IQRs for each tile imply whether the participants mostly perceived the parts to be of a higher or lower quality. The more times that a tile was chosen as the higher quality part of a pair indicated a higher perceived quality. As is evident from Figure 6.4, the natural and shot blasted tiles were perceived to be of the lowest quality and the 400, 800 and 1200 sanded tiles were the highest. The medians from this diagram also confirm the data given in Figure 6.3.

Spread

The spread of each boxplot suggests the amount of participant agreement for each tile. The tile with the most agreement was the 180 sanded tile because it had a small box for its IQR and small lines either side. The tile with the least participant agreement was the PUSh process tile. This was due to its large IQR box and lines that spread the whole range of the y-axis.

Statistics

Figure 6.4 also visually indicates the groupings from the Wilcoxon signed-rank test. Group 1 contains the natural and shot blasted tiles and Group 2 contains the 400, 800 and 1200 sanded tiles.

6.4 Semantic differential testing

In this test, each participant was asked to rank individual tiles on a set of scales relating to roughness, hardness, temperature, smoothness, quality, and furriness as identified in the focus groups. Both the order of the tiles and the scales were completely randomised and again, the participants were not allowed to see the parts. This test was designed to encourage the contributors to evaluate their initial contact with the tiles in the first test with scales that could quantify their opinions. To investigate this data, boxplots were created to show the spread of data for all tiles from the participants.

6.4.1 Roughness

The boxplot in Figure 6.5 shows that the overall spread of data implied that the participants had differing views of roughness between each tiles.

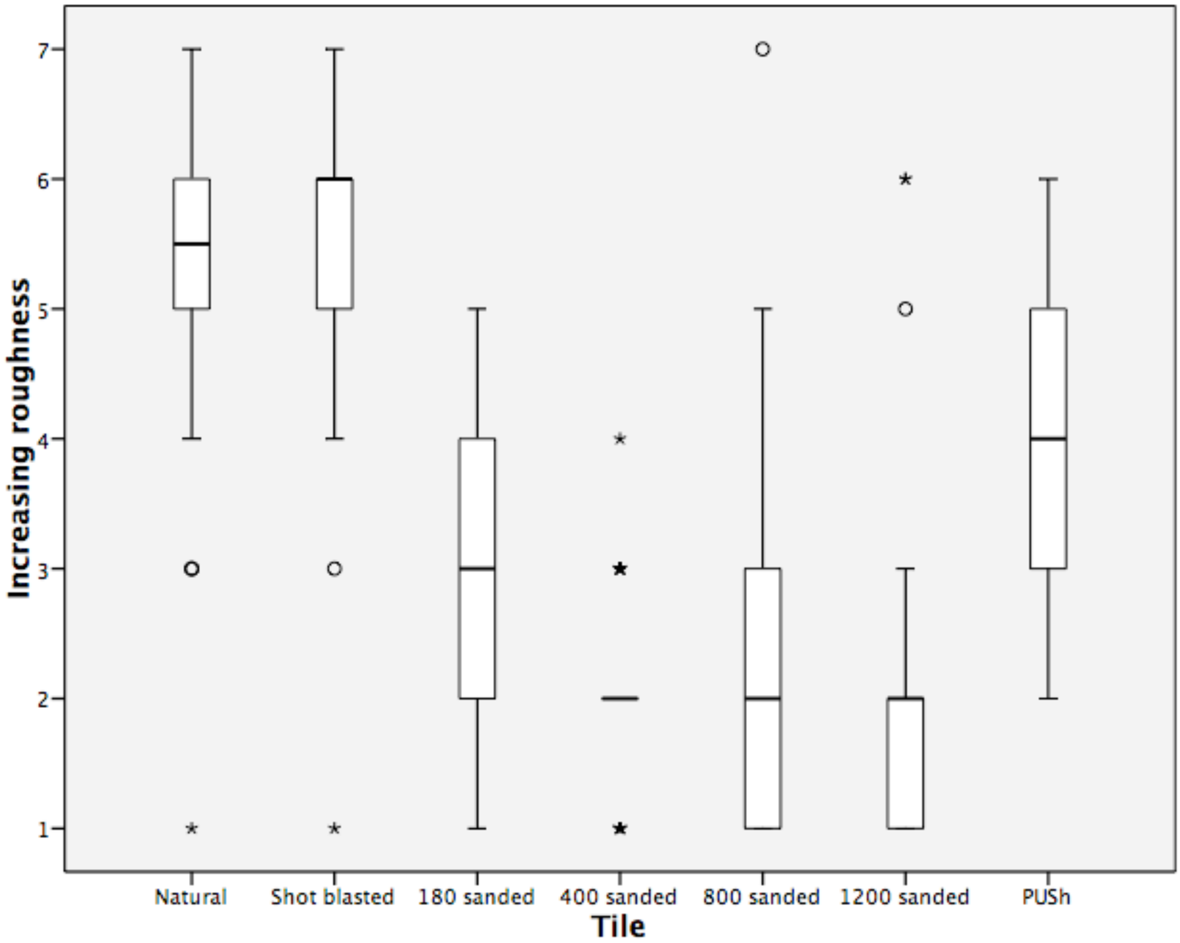


Figure 6.5 - Boxplot of the roughness scale data

Medians

The medians of the boxplot in Figure 6.5 show the mid-points of the data for each tile. The natural and shot blasted tiles have the highest perceived roughness medians and IQRs. The 400, 800 and 1200 sanded parts have equal medians with low roughness IQRs suggesting that these tiles were perceived to be the least rough and that the participants may not have been able to decipher a difference between those tiles. The 180 sanded and PUSh tiles were placed in between these two extremes.

Spread

The spread of the IQRs and boxplots indicate the amount of agreement of the participants. The 400 sanded tile has an IQR of 0 and no lines to the top or bottom of the median, which implies the majority of participants were in agreement on the roughness of this particular part. The 180 sanded and PUSh processed parts have the largest spread of all of the boxplots, with the PUSh part perceived rougher than the 180 sanded tile.

Statistics

The boxplot in Figure 6.5 suggests that there was a perceived difference in the tiles from their placement; the Friedman test supported this with a p-value of <0.001 which is less than the cut-off point of 0.05 for significance. A Wilcoxon signed-rank test was then carried out to confirm that there was no statistically significant difference between the 400, 800 and 1200 sanded parts and also between the natural and shot blasted parts. The data from these tests can be found in Appendix F.

6.4.2 Hardness

The boxplot shown in Figure 6.6 shows the data distribution from the participants when asked to analyse the tiles by their hardness.

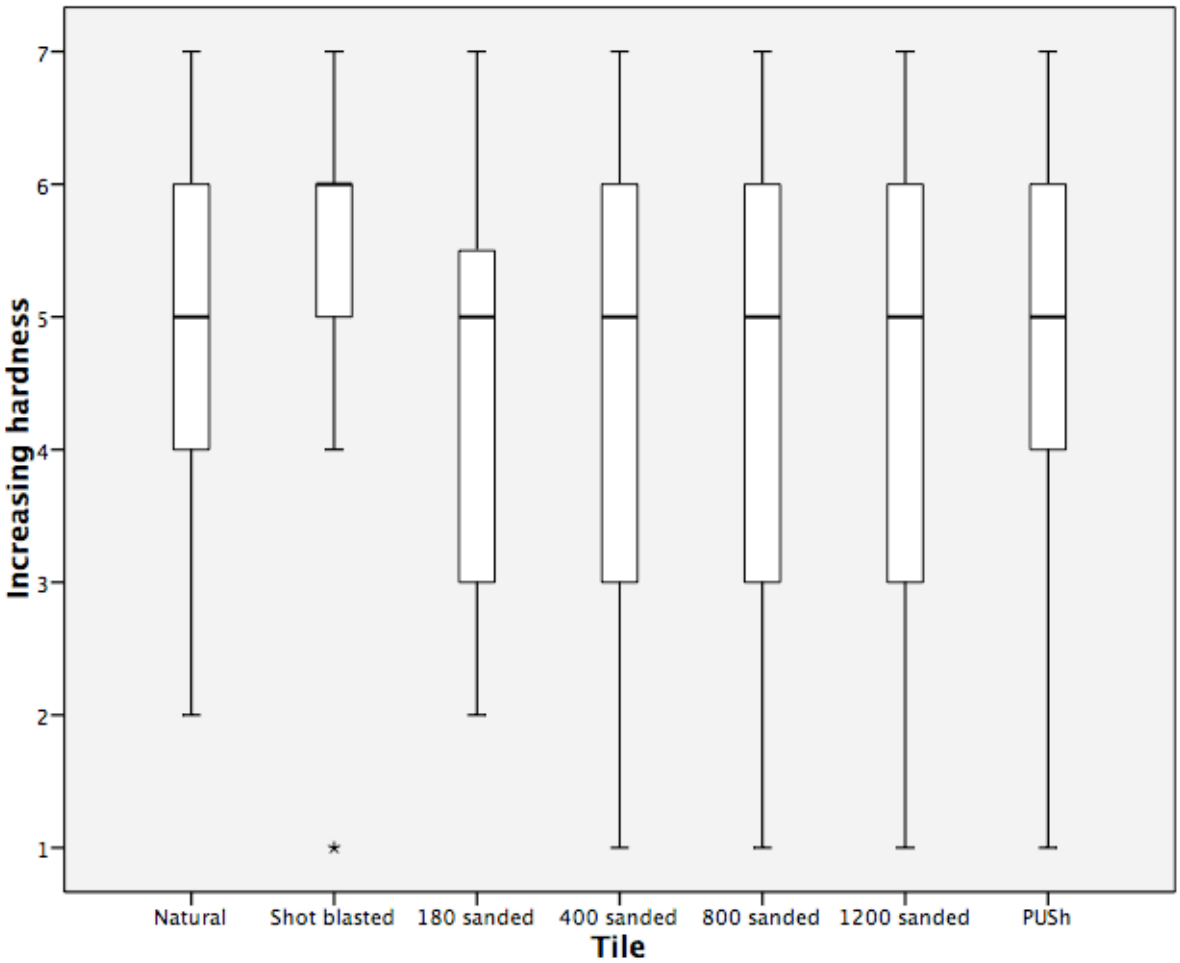


Figure 6.6 - Boxplot of the hardness scale data

Medians

The medians of each tile are equal apart from the shot blasted part which is slightly higher. This suggests that the participants have the same overall opinion of each of the tiles especially as they have similar IQRs.

Spread

The spread of the IQRs and outside lines shows that the data has a wide distribution for most tiles, with the shot blasted tile having the smallest spread. This implies the participants were not necessarily in agreement with each other due to the spread of the boxplots, but that they were largely in agreement of the hardness perceived for each plate to be the same. Figure 6.6 suggests that most participants gave the same value of rating for each tile, which was deduced from the very similar boxplot placements and shapes shown in Figure 6.6.

Statistics

Due to the large spread of each of the tiles' data, it was difficult to interpret whether there was a perceived difference between the tiles. The Friedman test gave a p-value of 0.004, which suggests that there was a significant difference as this p-value is lower than the significance level of 0.05. Therefore, a Wilcoxon signed-rank test was investigated to see where the differences in hardness perception were; see Appendix F for this data.

The main differences found were between the shot blasted tile compared to the others, although these were not found to be statistically significant. This is suggested in Figure 6.6 from the smaller spread of the boxplot for the shot blasted tile.

6.4.3 Temperature

The boxplot in Figure 6.7 shows the overall spread of data by the participants when testing the tiles with respect to temperature.

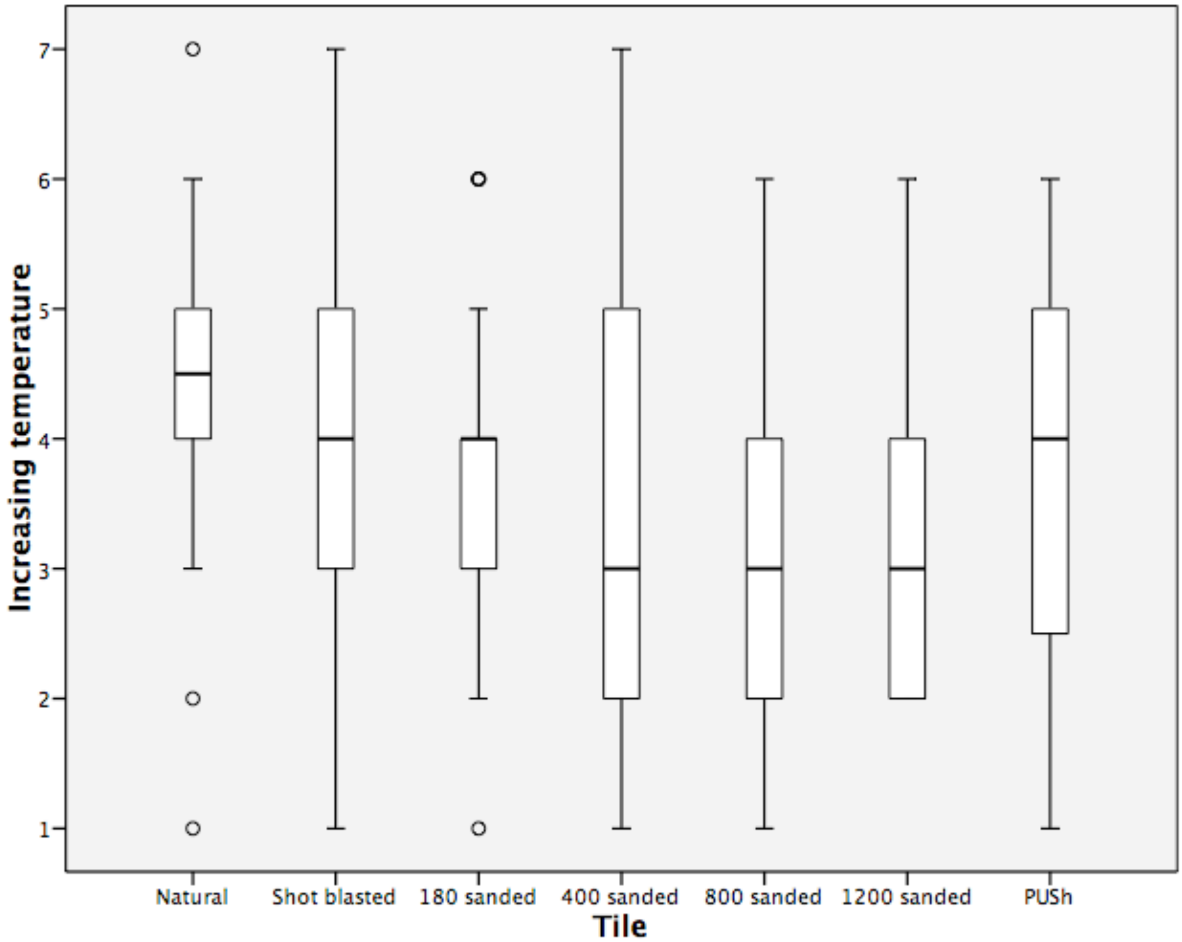


Figure 6.7 - Boxplot of the temperature scale data

Medians

The medians in Figure 6.7 reduce in size per tile and then increase again for the PUSh processed part. The medians for the 400, 800 and 1200 sanded parts are equal, again suggesting the participants perceived them to be similar.

Spread

The spread of the IQRs and outside lines are again, quite large for the most part. The natural and 180 sanded parts had the smallest distributions with the shot blasted and 400 sanded having the largest spreads. The participants were not as decisive for this scale as they were for roughness for example, this is shown by four of the plots spanning at least six of the scale points if not, the whole scale.

Statistics

Similarly to the hardness boxplot, the data shown in Figure 6.7 gave an ambiguous view of the data as to whether any of the tiles would be significantly different to each other. The Friedman test gave a p-value of <0.001 suggesting that there was a perceived difference. The Wilcoxon signed-rank test (see Appendix F) stated that the differences came from the natural tile compared to the 400, 800 and 1200 sanded tiles, which are the two extreme medians shown in Figure 6.7. There was also a significant difference found between the shot blasted and 800 sanded tile.

6.4.4 Smoothness

The boxplot in Figure 6.8 shows the overall spread of data by the participants when testing the tiles with respect to smoothness.

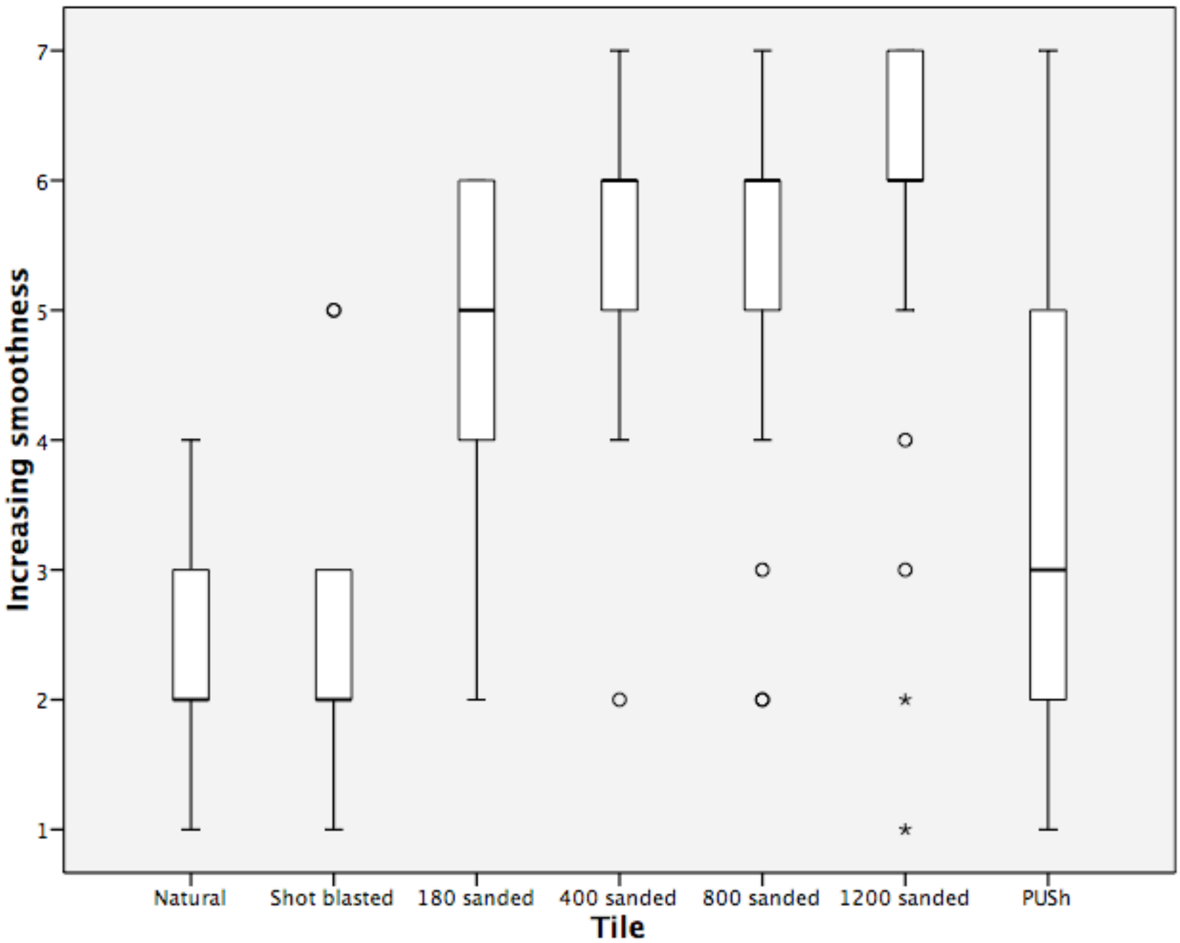


Figure 6.8 - Boxplot of the smoothness scale data

Medians

The medians shown in Figure 6.8 again show the mid points of the data for each tile. The natural and shot blasted tiles have the lowest perceived smoothness. The 400, 800 and 1200 sanded parts have the highest medians, but the 1200 sanded part has the highest perceived smoothness due to its IQR placing. The PUSh processed and 180 sanded parts are in between the two extremes respectively.

Spread

The highest and lowest perceived smoothness tiles have the smallest data distributions with the 180 sanded and PUSh tiles having much larger spreads due to their IQR and outside line sizes. This suggests that the participants were more in agreement with each other for the natural, shot blasted and higher sanded tiles, but for the other two, especially the PUSh tile, it was unclear as to their agreement.

Statistics

The boxplot in Figure 6.8 suggested that there may have been differences in perception of smoothness between the tiles, and the Friedman test confirmed this with a p-value under the 0.05 cut-off of <0.001. The Wilcoxon signed rank tests (see Appendix F), showed that there were many statistically significant differences between the tiles, however not between the natural and shot blasted and also between the higher sanded tiles.

7.1.1 Quality

The boxplot in Figure 6.9 shows the overall spread of data by the participants when testing the tiles with respect to quality.

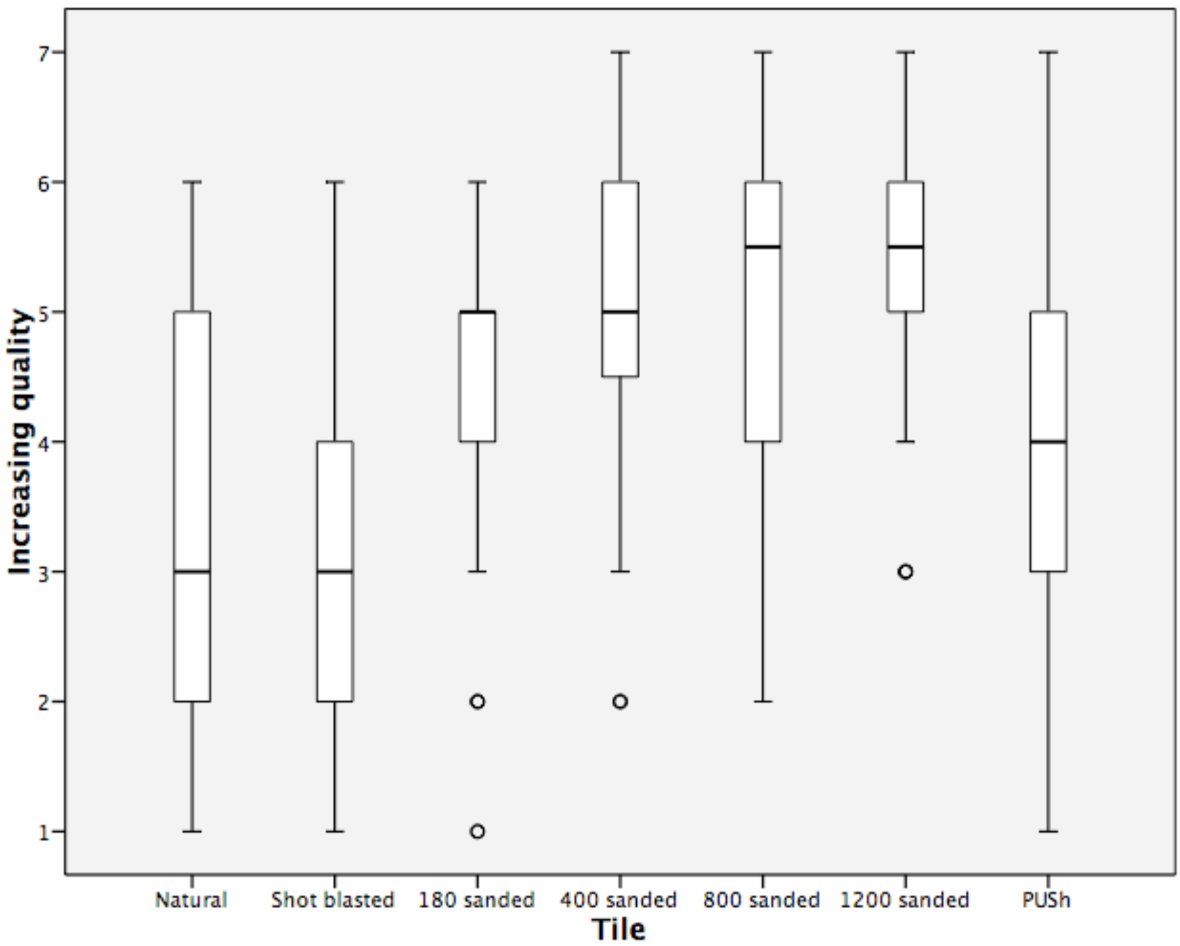


Figure 6.9 - Boxplot of the quality scale data

Medians

The medians in Figure 6.9 appear to increase with the measured smoothness of the tiles and then drop again for the PUSh processed part. The 800 and 1200 sanded tiles have the highest medians and the natural and shot blasted tiles have the lowest.

Spread

The PUSh processed part has the highest overall spread as the boxplot for that tile reaches the extremes of the whole quality scale, but it does not have the largest IQR. This suggests that the participants were not in agreement of the quality of the PUSh processed tile. The spreads and medians together suggest that the 400, 800 and 1200 sanded tiles were perceived to have the highest quality out of the tiles, with the natural and shot blasted tiles perceived as having the lowest quality.

Statistics

The boxplot in Figure 6.9 suggested that there may have been differences in perception of quality between the tiles, and the Friedman test confirmed this with a p-value of <0.001, which is below the significance value of 0.05. The Wilcoxon signed rank tests (see Appendix F), showed that the main differences lay between the natural and sanded parts as well as the shot blasted and sanded parts. There was also another significant difference found between the 1200 sanded part and the PUSh processed part.

6.4.5 Furriness

The furriness of each of the tiles was ranked in the semantic differential experiment and Figure 6.10 shows the outcome.

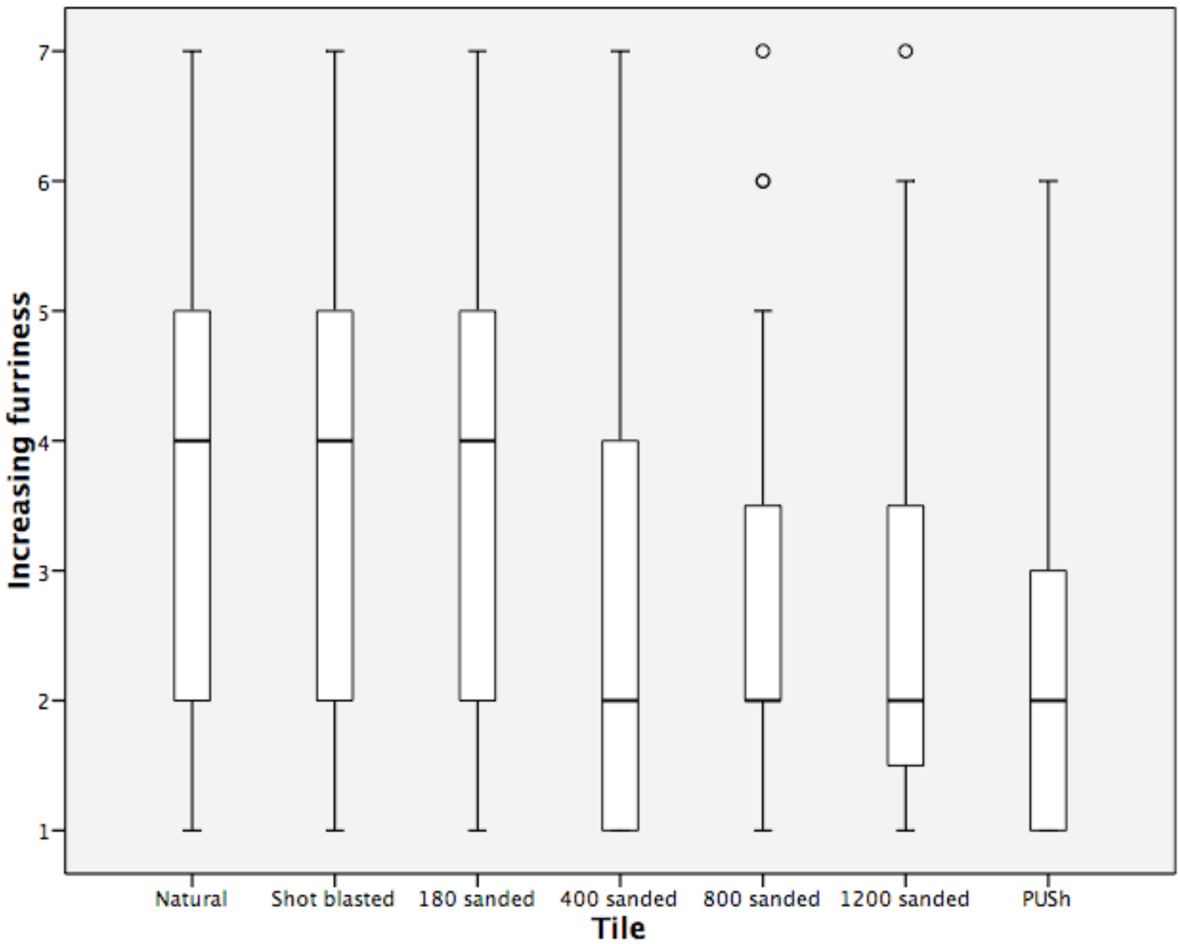


Figure 6.10 - Boxplot of the furriness scale data

Medians

The medians in Figure 6.10 have two values: the natural, shot blasted and 180 sanded have medians of 4 and the 400 sanded, 800 sanded, 1200 sanded, and PUSh processed parts have medians of 2. This shows a substantial divide between the two groups with regards to furriness.

Spread

The data is widely spread and gives a sense of ambiguity to the diagram suggesting that the participants were not in agreement. However, even though the data is largely distributed, there is a clear divide between the first three plates and the last four in distribution. The first three plots for the natural, shot blasted and 180 sanded tiles are identical and the last three plots are slight variations of each other. This implies a change in perceived furriness between the groups.

Statistics

The boxplot in Figure 6.10 is not clear on whether there are any obvious statistical differences between the furriness of the tiles. The Friedman test calculated a p-value of <0.001, which is below the significance level of 0.05 giving the p-value a statistically significant status. The Wilcoxon signed-rank tests (see Appendix F), showed that the differences were between the three most furry parts and the PUSh processed tile.

6.4.6 Participant consistency

The previous boxplots from the sematic differential tests show the overall consensus of the participants' opinions on different scales. From these the agreement can be quantified using an intra class correlation and comparing it with Cohen's effect sizes [136] as shown in Table 6.5.

Table 6.5 – ICC results from the semantic differential tests

Scale	ICC
Roughness	0.648
Hardness	0.080
Temperature	0.128
Smoothness	0.669
Quality	0.262
Furriness	0.118

The ICC calculated shows there were only two scales that had a strong effect size: roughness and smoothness. The other scales had weak effect sizes and hardness had the smallest coefficient overall. This suggests that hardness was the most ambiguous of the scales for the participants as there was not a strong agreement because it had the lowest coefficient. Roughness and smoothness had very similar, strong coefficients in value which suggests that they could be perceived as opposites.

6.5 Ranking of tiles

After the 2AFC and semantic differential tests had been carried out, the participants were asked to rank the parts against each other for a mobile phone case, in order of quality for a mobile phone case behind a screen. The results were then analysed using non-parametric statistical tests.

6.5.1 Friedman test

As this was the last part of the practical experiment for the participants, it meant that the data could be interpreted as a fuller and more informed perception of the surfaces compared with their first impressions in the data from the 2AFC test earlier. This meant that another Freidman test could be calculated and analysed.

The Friedman test showed that there was a significant difference between the tiles ($p<0.001$), but not between which specific tiles. Again as the data was ordinal, a repeated measures

Wilcoxon signed-rank test was then used to compare across all of the tiles to determine where the differences in perception were.

6.5.2 Wilcoxon signed-rank test

The results from the repeated measures Wilcoxon signed-rank test suggest that the differences lay between the natural tile and the sanded tiles, the shot blasted tile and the sanded tiles and the 1200 grade sanded tile and the PUSh processed tile. This can be better illustrated using a boxplot as shown in Figure 6.11.

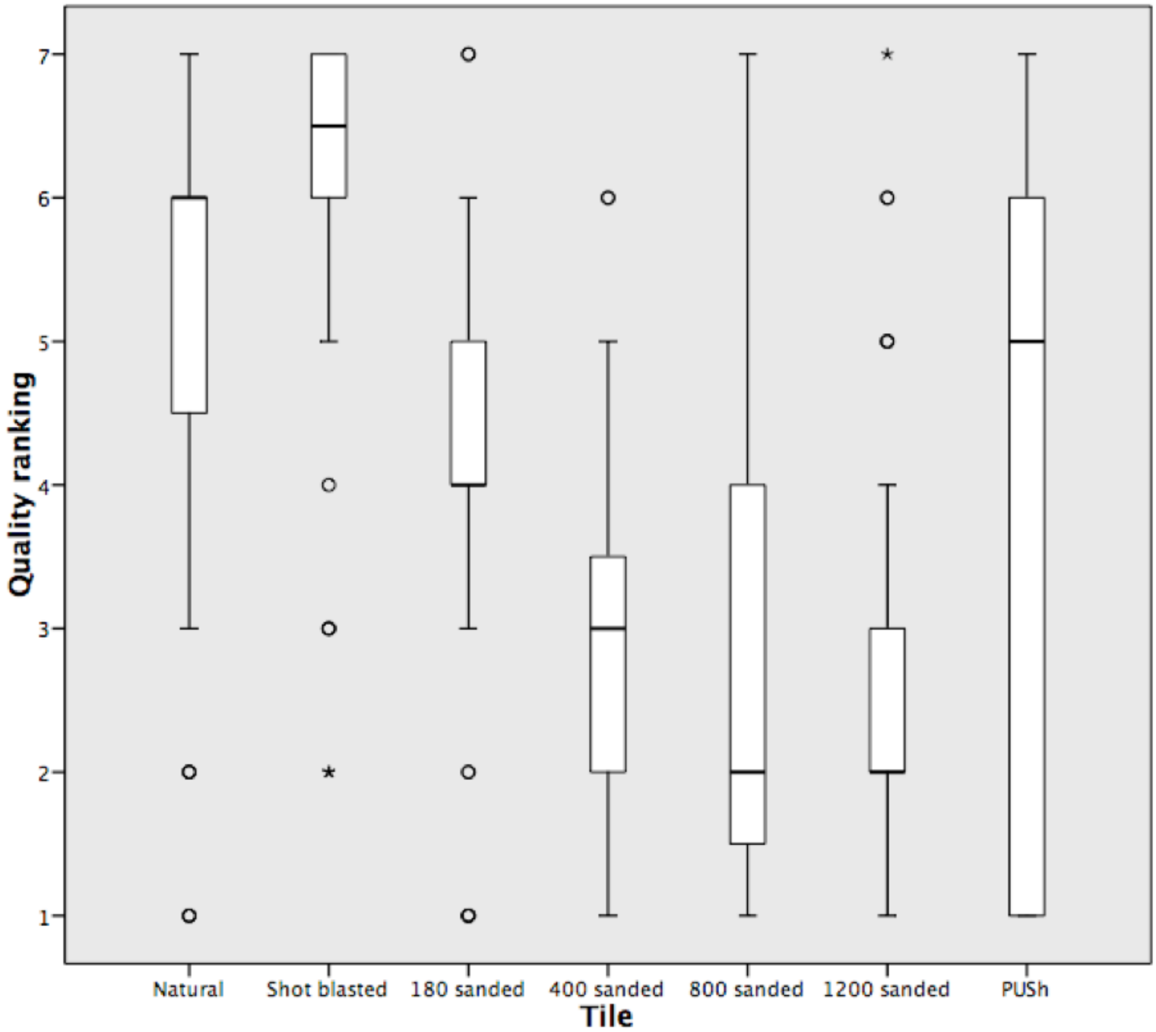


Figure 6.11 - Boxplot of the participants' data for quality ranking from first to seventh

Medians

The medians in Figure 6.11 show the shot blasted tile to have the lowest median quality ranking and the 800 and 1200 sanded parts to have the highest median quality rankings.

Spread and Statistics

The boxplots in Figure 6.11 show that the shot blasted, 180 sanded and 1200 sanded parts have the smallest IQRs and outside lines, which implies that many of the participants agreed on the rankings of these tiles. The 800 sanded and PUSh processed tiles have much larger spreads. The PUSh part's IQR spans most of the scale indicating that the participants were not in agreement of these tiles, especially the PUSh processed tile. From the Wilcoxon signed rank tests (see Appendix F), there was evidence pointing to the PUSh processed part being perceived as a different quality and the boxplot supports this finding in that most of the participants were not consistent with their opinion of it. The data for this tile spans the whole scale and the IQR is from first to sixth.

6.6 Touch and sight comparison

After the main part of the experiment was complete, each participant was then interviewed about their experience; they were shown the parts in the order that they had been ranked and were given the option to change their ranking, now that they had a visual of the parts. Out of all of the participants, exactly half decided to change their previous order of quality. This implies that the perception of quality is highly dependent on sight as well as through touch. The boxplot shown in Figure 6.12 was generated to show the difference in spread of data by the participants from before and after seeing the parts. The white boxes depict the touch-only rankings and the dark boxes represent the sight data.

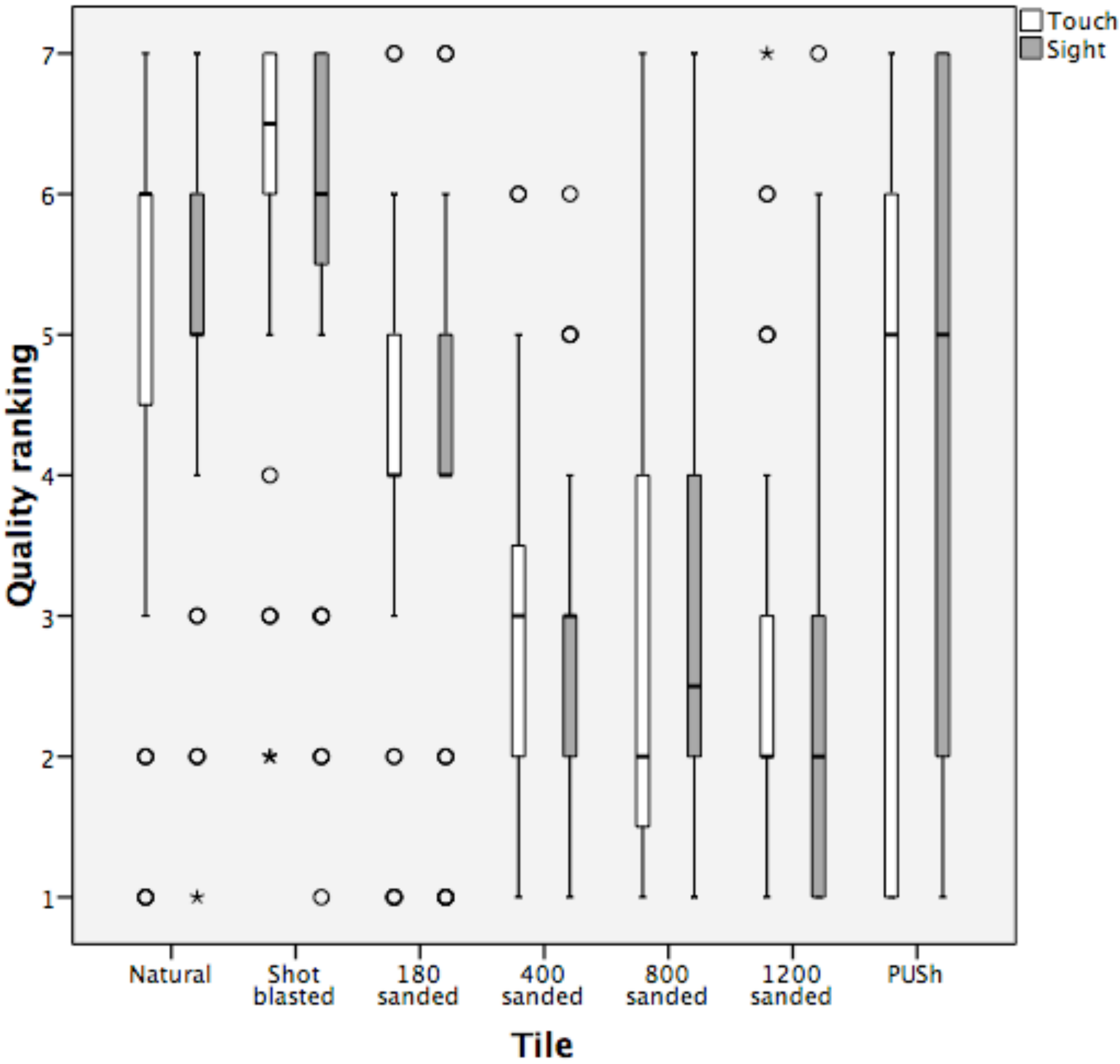


Figure 6.12 - Boxplot of the differences in data spread before and after seeing the tiles. Ranking is from first to seventh.

As shown in Figure 6.12, most of the plots for each tile did not change drastically after the participants were shown the tiles.

Medians

All of the medians were similar for each tile, with no sight median straying further than one full rank away from its touch median. This indicates that although some of the participants may have changed their ranking order after seeing the plates, it didn't greatly affect the overall data. The natural and shot blasted tiles were both consistently ranked lower than the other tiles, but their medians both improved in rankings when including the visual data.

Spread

The spread of the IQRs tended to be fairly conservative and similar between the touch and sight plots. The spread for the 180 sanded tile hardly changed at all, except it lost the bottom line, which implies that the participants who ranked this tile slightly higher decided it was of a lower quality when they saw it as the median stayed the same. The opposite can be said for the 400 sanded part as overall the spread was slightly improved after being seen.

The plots for the 800 sanded tile suggest that the participants were not as consistent on their views as there was a large spread of participant data. The IQRs and medians for the 800 sanded tile were still ranked highly suggesting that the majority of people ranked it higher than the other tiles. After being seen, the 800 sanded tile was moved down slightly.

The 1200 sanded tile shows it had the majority of participants ranking it higher before it was seen, as the median was set in the second rank and the IQR spans only two ranks. However, after participants viewed the tile, even though the median stayed the same, the spread of data became larger suggesting those who initially ranked it highly, ranked it higher and those who ranked it lower than the median dropped their ranking slightly.

The PUSh processed tile again was not consistently ranked for quality by the participants as the data spread and IQR range were both very large. The touch-only and sight plots do show that sight was seemingly important to the ranking of this tile. It implies that those who ranked the tile highly, changed their opinion when they viewed the tile. It is difficult to say by how much the tile changed in ranking as the data is so widely spread.

6.7 Interviews

The interviews gave the participants a chance to explain their opinions and findings and talk about their past experiences with phone cases. This was structured into three stages:

1. Questions about the experiment
2. Initial viewing of tiles
3. Personal experiences

6.7.1 Questions about the experiment

The participants were first given a recap of what was covered in the experiments and then they were asked if they had found themselves favouring (or not) certain parts. 93.2% of participants believed they did favour and recognise certain parts throughout the testing process.

The participants were then asked what their main factor was when deciding on the quality of each tile examined. The most common adjective answered for this question was smoothness. Over half of the participants (54.5%) stated that smoothness was one of the main factors they used when deciding on the quality.

6.7.2 Initial viewing of tiles

The reveal of the tiles caused many of the volunteers to inform the facilitator the plates were not what they expected. Many believed the tiles to be made of different materials and colours. The participants were then offered the opportunity to change their ranking from the experiment, with sight included in the decision and exactly half of the participants decided to change their initial ranking.

6.7.3 Personal experiences

68.2% of participants owned and used a mobile phone case for their own phone at the time of testing and 63.6% claimed that protection was one of the most important factors that they would look for in a mobile phone case.

When asked if they would consider buying a phone case with any of the surface finishes on the tiles, all participants agreed that they would however some were price and design dependent. The participants were asked to pick out which surface finishes they would most be tempted to have on a mobile phone case; Figure 6.13 shows the outcome.

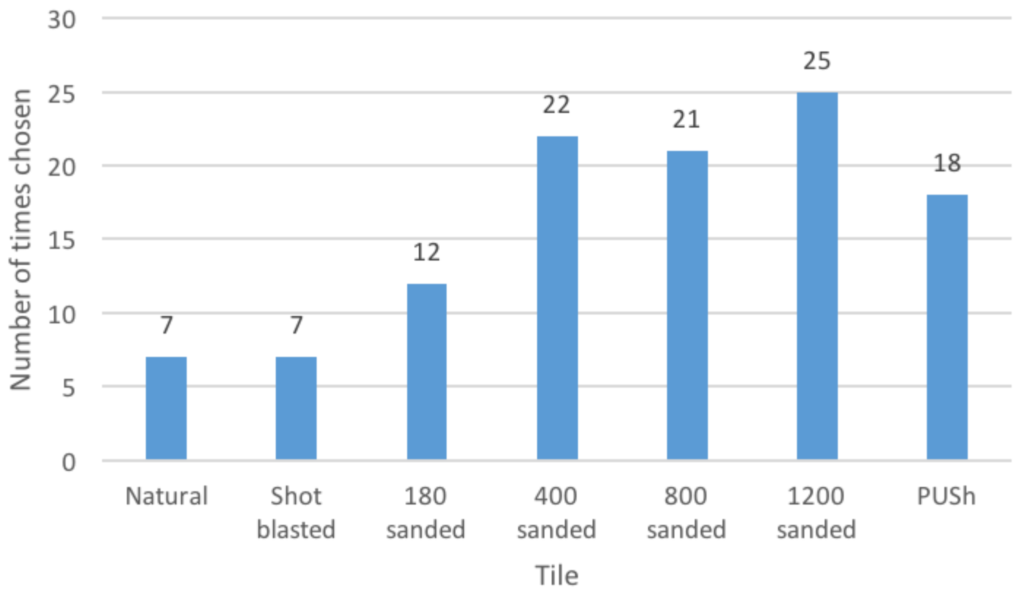
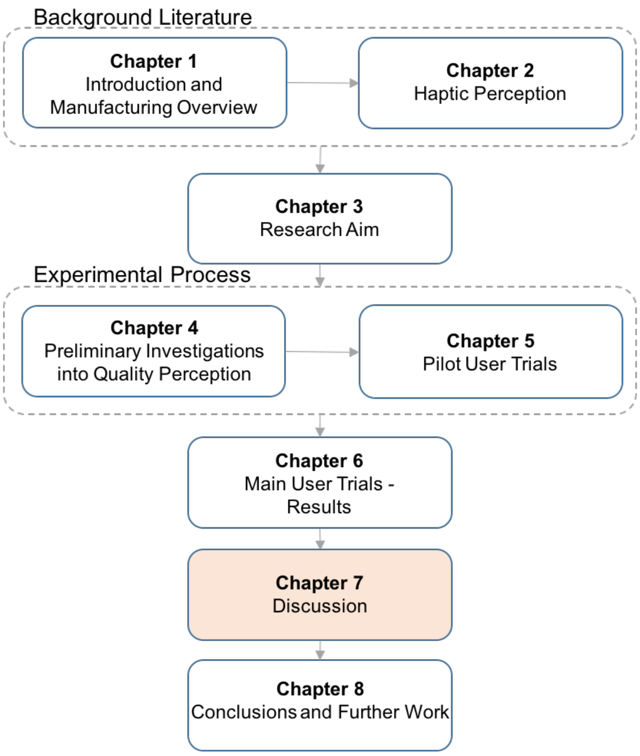


Figure 6.13 - Bar chart of tiles chosen for a phone case

Figure 6.13 shows that the 1200 sanded part is the clear favourite as it was chosen the most amount of times, with the 400 and 800 sanded parts in second and third rank respectively. The PUSh processed part was not far behind the top three, and many participants described having mixed feelings towards this surface. The overall consensus tended to be that the PUSh processed tile was not deemed to be of a high quality, but the nature of it meant that the grip would be better than others. The natural and shot blasted parts were chosen the least, which was reflected in all of the previous tests from this experiment. Again, this result confirms the data shown throughout this chapter.

Chapter 7 presents a discussion of the results.

7 Discussion



Chapter 6 stated all of the results obtained from the main testing experiments. This chapter interprets these results and suggest how they fit into the wider field.

7.1 Review

7.1.1 Problem Definition

The advances of AM are guided mostly by the decisions of machine manufacturers and researchers. Industry is now becoming more prominent in the progression of the technology, yet customer input is still absent. The surface finish of LS parts is also a key aspect that is often portrayed as a challenge to AM, especially for LS [7]. Therefore, this thesis investigates both of these subjects and the initial aim was outlined in Chapter 3:

"This thesis utilises techniques from human factors research to provide a novel understanding of the way in which surface finish affects users' perception of the quality of a LS part."

7.1.2 Objectives

From this initial description, specific objectives were set to guide the progression:

1. Identify range of roughness achievable with “standard” LS finishing techniques.
2. Identify relevant human interactions techniques to assess quality perception of LS finishing techniques.
3. Design and conduct experimental work to quantify the perceptions of quality.
4. Identify how the findings from this research can be applied to industry.

The three objectives were met through the experimental design process that followed.

1. The range of roughness achievable was conducted with test tiles in different orientations, from a build using standard machine parameters in three different types of powders. These were then measured using profilometry. The range of roughness was found to be between 10.15-20.40μm. These tiles were then applied in the focus groups.
2. The tiles were used to confirm if there was a perceived difference between the two ends of the roughness scale by the participants. The focus groups were used to gather opinions and adjectives from participants about LS parts. The adjectives collected were used to develop the language for the human interactions tests influenced by the literature.
3. The language then contributed to forming the sample experiments. These were carried out with five trial participants to gather feedback on the experimental process. These iterations formed the main testing experiment and the results were outlined in Chapter 6.

The fourth objective will be addressed later in this chapter.

By completing the experimental design process and following the original objectives set out at the start, this addressed the initial problem definition set out in Chapters 1 and 3.

7.2 Effect of roughness on quality perception

7.2.1 Trend

The overall analysis from the main experimentation showed an increase in quality perception with decreasing roughness, up to a certain point after which no further improvement was observed. This coincides with the main surface finish limitation and Ariadi et al.'s work, which also suggested that the smoother surfaces were favoured by consumers [76, 77]. The smoothest sample showed an apparent decrease in quality perception, although it should be noted that this sample showed the greatest variation. This trend is apparent in Figure 7.1, which was taken from the quality ranking section of the tests.

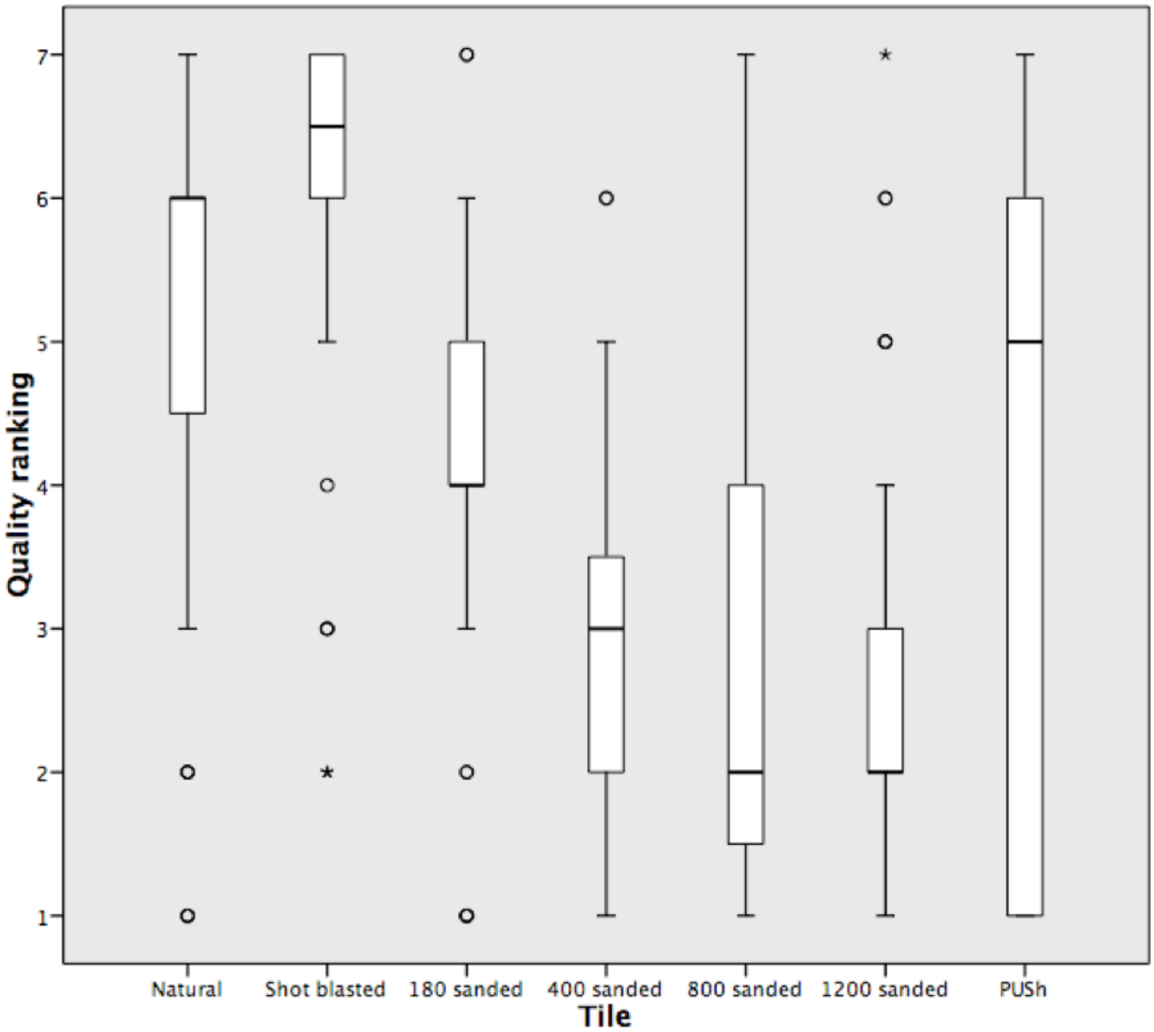


Figure 7.1 - Quality ranking of the tiles

The tiles were placed in decreasing roughness order for the boxplot, with the natural part having the roughest surface finish and the PUSh processed part having the smoothest surface finish. The quality ranking scale showed the quality decreasing as the rank order increased, with the number rank of one having the highest quality ranking.

7.2.2 Levels of sanding

In particular, the statistical analysis of the 2AFC test showed that most people could distinguish between sanded and non-sanded parts, but not between levels of sanding. This coincides with the similar surface profilometry results of the sanded parts stated in Chapter 6. This is shown in Figure 7.2.

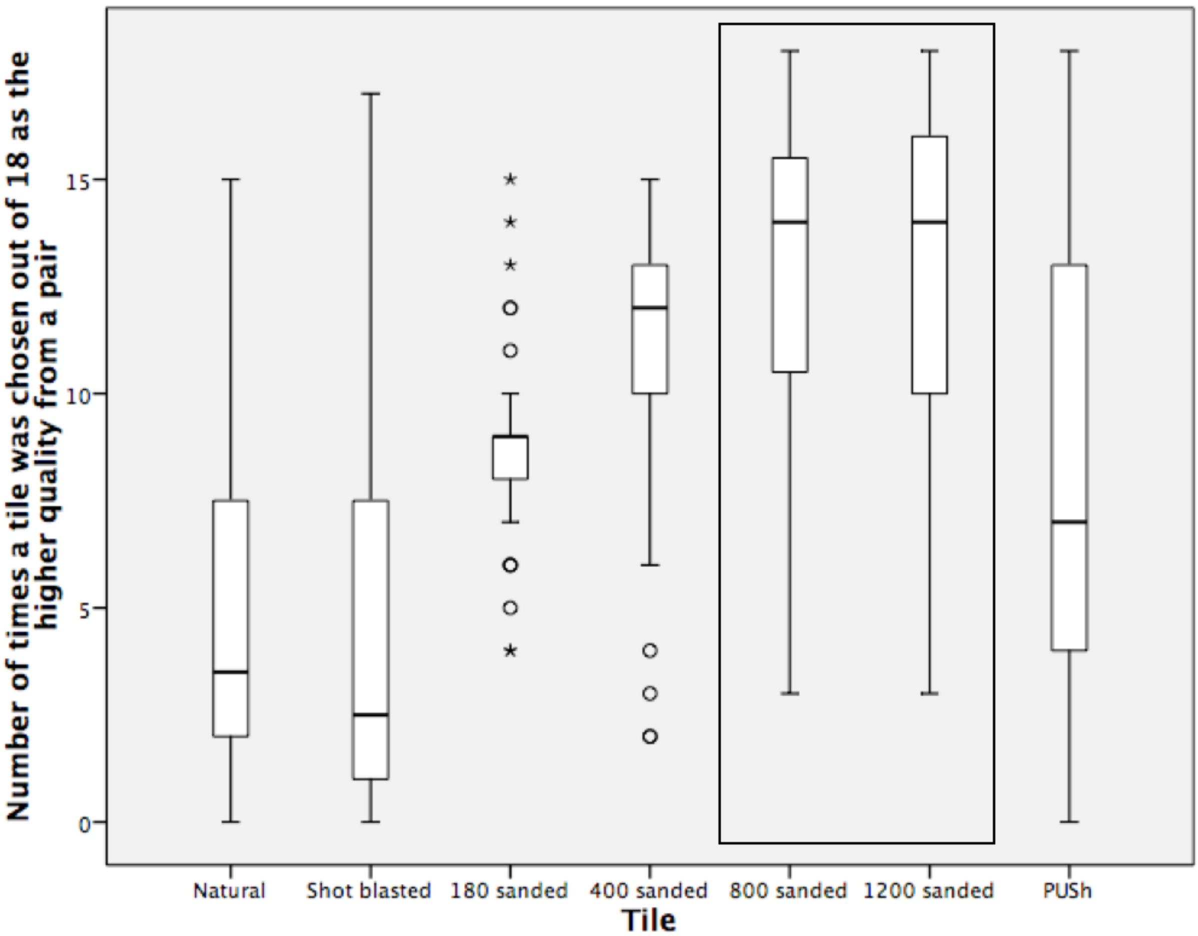


Figure 7.2 - Boxplot depicting the number of times each tile was chosen out of a possible 18 pairings, to be of a higher quality by all participants during the 2AFC tests

Figure 7.2 shows the number of times out of 18 that each tile was chosen to be the higher quality tile of a pairing; the 800 and 1200 sanded tiles were chosen the most overall as highlighted on the diagram, as the IQRs and medians were placed in the highest position on the graph and they had almost identical plots. This data took into account all of the participants' results, and suggested that most of the participants thought the higher graded sanded parts were of a similar high quality, especially the 800 and 1200 sanded tiles. However, the other tiles have different placings on the diagram. The natural and shot blasted parts have opposite shaped plots to those perceived to be of higher quality with lower placing IQRs and medians. This suggested that they were perceived to be of a lower quality, but were also perceived to be similar to each other due to their similar size and shape.

Again, note in Figure 7.2 the increase in quality of the tiles and then the drop off at the end, mirroring the trend from the quality ranking test. Crucially, this trend is backed up by data from all of the tests in the main experimentation. This further supports the theory of other potential factors affecting quality perception (such as friction measurements).

Another example can be seen in Figure 7.3 from the results of the semantic differential test for quality. The overall trend of quality increases as roughness decreases and then drops off for the last tile. Also, the boxplot shows a similar quality placing for both the 800 and 1200 sanded tiles. This eliminates the specific test method from being the cause of the two main outcomes of trend and perception between sanded parts and gives confidence in the data.

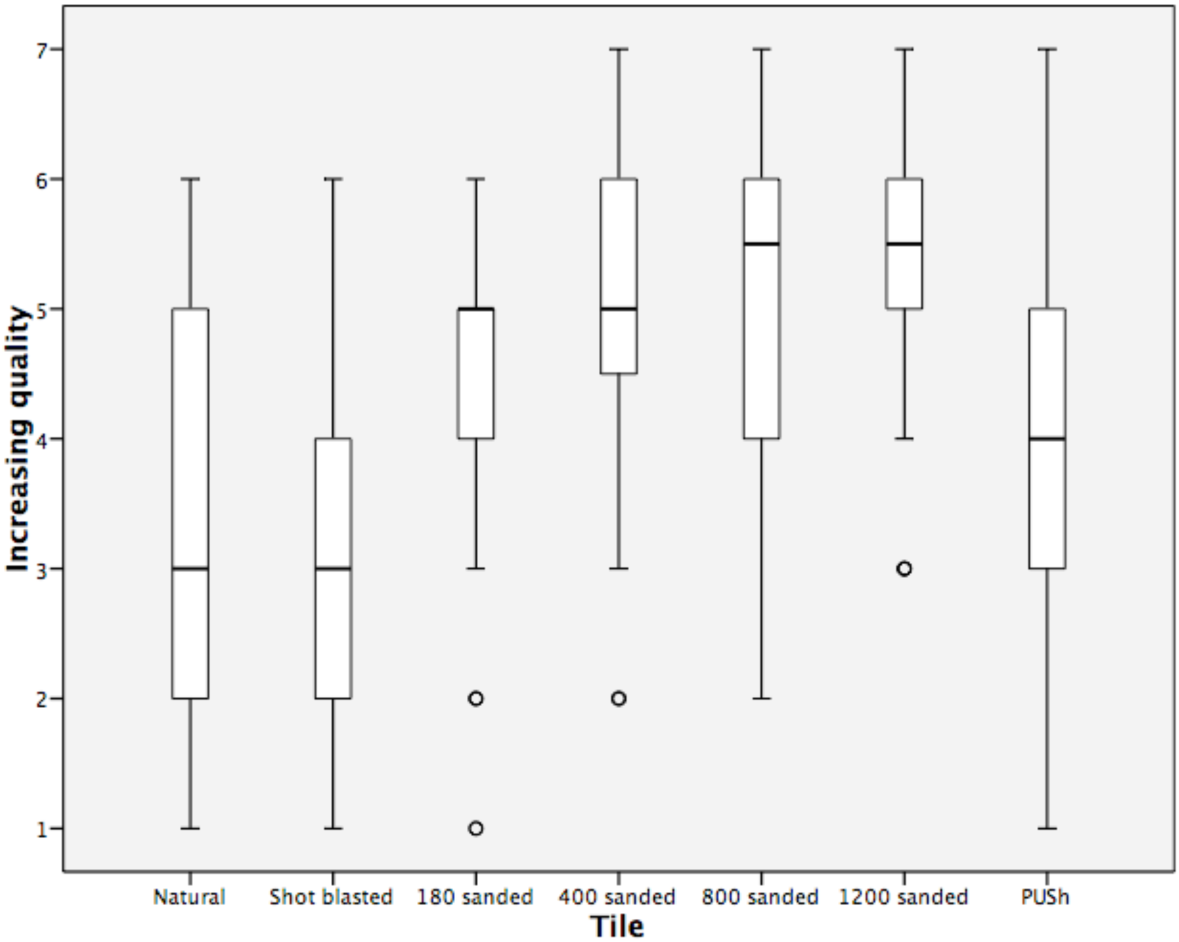


Figure 7.3 - Data from the semantic differential test for quality

7.3 Effects of other factors

7.3.1 Smoothness

Based on the vocabulary generated from the focus groups, different adjectives were also assessed (other than roughness), one of which was smoothness. One of the main rules used when deciding on adjectives to be included was to "*remove ambiguous adjectives*", developed using the guidelines suggested by Barnes, Lillford and colleagues [79, 80, 82]. Smoothness was allocated its own scale as it was one of the most widely used adjectives collected in the focus groups. It was also, given its own scale so as not to cause confusion among the participants in case they did not perceive smoothness to be the opposite adjective to roughness. The results however, show a clear correlation between smoothness and quality and an inverse relationship between roughness and quality, as shown in Figure 7.4.

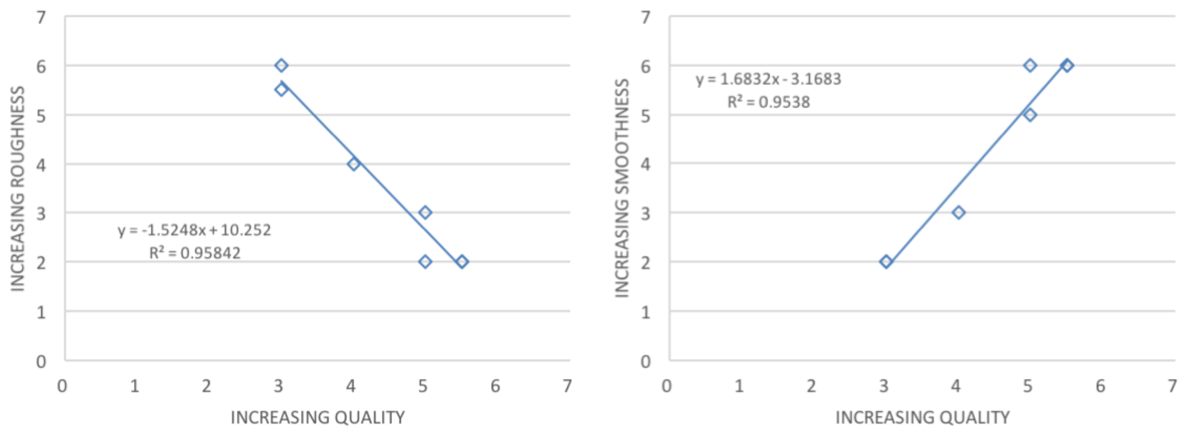


Figure 7.4 - Scatter plots of the relationships between smoothness and quality, and roughness and quality

Figure 7.4 shows that the trends for roughness and smoothness were almost opposite to each other, having gradient values of -1.52 and 1.68 respectively. The R^2 value determines how closely the data fits a line of regression, or the strength of correlation of the data. The value represents a percentage, with a higher number indicating a stronger correlation and relationship. The R^2 values of both of the graphs were very strong and similar to each other with 0.96 (96%) and 0.95 (95%) respectively. This suggests a strong relationship between both roughness and smoothness with respect to quality.

The contrasting gradients imply that the participants mostly perceived smoothness and roughness to be polar opposites of each other, meaning that two separate scales would not need to be used in further semantic differential tests for smoothness and roughness. This relationship can be seen from the inversely proportional graph in Figure 7.5.

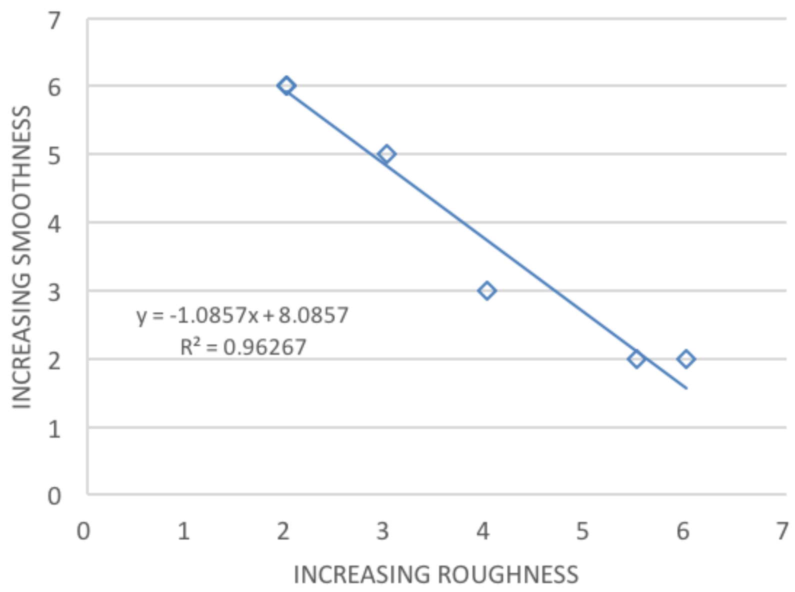


Figure 7.5 - Graph depicting the relationship between the smoothness and roughness scales

The data from Figure 7.5 depicts the relationship gradient as -1.09, indicating an inversely proportional relationship which shows as smoothness decreases, roughness increases at a very similar rate, suggesting the two adjectives are opposite in perceived meaning. The R^2 value again shows a strong, linear relationship of 0.96, which shows that 96% of the total variation in smoothness can be explained by the linear relationship between smoothness and roughness.

The data points used in Figure 7.4 and Figure 7.5 were the medians for each tile from the semantic differential scales. This was to be in keeping with the non-parametric methods used in Chapter 6. Due to the wide range and outliers of the ordinal data, the medians gave a more accurate image of the overall consensus rather than the mean averages, which would be influenced greatly by extreme values.

Over half of the participants claimed that smoothness was the main factor that they used when deciding if the tiles were of a high quality or not. From the results in the semantic differential tests, this supports the claim that smoothness increases with quality and again gives confidence in the data. However, as shown in many of the results (Figure 6.3 - Figure 6.5) there must be other less definable factors involved when examining the relationship between roughness and quality or smoothness and quality.

The PUSh tile, whilst measuring as the smoothest tile during profilometry, had a different appearance to the other tiles. It was that of a shiny material compared to the other tiles that were matte and therefore had a different feel to it other than roughness. One way in which this could be addressed would be to look at the friction measurements of the tiles and compare them with quality. This would give more depth to the understanding of the relationship between surface finish and quality.

7.3.2 Other adjectives

Whilst the other factors showed some minor effects in places, none showed a substantial correlation with quality compared to roughness and smoothness. Figure 7.6 shows the relationships, or lack of, between quality and the other adjectives assessed in the semantic differential tests.

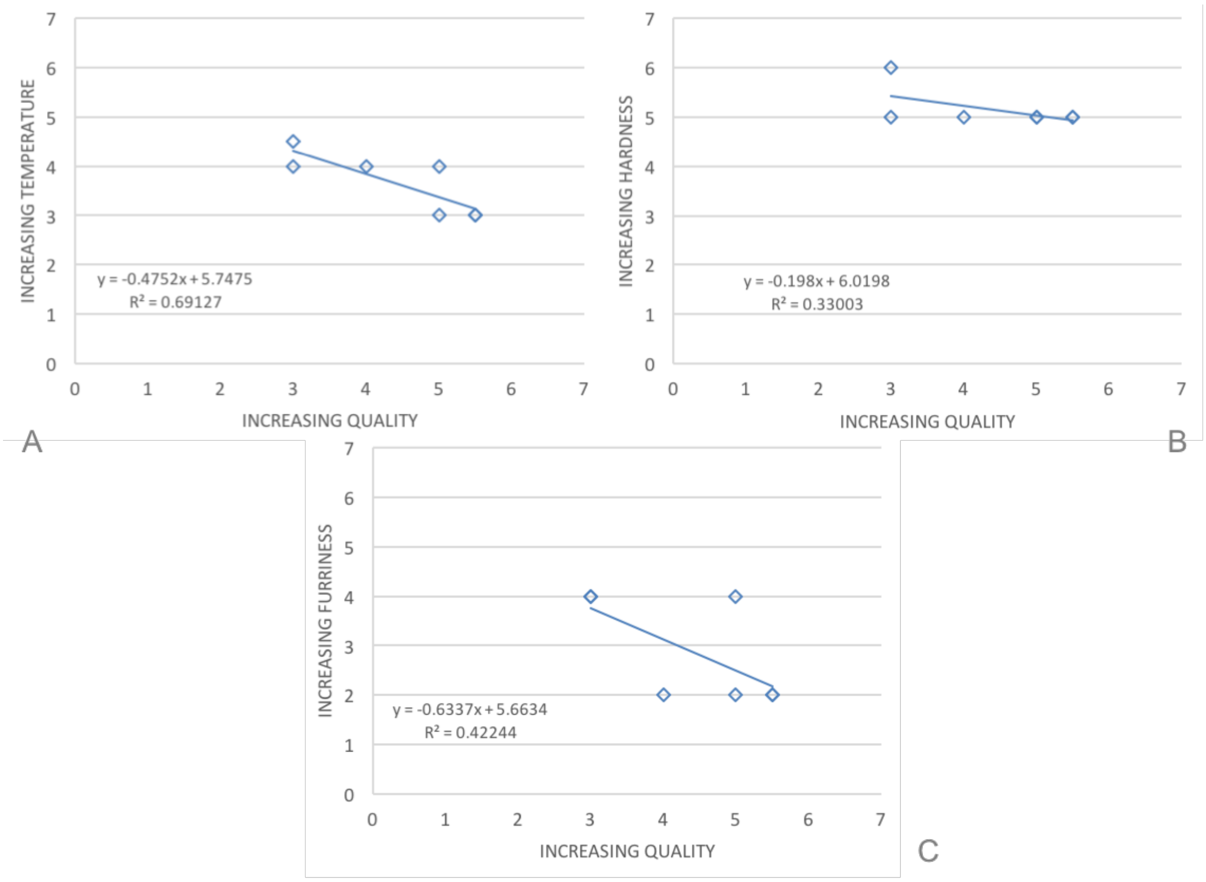


Figure 7.6 - Graphs depicting the relationships between quality and A.) temperature, B.) hardness and C.) furriness

As is apparent in Figure 7.6, none of these results showed a strong relationship with quality. All three graphs show low value gradients and R^2 values. Graph A shows a slight negative relationship between temperature and quality (gradient of -0.48), which suggests that a lower material temperature implies a higher perceived quality. However, with a low R^2 value (0.69), this suggests this relationship may not be consistent over the whole data set. The same material was used to create all seven tiles, which should not give differing material temperatures. This disparity could be due to preconceptions made throughout the testing, of participants evaluating a part to be of a higher quality and then assuming it has a lower material. However, with a low R^2 value, further work would need to be carried out to investigate this claim.

Graph B shows a weak relationship between hardness and quality with a very small gradient of -0.19 and a very low R^2 value of 0.33. This lack of clarity could be due to adjective ambiguity. The words soft and hard were used in this scale, and whilst being commonly used to quantify quality in this research area [105], these can be mistaken for other meanings. The exploratory procedure used to evaluate hardness is a pressing gesture [9, 10], which not all of the participants used when analysing the tiles during the testing procedure.

Graph C again shows that furriness does not affect quality perception. Whilst the data does not show a strong correlation between furriness and quality (with a gradient of -0.63 and a R^2 value of 0.42), it does show that the participants consistently placed the tiles in one of two furriness groups and were either given an overall score of 2 or 4. These groups consisted of the natural, shot blasted and 180 sanded tiles (deemed as furrier) and the PUSh, 400, 800 and 1200 sanded tiles (considered as less furry). This could imply that furry could be linked to roughness, with the furrier tiles having much rougher surface finishes compared to the other tiles.

The furriness scale is an example of how the perception of a word can change from person to person. The original word that was going to be used instead of furry was velvety, which was deemed to have too much of a link towards luxurious items so was discarded in favour of furry. However, in hindsight, velvety would have probably been a better adjective to use in this instance as the data suggests that furry was an ambiguous word choice. The rules outlined by Barnes, Lillford and colleagues [79, 80, 82] should be followed more closely in further work.

7.4 Effect of sight

Sight is a factor that has been debated by many academics as to whether it is necessary for quantifying perceived quality [89, 100-104]. The choice was made not to use sight in the main testing procedure for this thesis, as the main focus was the perception of quality through touch. However, after feedback from the trial testing, a reveal was included after the participants had blindly ranked the tiles. The participants were then asked if they would change their ranking based on their new sight knowledge. Exactly half of the participants decided to change their rank order when they saw the tiles. This is a substantial proportion of the volunteers and even though sight may not have been needed or used for this particular project, it definitely emphasised that vision is an important factor when shaping perceptions. Figure 7.7 shows the difference in data spread between the touch only ranking and the ranking that included sight.

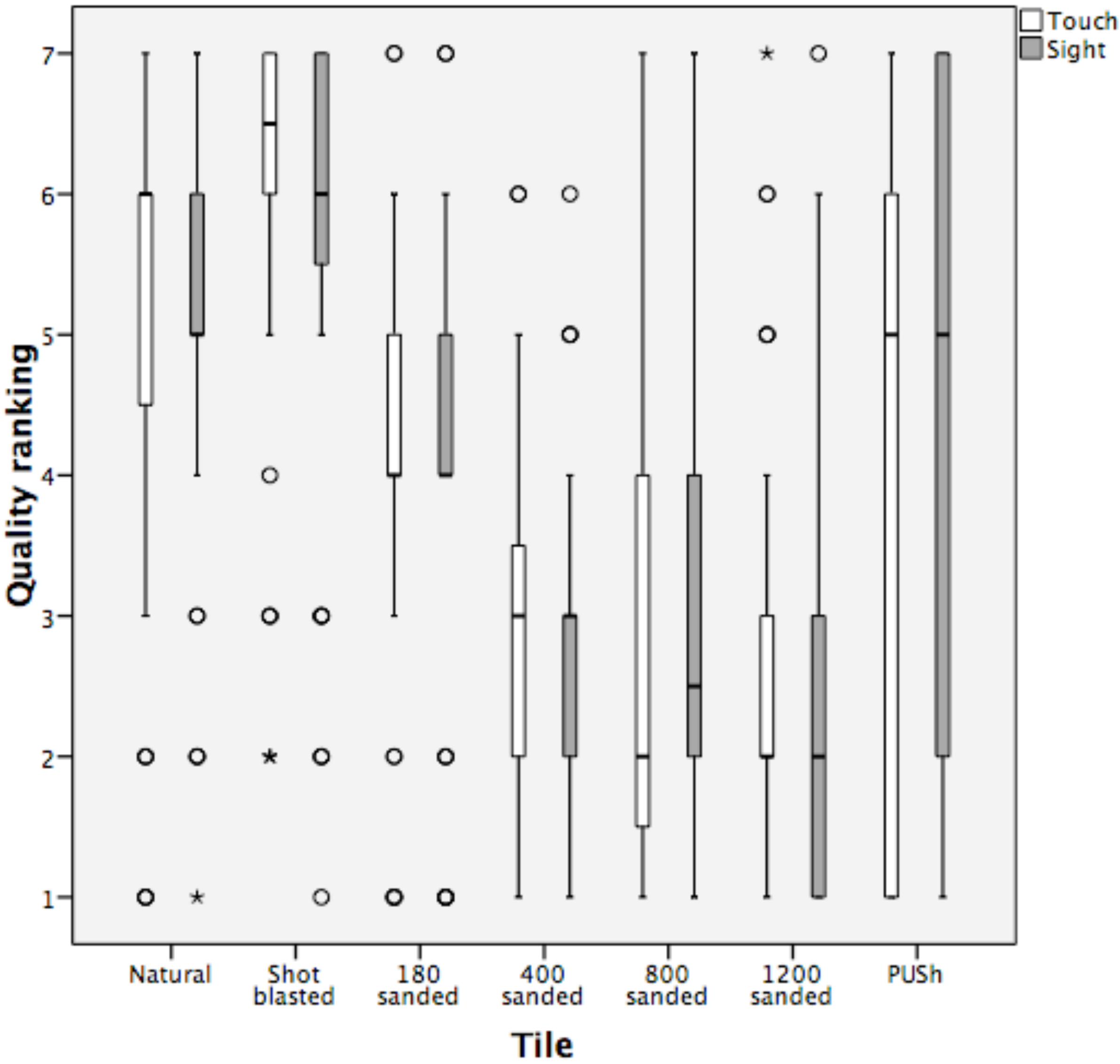


Figure 7.7 - Boxplot of the differences in data spread before and after seeing the tiles

While the boxplots do change in shape between the two instances, it is very little, suggesting that the participants who did change their rankings did not differ by much. The PUSh processed part seems to drop in perceived quality when sight was involved in the test. Out of all of the tiles, it was evident from the interview that most participants were very opinionated and divided over the quality of the PUSh tile. Their perceptions were either one extreme or the other and rarely did it fall into any middle ranking positions. This is a valid reason as to why the data is so largely spread. Figure 7.7 also supports the group theory developed earlier in this chapter where the natural and shot blasted tiles have very similar plots and the three higher sanded parts (i.e. the 800 and 1200 sanded have comparable plots).

There seemed to be more variability in the ranking results to that of the semantic differential and 2AFC tests. This could be due to the type of test used. The 2AFC and semantic differential tests did not allow the participants to compare the tiles directly altogether. At this point, they did not know how many tiles there were or their differing qualities. By giving the volunteers the chance to compare the tiles altogether, this allowed them to scrutinise each one rather than perceiving some tiles to be the same or similar. For example, the spread of data for the 800 and 1200 sanded tiles, as shown in Figure 7.7, is very different for those two tiles compared to the data in the other results. (e.g. Figure 7.2 in the 2AFC test).

Therefore, for further work, sight should be incorporated into the methodology as it does have a substantial effect on the perception of quality as stated by Klatzky in much of the work they published [101, 104].

7.5 Applying these findings to industry

The fourth objective of this project was to identify how the findings from this research can be applied to industry. Currently, it is widely believed that AM products, and in particular LS, do not have the immediate quality of surface finish that industry requires to take on this type of manufacture [7].

The findings from this project are the beginnings of a robust and usable method to better understand the perception of quality of AM parts and more importantly, what the consumer wants. The combination of AM with the affective engineering techniques outlined by Barnes, Childs and Lillford [78-82] opens a new strand of comprehension that can be further explored. This method could be utilised to not only compare AM parts individually, but also compare the perceptions AM techniques with how they would fit in alongside the rivals in the market.

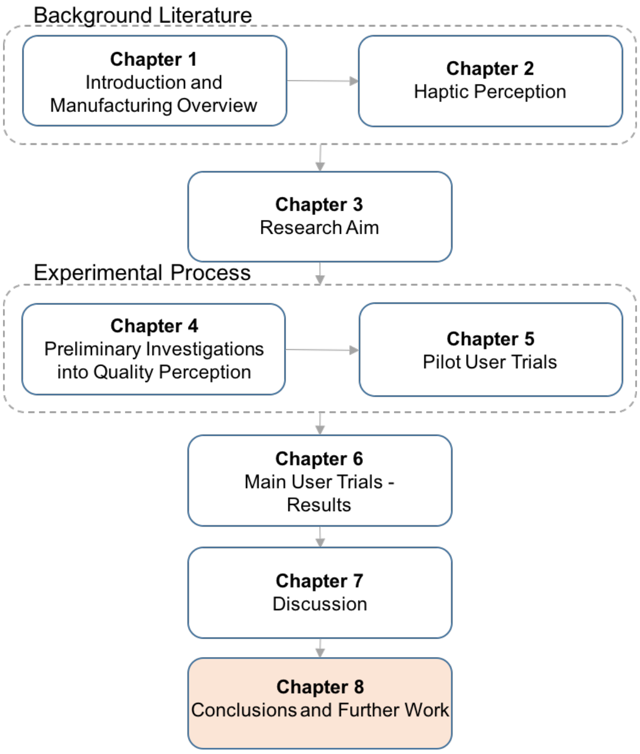
7.6 Summary

The key points of the discussion are:

- There was an increase in quality perception with decreasing roughness, but this evened out at a certain point after which no further improvement was observed.
- Most participants could tell the difference between sanded and non-sanded parts, but not between levels of sanding.
- There was a clear correlation between smoothness and quality.
- Smoothness was the main factor used by most participants when deciding on which tiles were of high quality.
- Sight has a substantial effect on the perception of quality.

Chapter 8 concludes this thesis and suggests further areas to be explored.

8 Conclusions and Further Work



8.1 Conclusions

This thesis has created a novel insight into the effect of LS surface finish on perceived quality; Section 8.1 outlines the key findings.

8.1.1 Effect on roughness on quality perception

It was identified that surface finish does affect quality perception, with a decrease in roughness leading to an increase in perceived quality. Crucially, this holds true until a certain roughness, after which, this trend appears to reverse.

In practice this means there may be benefits to companies in providing some post-processing to their manufactured products, but that beyond a certain point, the additional time and cost will not add any increase in the perceived quality of a product.

8.1.2 Focus groups identified key vocabulary describing quality

Focus groups identified key vocabulary used to describe quality and encouraged collaborative thinking of the participants, which in turn generated more varied adjectives. Several adjectives were identified to be useful when describing quality, but only certain ones had real impact. When selecting the adjectives, it was important to define which rules are key in developing scales that were not ambiguous. Developing an adapted set of rules from the literature [79, 81, 82] was imperative when creating meaningful semantic differential scales. The use of two opposites in roughness and smoothness showed consistency. The use of the "soft-hard" scale was an example of a not so impactful choice of adjective pairing, even though it is widely used in the literature for roughness and quality testing [105].

In practice, this suggests that the semantic scales should be generated for each application to ensure that the adjectives developed have an impact on the method of testing for each product.

8.1.3 Effect of sight

It was identified that sight is a considerable factor for participants to perceive quality in a product. The sense of sight was prohibited for most of the testing process to focus on the sense of touch when comparing roughness to quality. However, when vision was permitted after the tiles had been ranked in quality behind a screen, half of the participants changed their ranking on sight.

In practice, this suggests that the surface finish of LS parts is not only a perceived issue of roughness or smoothness, but that the appearance of the product should also be factored into the equation.

8.2 Further work

To build upon this research, additional work should focus on extending our understanding of quality perception further. Specific areas of investigation to be targeted are:

1. **Identification of optimum surface roughness** – One crucial finding of this work is that decreasing surface roughness does not lead to a linear increase in quality perception. Further investigations should be conducted to identify the optimum roughness to provide the highest perception of quality, particularly into other factors that may affect the perception of quality such as friction measurements of surfaces. It was not necessary to cover other aspects of quality within this work, however, it would be the next logical step in this process.
2. **Effect of interaction method** – This work focussed around a single exploratory procedure, with others identified by Lederman and Kaltzky [9, 10, 94, 97]. These other methods of interaction (e.g. gripping) should be explored in order to build a comprehensive view of the effects of roughness when related to specific actions.
3. **Effect of sight** – This thesis briefly touched upon the effect of sight, which was concluded to be a considerable factor when perceiving quality. Investigating how sight relates to quality of LS parts would be beneficial, especially for different applications.
4. **Effect of application** – Only one application (mobile phone cases) was used to investigate the perception of quality for this project. By exploring other applications, the perception of quality may differ slightly for each products' use. As Norman stated: "*No single product can hope to satisfy everyone*" [106]. This method could be adapted to many other consumer goods and packaging. This should also include comparison to injection moulded parts.

9 References

[1] V. P. Baya, "How is software advancing 3D printing?," 2014. Accessed on: 5 July 2016Available: http://usblogs.pwc.com/emerging-technology/how-is-software-advancing-3d-printing/

[2] *Additive manufacturing - General principles - Terminology*, BS ISO/ASTM 52900, 2015.

[3] N. Hopkinson, R. J. M. Hague, and P. M. Dickens, *Rapid Manufacturing: An industrial revolution for the digital age*. Chichester: Wiley, 2006.

[4] LimitState, "LimitState:FORM - Design Optimisation Software Brochure - A breakthrough in design optimisation software," 2014. Accessed on: 20 July 2016Available: http://limitstate3d.com/limitstateform/

[5] 3ders, "Italy's WASP teams with Rizzoli Institute to create breakthrough 3D printed splints and cranial implants," 2015. Accessed on: 5 July 2016Available: http://www.3ders.org/articles/20150514-wasp-teams-with-rizzoli-institute-to-create-3d-printed-splints-cranial-implants.html

[6] C. Majewski, "Additive Manufacturing Principles and Applications 1," in *Mechanical Engineering Department Module*, ed: The University of Sheffield, 2013.

[7] R. D. Goodridge, C. J. Tuck, and R. J. M. Hague, "Laser sintering of polyamides and other polymers," *Progress in Materials Science,* vol. 57, no. 2, pp. 229-267, 2// 2012.

[8] S. J. Lederman and R. L. Klatzky, "Extracting object properties through haptic exploration," *Acta Psychologica,* vol. 84, pp. 29-40, 1993.

[9] S. J. Lederman and R. L. Klatzky, "Hand movements: A window into haptic object recognition," *Cognitive Psychology,* vol. 19, no. 3, pp. 342-368, 1987.

[10] S. J. Lederman and R. L. Klatzky, "Haptic perception: A tutorial," *Attention, Perception & Psychophysics,* vol. 71, no. 7, pp. 1439-1459, 2009.

[11] J. M. Carpenter, M. Moore, and A. E. Fairhurst, "Consumer shopping value retail brands," *Journal of Fashion Marketing and Management,* vol. 9, no. 1, pp. 43-53, 2005.

[12] A. Stevenson and M. Waite, *Concise Oxford English Dictionary: Book & CD-ROM Set*, 11 ed. Oxford University Press, 2011.

[13] A. Nold, J. Zeiner, T. Assion, and R. Clasen, "Electrophoretic deposition as rapid prototyping method," *Journal of the European Ceramic Society,* vol. 30, no. 5, Mar 2010.

[14] C. K. Chua and K. F. Long, "Rapid prototyping: principles and applications," *Singapore: World Scientific,* vol. 1, 2003.

[15] I. Gibson, D. W. Rosen, and B. Stucker, *Additive Manufacturing Technologies*. London: Springer, 2010.

[16] T. Campbell, C. Williams, O. Ivanova, and B. Garrett, "Could 3D printing change the world?," in *Technologies, Potential and Implications of Additive Manufacturing*, Washington, DC, 2011: Atlantic Council.

[17] L. University, "About Additive Manufacturing - Binder Jetting," 2017. Accessed on: 15 March 2017Available: http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/binderjetting/

[18] Threeding, "Binder Jetting 3D Printing Technology," 2016. Accessed on: 15 March 2017Available: https://www.threeding.com/blog/%E2%80%8Bbinder-jetting-3d-printing-technology

[19] L. University, "Directed Energy Distribution," 2016. Accessed on: 15 March 2017Available: http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/directedenergydeposition/

[20] S. Inc., "Wire feed Additive Manufacturing vs. Powder Methods," 2017. Accessed on: 15 March 2017Available: http://www.sciaky.com/additive-manufacturing/wire-am-vs-powder-am

[21] CustomPartNet, "Fused Deposition Modelling (FDM)," 2008. Accessed on: 15 June 2016Available: http://www.custompartnet.com/wu/fused-deposition-modeling

[22] H. Li, P. Wang, L. Qi, H. Zuo, S. Zhong, and X. Hou, "3D numerical simulation of successive deposition of uniform molten Al droplets on a moving substrate and experimental validation," *Computational Materials Science,* vol. 65, pp. 291-301, 2012.

[23] J. Park, M. J. Tari, and H. T. Hahn, "Characterisation of the laminated object manufacturing (LOM) process," *Rapid Prototyping Journal,* vol. 6, no. 1, pp. 36-50, 2000.

[24] CustomPartNet, "Laminated Object Manufacturing (LOM)," 2008. Accessed on: 15 June 2016Available: http://www.custompartnet.com/wu/laminated-object-manufacturing

[25] S. H. Huang, P. Liu, A. Mokasdar, and L. Hou, "Additive manufacturing and its societal impact: a literature review," *The International Journal of Additive Manufacturing Technology,* vol. 67, no. 5-8, pp. 1198-1203, 2013.

[26] CustomPartNet, "Stereolithography," Accessed on: 15 June 2016Available: http://www.custompartnet.com/wu/stereolithography

[27] J. P. Kruth, "Material incress manufacturing by rapid prototyping techniques," *CIRP Annals-Manufacturing Technology,* vol. 40, no. 2, pp. 603-614, 1991.

[28] CustomPartNet, "Selective Laser Sintering," 2008. Accessed on: 15 June 2016Available: http://www.custompartnet.com/wu/selective-laser-sintering

[29] E. Grenda, *Printing the future*, 3 ed. Arlington, Massachusetts, US: Castle Island Co., 2009.

[30] D. Tamarjan, "9 Benefits of 3D Printing," 2012. Accessed on: 5 July 2016Available: http://augmentedtomorrow.com/9-benefits-3d-printing/

[31] 3Ders, "New Balance's 3D printed running shoes to arrive by April 2016," 2015. Accessed on: 5 July 2016Available: http://www.3ders.org/articles/20151119-new-balances-3d-printed-shoes-to-arrive-by-april-2016.html

[32] J. Flaherty, "This Dress Is Made From 3-D Printed Plastic, But Flows Like Fabric," 2014. Accessed on: 5 July 2016Available: https://www.wired.com/2014/12/dress-made-3-d-printed-plastic-flows-like-fabric/

[33] B. Butler Millsaps, "Architect Jenny Wu Builds Avante Garde Jewelry Line with Stratasys 3D Printing," 2014. Accessed on: 5 July 2016Available: https://3dprint.com/13609/jenny-wu-3d-printed-jewelry/

[34] K. Levy, "A Chinese Company 3-D Printed 10 Houses In A Day," 2014. Accessed on: 5 July 2016Available: http://www.3ders.org/articles/20151119-new-balances-3d-printed-shoes-to-arrive-by-april-2016.html

[35] 3ders, "Ford uses 3D printed parts in EcoBoost race engine, and wins 24 Hours of Daytona race," 2015. Accessed on: 5 July 2016Available: http://www.3ders.org/articles/20150530-ford-uses-3d-printed-parts-in-ecoboost-race-engine-and-wins-24-hours-of-daytona-race.html

[36] R. M. German, *Sintering Theory and Practice*. Toronto: John Wiley & Sons Inc., 1996.

[37] E. A. Olevsky, "Theory of sintering: from discrete to continuum," *Materials Science & Engineering R-Reports,* vol. 23, no. 2, Jun 30 1998.

[38] M. N. Rahaman, *Sintering of Ceramics*, 1st ed. Boca Raton: CRC Press, 2007.

[39] G. M. M. M. Lustosa, N. Jacomaci, J. P. C. Costa, G. Gasparotto, L. A. Perazolli, and M. A. Zaghete, "New Approaches to Preparation of SnO2-Based Varistors - Chemical Synthesis, Dopants, and Microwave Sintering, Advanced Ceramic Processing," in *Advanced Ceramic Processing*, A. Mohamed, Ed.: InTech, 2015.

[40] J. K. Mackenzie and R. Shuttleworth, "A Phenomenological Theory of Sintering," *Proceedings of the Physical Society,* vol. 62, no. 12, pp. 833-852, 1949.

[41] H. Tanaka, A. Yamamoto, J.-i. Shimoyama, H. Ogino, and K. Kishio, "Strongly connected ex situ MgB2 polycrystalline bulks fabricated by solid-state self-sintering," *Superconductor Science & Technology,* vol. 25, no. 11, Nov 2012, Art. no. 115022.

[42] M. M. Ristic and S. D. Milosevic, "Frenkel's Theory of Sintering," *Science of Sintering,* vol. 38, pp. 7-11, 2006.

[43] J. Frenkel, "Viscous Flow of Crystalline Bodies Under Action of Surface Tension," *Journal of Physics,* vol. 9, no. 5, pp. 385-391, 1945.

[44] S.-J. L. Kang, *Sintering: Densification, Grain Growth and Microstructure*. Oxford: Elsevier, 2005.

[45] E. e.-M. Solutions, "Additive Manufacturing, Laser-Sintering and Industrial 3D Printing - Benefits and Functional Principle," 2010. Accessed on: 15 June 2016Available: https://www.eos.info/additive_manufacturing/for_technology_interested

[46] EOS, "EOS Formiga P100 System Manual," ed. (Provided with machine): EOS, 2010.

[47] E. Bassoli, A. Gatto, and L. Luliano, "Joining mechanisms and mechanical properties of PA composites obtained by selective laser sintering," *Rapid Prototyping Journal,* vol. 18, no. 2, 2012.

[48] U. Ajoku, N. Saleh, N. Hopkinson, R. Hague, and P. Erasenthiran, "Investigating mechanical anisotropy and end-of-vector effect in laser-sintered nylon parts," *Proceedings of the Institution of Mechanical Engineers, Part B, Journal of Engineering Manufacture,* 2006.

[49] A. Ellis, R. Brown, and N. Hopkinson, "The effect of build orientation and surface modification on mechanical properties of high speed sintered parts," *Surface Topography: Metrology and Properties,* vol. 3, no. 3, p. 034005, 2015.

[50] C. Majewski and N. Hopkinson, "Effect of section thickness and build orientation on tensile properties and material characteristics of laser sintered nylon-12 parts," *Rapid Prototyping Journal,* vol. 17, no. 3, pp. 176-180, 2011.

[51] *Surface roughness and its parameters*, 1987.

[52] J. Williams, *Engineering Tribology*. Cambridge: Cambridge University Press, 2005.

[53] D. J. Whitehouse, "Surfaces - a link between manufacture and function," *Proceedings of the Institution of Mechanical Engineers,* vol. 192, no. 1, pp. 179-188, 1978.

[54] M. A. Beard, O. R. Ghita, and K. E. Evans, "Monitoring the effects of selective laser sintering (SLS) build parameters on polyamide using near infrared spectroscopy," *Journal of Applied Polymer Science,* vol. 121, no. 6, pp. 3153-3158, 2011.

[55] A. Sachdeva, S. Singh, and V. S. Sharma, "Investigating surface roughness of parts produced by SLS process," *The International Journal of Advanced Manufacturing Technology,* vol. 64, no. 9-12, pp. 1505-1516, 2013.

[56] K. Mumtaz and N. Hopkinson, "Top surface and side roughness of Inconel 625 parts processed using selective laser melting," *Rapid Prototyping Journal,* vol. 15, no. 2, pp. 96-103, 2009.

[57] J. P. Kruth, L. Froyen, J. Van Vaerenbergh, P. Mercelis, M. Rombouts, and B. Lauwers, "Selective laser melting of iron-based powder," *Journal of Materials Processing Technology,* vol. 149, no. 1, pp. 616-622, 2004.

[58] E. Yasa, J. Deckers, and J. P. Kruth, "The investigation of the influence of laser re-melting on density, surface quality and microstructure of selective laser melting parts," *Rapid Prototyping Journal,* vol. 17, no. 5, pp. 312-327, 2011.

[59] V. Petrovic, J. Vincente Haro Gonzalez, O. Jorda Ferrando, J. Delgado Gordillo, J. Ramon Blasco Puchades, and L. Portoles Grinan, "Additive layered manufacturing:

sectors of industrial application shown through case studies," *International Journal of Production Research,* vol. 49, no. 4, pp. 1061-1079, 2011.

[60] K. Shahzad, J. Deckers, J. P. Kruth, and J. Vieugels, "Additive manufacturing of alumina parts by indirect selective laser sintering and post processing," *Journal of Materials Processing Technology,* vol. 213, no. 9, pp. 1484-1494, 2013.

[61] J. Keitzmann, L. Pitt, and P. Berthon, "Disruptions, decisions and destinations: Enter the age of 3-D printing and additive manufacturing," *Business Horizons,* vol. 58, no. 2, pp. 209-215, 2015.

[62] K. I. Inc., "Barrel Tumbling Guide," 2005. Accessed on: 20 March 2017Available: http://www.kramerindustriesonline.com/finishing-guides/barrel-finishing-guide.htm

[63] M. Schmid, C. Simon, and G. N. Levy, "Finishing of SLS-Parts for Rapid Manufacture (RM) - A comprehensive approach," *Solid Freeform Fabrication Proceedings,* pp. 1-10, 2009.

[64] A. Ellis, "PUSh Process," 2014. Accessed on: 20 April 2015Available: https://www.pushprocess.technology/

[65] S. Lagrosen, "Customer involvement in new product development: A relationship marketing perspective," *European Journal of Innovation Management,* vol. 8, no. 4, pp. 424-36, 2005.

[66] W. D. Hoyer, R. Chandy, M. Dorotic, M. Krafft, and S. S. Singh, "Consumer Cocreation in New Product Development," *Journal of Service Research,* vol. 13, no. 3, pp. 283-96, 2010.

[67] Trimble. (2015, 11 March). *SketchUp: The easiest way to draw 3D*. Available: http://www.sketchup.com/

[68] D. Systèmes, "3DVIA shape: Perfect for the beginner, powerful enough for the expert," 2017. Available: http://www.3dvia.com/products/3dvia-shape/

[69] Pixologic, "Sculptris: Enter a world of digital art without barriers," 2014. Available: http://pixologic.com/sculptris/

[70] B. Sevenson, "3D print a life-size replica of yourself at Pinla3D for 2014," 2014. Accessed on: 11 March 2017Available: http://3dprint.com/1435/3d-print-a-life-size-replica-of-yourself-at-pinla3d-for-28500/

[71] C. Kopf, C. Heindl, M. Rooker, H. Bauer, and A. Pichler, "A portable, low-cost 3D body scanning system," *3D Body Scanning Technologies,* pp. 417-425, 2013.

[72] D. P. Industry, "The free beginner's guide to 3D printing," 2014. Accessed on: 11 March 2017Available: http://3dprintingindustry.com/wp-Available: content/uploads/2014/07/3D-Printing-Guide.pdf

[73] E. Malone and H. Lipson, "Fab@Home: the personal desktop fabricator kit," *Rapid Prototyping Journal,* vol. 4, no. May, pp. 245-255, 2007.

[74] W. Inc., "3Doodler," 2015. Accessed on: 21 July 2016Available: http://the3doodler.com/

[75] R. D. Goodridge, C. J. Tuck, and R. J. M. Hague, "Laser sintering of polyamides and other polymers," *Progress in Materials Science,* vol. 57, pp. 229-267, 2011.

[76] Y. e. a. Ariadi, "Combining additive manufacturing with computer aided consumer design," *Proceedings of the solid freeform fabrication symposium,* pp. 238-249, 2012.

[77] Y. Ariadi, *Facilitating consumer involvement in design for additive manufacturing/3D printing products* (PhD Thesis). Loughborough University, 2016.

[78] C. J. Barnes, T. H. C. Childs, B. Henson, and C. H. Southee, "Surface finish and touch - a case study in a new human factors tribology," *Wear,* vol. 257, no. 7-8, Oct 2004.

[79] J. Delin, S. Sharoff, S. Lillford, and C. Barnes, "Linguistic support for concept selection decisions," *AI EDAM: Artificial Intelligence for Engineering Design, Analysis and Manufacturing,* vol. 21, no. 2, pp. 123-135, 2007.

[80] C. J. Barnes and S. P. Lillford, "Affective design decision making - issues and opportunities," *CoDesign,* vol. 3, no. S1, pp. 135-146, 2007.

[81] C. Barnes, T. Childs, B. Henson, and S. Lillford, "Kansei engineering toolkit for the packaging industry," *The TMQ Journal,* vol. 20, no. 4, pp. 372-388, 2008.

[82] C. Barnes and S. P. Lillford, "Decision support for the design of affective products," *Journal of Engineering Design,* vol. 20, no. 5, pp. 477-492, 2009.

[83] V. G. Chouvardas, A. N. Miliou, and M. K. Hatalis, "Tactile displays: Overview and recent advances," *Displays,* vol. 29, no. 3, pp. 185-194, Jul 2008.

[84] W. Penfield and E. Boldrey, "Somatic motor and sensory representation in the cerebral cortex of man as studied by electrical stimulation," *Brain,* vol. 60, pp. 389-443, 1937.

[85] G. D. Schott, "Penfield's homunculus: a note on cerebral cartography," *Journal of neurology, neurosurgery and psychiatry,* vol. 56, no. 4, p. 329, 1993.

[86] S. M. Breedlove, N. V. Watson, and M. R. Rosenzweig, *Biological Psychology: An Introduction to Behavioural, Cognitive and Clinical Neuroscience*, 6th ed. Sinauer Associates, 2010.

[87] E. P. Gardner, "Touch," in *Encyclopaedia of Life Sciences (ELS)*, ed. Chichester: John Wiley & Sons, Ltd, 2010.

[88] J. M. Wolfe *et al.*, *Sensation and Perception*, 3rd ed. Sinauer Associates, 2012.

[89] D. Katz and L. E. T. Krueger, *The World of Touch*. Hillsdale, New Jersey: Lawrence Erlbaum Associates, 1989.

[90] K. O. Johnson and S. S. Hsiao, "Evaluation of the relative roles of slowly and rapidly adapting afferent-fibres in toughness perception," *Canadian Journal of Physiology and Pharmacology,* vol. 72, pp. 488-497, 1994.

[91] J. N. Napier, "The prehensile movements of the human hand," *Journal of Bone and Joint Surgery - British Volume,* vol. 38, pp. 902-913, 1956.

[92] R. L. Klatzky, S. J. Lederman, and C. Reed, "There;s more to touch than meets the eye: The salience of object attributes for haptic with and without vision," *Journal of Experimental Psychology: General,* vol. 116, no. 4, p. 356, 1987.

[93] R. L. Klatzky and S. J. Lederman, "Haptic object perception: spatial dimensionality and relation to vision," *Philosophical Transactions of the Royal Society B: Biological Sciences,* vol. 366, no. 1581, pp. 3097-3105, 2011.

[94] R. L. Klatzky, S. J. Lederman, and V. A. Metzger, "Identifying objects by touch: An "expert system"," *Perception & Psychophysics,* vol. 37, no. 4, pp. 299-302, 1985.

[95] R. L. Klatzky and S. J. Lederman, "Tactile roughness perception with a rigid link interposed between skin and surface," *Perception & Psychophysics,* vol. 61, no. 4, pp. 591-607, 1999.

[96] R. L. Klatzky, S. J. Lederman, and C. Reed, "Haptic integration of object properties: texture, hardness, and planar contour," *Journal of Experimental Psychology: Human Perception and Performance,* vol. 15, no. 1, p. 45, 1989.

[97] S. J. Lederman and R. L. Klatzky, "Haptic classification of common objects: Knowledge-driven exploration," *Cognitive Psychology,* vol. 22, no. 4, pp. 421-459, 1990.

[98] K. B. Duvefelt, U. L. Olofsson, and C. M. J. Johannesson, "Towards simultaneous measurements of skin friction and contact area: Results and experiences," in *Part J: Journal of Engineering Tribology*, 2014.

[99] S. E. Tomlinson, R. Lewis, M. J. Carre, and S. E. Franklin, "Human finger friction in contacts with ridged surfaces " *Wear,* no. 301, pp. 330-337, 2013.

[100] H. Nagano, S. Okamoto, and Y. Yamada, "Visual and sensory properties of textures that appeal to human touch," *International Journal of Affective Engineering,* vol. 12, no. 3, pp. 375-384, 2013.

[101] R. L. Klatzky and J. Peck, "Please touch: Object properties that invite touch," *IEEE Transactions on Haptics,* vol. 5, no. 2, pp. 139-147, 2012.

[102] A. Klöcker, C. Arnould, M. Penta, and J. L. Thonnard, "Rasch-built measure of pleasant touch through active fingertip explorations," *Frontiers in Neurorobotics,* vol. 6, no. 5, 2012.

[103] L. Skedung *et al.*, "Tactile perception: finger friction, surface roughness and perceived coarseness," *Tribology International,* vol. 44, no. 5, pp. 505-512, 2011.

[104] S. J. Lederman, G. Thorne, and B. Jones, "Perception of texture by vision and touch: multidimensionality and intersensory integration," *Journal of Experimental Psychology: Human Perception and Performance,* vol. 12, no. 2, p. 169, 1986.

[105] X. Chen, F. Shao, C. Barnes, T. Childs, and B. Henson, "Exploring relationships between touch perception and surface physical properties," *International Journal of Design,* vol. 3, no. 2, pp. 67-76, 2009.

[106] D. A. Norman, *Emotional design: Why we love (or hate) everyday things*. New York: Basic Books, 2005.

[107] M. Nagamachi, "Kansei engineering: a new ergonomic consumer-oriented technology for product development," *International Journal of Industrial Ergonomics,* vol. 15, no. 1, pp. 3-11, 1995.

[108] J. J. Dahlgaard, S. Schütte, E. Ayas, and S. Mi Dahlgaard-Park, "Kansei/Affective Engineering Design: A methodology for profound affection and attractive quality creation," *The TQM Journal,* vol. 20, no. 4, pp. 299-311, 2008.

[109] W. G. f. C. H. a. Development. (2016, 5 October). *Qualitative Methods to Assess Community Issues*. Available: http://ctb.ku.edu/en/table-of-

contents/assessment/assessing-community-needs-and-resources/qualitative-methods/main

[110] J. Ritchie, J. Lewis, C. M. Nicholls, and R. Ormston, *Qualitative research practice: A guide for social science students and researchers*. London: Sage Publications Ltd., 2013.

[111] R. A. Krueger and M. A. Casey, *Focus groups: a practical guide for applied research*, 4th ed. London: SAGE Publications, 2009.

[112] R. A. Krueger and M. A. Casey, "Designing and conducting focus group interviews," *Social Analysis, Selected Tools and Techniques,* pp. 4-23, 2002.

[113] R. A. Krueger and M. A. Casey, "Focus group interviewing," in *Handbook of practical program evaluation*3rd ed. San Francisco: Jossey-Boss, 2010, pp. 378-403.

[114] T. Freeman, ""Best practice" in focus group research: making sense of different views," *Journal of Advanced Nursing,* vol. 56, no. 5, pp. 491-497, 2006.

[115] R. A. Powell and H. M. Single, "Focus groups," *International Journal for Quality in Health Care,* vol. 8, no. 5, pp. 499-504, 1996.

[116] J. Kitzinger, "The methodology of focus groups - the importance of interaction between research participants," *Sociology of Health & Illness,* vol. 16, pp. 103-121, 1994.

[117] J. Kitzinger, "Qualitative research. Introducing focus groups," *BMJ: British Medical Journal,* vol. 311, no. 7000, p. 299, 1995.

[118] N. Grudens-Schuck, B. L. Allen, and K. Larson, "Methodology Brief: Focus Group Fundamentals," *Extension Community and Economic Development Publications,* vol. 12, no. 1, 2004.

[119] S. N. Young and M. Leyton, "The role of serotonin in human mood and social interaction: insight from altered tryptophan levels," *Pharmacology Biochemistry and Behavior,* vol. 71, no. 4, pp. 857-865, 2002.

[120] R. Bogacz, E. Brown, J. Moehlis, P. Holmes, and J. D. Cohen, "The physics of optimal decision making: a formal analysis of models of performance in two-alternative forced-choice tasks," *Psychological Review,* vol. 113, no. 4, p. 700, 2006.

[121] J. Jou, S. Flores, H. M. Cortes, and B. G. Leka, "The effects of weak versus strong relational judgements on response bias in Two-Alternative-Forced-Choice recognition: is the test criterion-free?," *Acta Psychologica,* vol. 167, pp. 30-44, 2016.

[122] L. Ashendorf and M. A. Sugarman, "Evaluation of performance validity using a Rey Auditory Verbal Learning Test forced-choice trial," *The Clinical Neuropsychologist,* pp. 1-11, 2016.

[123] C. E. Osgood and Z. Luria, "A blind analysis of a case of multiple personality using the semantic differential," *The Journal of Abnormal and Social Psychology,* vol. 49, no. 1, part 1, p. 579, 1954.

[124] B. Henson, C. Barnes, R. Livesey, T. Childs, and K. Ewart, "Affective consumer requirements: A case study of moisturizer packaging," *Concurrent Engineering,* vol. 14, no. 3, pp. 187-196, 2006.

[125] R. D. Goodridge, C. J. Tuck, and R. J. M. Hague, "Laser sintering of polyamides and other polymers," *Progress in Materials Science,* vol. 57, no. 2, Feb 2012.

[126] N. Padhye and K. Deb, "Multi-objective optimisation and multi-criteria decision making in SLS using evolutionary approaches," *Rapid Prototyping Journal,* vol. 17, no. 6, pp. 458-478, 2011.

[127] Mitutoyo, *Surftest SJ-400 System Manual: Mitutoyo*. (Provided with machine): Mitutoyo, 1985.

[128] R. Mazza and A. Berre, "Focus group methodology for evaluating information visualization techniques and tools," presented at the 11th International Conference, Information Visualization, 2007.

[129] A. Bruseberg and D. McDonagh-Philp, "Focus groups to support the industrial/product designer: a review based on current literature and designers' feedback," *Applied Ergonomics,* vol. 33, no. 1, pp. 27-38, 2002.

[130] J. M. Carpenter, M. Moore, and A. E. Fairhurst, "Consumer shopping value for retail brands," *Journal of fashion marketing and management: an international journal,* vol. 9, no. 1, pp. 43-53, 2005.

[131] L. Skedung, M. Arvidsson, J. Y. Chung, C. M. Stafford, B. Berglund, and R. M. W., "Feeling small: exploring the tactile perception limits," *Scientific Reports,* vol. 3, p. 2617, 2013.

[132] A. Ellis. (2014, December). *PUSh Process*. Available: http://www.pushprocess.technology/

[133] X. Chen, C. J. Barnes, T. H. C. Childs, B. Henson, and F. Shao, "Materials' tactile testing and characterisation for consumer products' affective packaging design," *Materials & Design,* vol. 30, no. 10, pp. 4299-4310, 2009.

[134] E. Marshall, "Getting started with SPSS," 2015. Accessed on: 12 August 2015Available: http://www.sheffield.ac.uk/mash/workshops

[135] E. Marshall, "Choosing the right test and recap of hypothesis tests," 2015. Accessed on: 12 August 2015Available: http://www.sheffield.ac.uk/mash/workshops

[136] J. Cohen, "A Power Primer," *Psychological Bulletin,* vol. 112, no. 1, p. 155, 1992.

[137] E. Marshall, "Introduction to hypothesis testing," 2015. Accessed on: 14 August 2015Available: http://www.sheffield.ac.uk/mash/workshops

[138] R. A. Fisher, *Statistical methods for research workers*, 11th ed. Edinburgh: Oliver and Boyd, 1950.

10 Appendices

10.1 Appendix A

Eithics letter of approval for this thesis.

The University Of Sheffield.

Department Of Mechanical Engineering.

- APPLICATION IS UNCONDITIONALLY APPROVED -

****

5 March 2014

Mr Charis Lestrange

Mechanical Engineering

Dear Mr Lestrange,

PROJECT TITLE: Quality Perception of Laser Sintered Parts

On behalf of the Project supervisor who reviewed your project, I am pleased to inform you that on 5 March 2014 the above-named project was unconditionally approved on ethics grounds as a low risk project, on the basis that you will adhere to the following document that you submitted for ethics review:

- University research ethics application form (4/03/2014)
- Information Sheet (4/03/2014)
- Participant consent form (4/03/2014)

If during the course of the project you need to deviate significantly from the above-approved document please inform me since written approval will be required. Please also inform me should you decide to terminate the project prematurely.

Yours sincerely

Mrs Galina Balikhin
Ethics Administrator

The Queen's Anniversary Prizes
1998 2000 2002

10.2 Appendix B

Virgin powder profilometry data

Part	Top (um)								Bottom (um)							
	Ra1	Ra2	Ra3	Ra avg	Rz1	Rz2	Rz3	Rz avg	Ra1	Ra2	Ra3	Ra avg	Rz1	Rz2	Rz3	Rz avg
0 C 1	10.042	9.99	10.428	10.1533333	68.396	71.604	75.808	71.936	12.615	11.989	11.891	12.165	86.06	82.29	85.651	84.667
0 C 2	12.135	11.622	11.821	11.8593333	83.6	71	77.217	77.2723333	13.051	11.532	12.207	12.2633333	92.69	76.089	86.683	85.154
0 C 3	11.555	11.391	10.39	11.112	76.141	79.768	74.902	76.937	11.555	13.311	12.173	12.3463333	85.481	87.072	86.395	86.316
0 E 1	12.262	11.474	11.992	11.9093333	84.077	73.592	83.689	80.4526667	12.825	13.283	12.146	12.7513333	85.468	86.874	87.494	86.612
0 E 2	11.025	11.088	9.78	10.631	78.643	76.661	74.917	76.7403333	11.276	12.305	12.481	12.0206667	80.189	91.155	84.208	85.184
0 E 3	12.086	11.474	11.357	11.639	82.79	77.187	81.179	80.3853333	12.562	14.164	13.414	13.38	86.536	104.766	89.671	93.6576667
45 C 1	14.371	17.005	16.487	15.9543333	101.87	109.587	102.415	104.624	14.049	13.253	12.457	13.253	97.822	90.768	87.79	92.1266667
45 C 2	13.611	14.34	17.694	15.215	95.011	99.469	111.721	102.067	13.555	13.278	13.846	13.5596667	84.753	88.127	87.924	86.9346667
45 C 3	15.475	14.842	15.868	15.395	110.617	107.1	115.899	111.205333	14.237	13.417	12.965	13.5396667	93.22	90.344	81.045	88.203
45 E 1	17.266	18.675	15.777	17.2393333	114.835	118.617	106.68	113.377333	11.586	11.933	11.673	11.7306667	85.579	79.466	84.791	83.2786667
45 E 2	15.281	16.243	17.221	16.2483333	103.371	109.719	100.673	104.587667	12.613	13.258	14.164	13.345	94.334	94.408	96.157	94.9663333
45 E 3	19.404	19.428	19.544	19.4586667	138.431	126.125	118.416	127.657333	12.263	12.598	12.879	12.58	83.96	83.115	89.659	85.578
90 C 1	12.435	12.638	11.384	12.1523333	86.379	92.648	87.429	88.8186667	10.988	12.521	12.182	11.897	81.644	80.121	82.236	81.3336667
90 C 2	12.303	12.091	13.161	12.5183333	92.815	85.434	93.677	90.642	11.801	11.708	12.408	11.9723333	82.139	82.035	88.916	84.3633333
90 C 3	13.762	12.601	12.525	12.9626667	85.836	88.986	87.723	87.515	11.474	12.522	12.502	12.166	81.154	84.941	84.726	83.607
90 E 1	12.805	11.729	12.311	12.2816667	93.001	80.189	75.507	82.899	12.567	12.217	12.17	12.318	89.725	96.61	88.913	91.7493333
90 E 2	12.541	12.336	12.138	12.3383333	90.027	87.392	92.1	89.8396667	12.943	12.38	12.268	12.5303333	88.775	86.246	86.609	87.21
90 E 3	11.621	13.891	13.369	12.9603333	90.424	97.405	95.218	94.349	12.704	12.99	13.644	13.1126667	89.623	93.155	103.992	95.59
			Ra Total	13.4460185			Rz Total	92.2947593			Ra Total	12.6072778			Rz Total	87.5850741

50-50 powder profilometry data

Part	Top (um)								Bottom (um)							
	Ra1	Ra2	Ra3	Ra avg	Rz1	Rz2	Rz3	Rz avg	Ra1	Ra2	Ra3	Ra avg	Rz1	Rz2	Rz3	Rz avg
0 C 1	12.076	12.985	12.063	12.3746667	78.468	89.86	82.314	83.5473333	11.107	11.447	11.103	11.219	79.215	80.867	77.702	79.2613333
0 C 2	13.942	13.695	14.884	14.1736667	88.415	97.593	86.11	90.706	10.546	10.751	10.913	10.7366667	83.048	73.722	78.776	78.5153333
0 C 3	13.315	13.258	13.511	13.3613333	91.15	88.25	98.087	92.4956667	11.723	10.177	11.108	11.0026667	77.228	84.753	79.557	80.5126667
0 E 1	12.953	13.415	12.76	13.0426667	94.282	90.344	92.654	92.4266667	11.172	11.736	11.362	11.4233333	71.769	82.226	83.565	79.1866667
0 E 2	12.405	11.145	11.734	11.7613333	86.546	71.727	81.049	79.774	12.789	13.235	12.895	12.973	94.353	90.428	83.59	89.457
0 E 3	13.765	13.116	12.871	13.2506667	93.072	88.008	87.631	89.5703333	10.279	11.661	11.622	11.1873333	70.889	83.886	87.215	80.6633333
45 C 1	16.998	18.157	17.171	17.442	102.471	105.987	110.565	106.341	13.977	11.08	13.053	12.7033333	90.184	74.658	87.907	84.2496667
45 C 2	15.634	18.086	18.694	17.4713333	95.07	109.739	131.848	112.219	12.947	12.561	13.006	12.838	86.597	89.406	89.501	88.5013333
45 C 3	16.268	15.765	16.653	16.2286667	101.139	104.951	120.131	108.740333	12.611	12.452	14.081	13.048	86.984	80.725	100.656	89.455
45 E 1	16.577	16.633	15.034	16.0813333	108.499	113.326	95.748	105.857667	11.655	11.787	12.321	11.921	79.395	82.4	84.867	82.2206667
45 E 2	16.787	15.788	16.34	16.305	116.712	105.994	104.54	109.082	12.871	10.888	11.946	11.9016667	89.066	82.715	83.911	85.2306667
45 E 3	21.545	19.466	20.193	20.4013333	133.834	120.78	124.677	126.430333	13.426	13.709	13.381	13.5053333	96.578	96.125	97.202	96.635
90 C 1	12.698	11.781	13.031	12.5033333	84.7	85.052	93.892	87.8813333	13.584	14.109	12.008	13.2336667	85.161	93.191	82.514	86.9553333
90 C 2	12.605	14.689	12.184	13.1593333	90.331	101.69	93.068	95.0296667	14.244	11.765	15.525	13.8446667	94.736	77.112	99.569	90.4723333
90 C 3	13.334	12.252	12.227	12.6043333	89.953	95.962	88.503	91.4726667	13.952	13.545	14.582	14.0263333	95.529	96.061	101	97.53
90 E 1	13.02	13.032	13.019	13.0236667	82.138	95.058	96.435	91.2103333	14.354	11.57	13.902	13.2753333	102.219	78.944	105.333	95.4986667
90 E 2	15.008	13.382	13.143	13.8443333	104.392	91.506	88.453	94.7836667	14.193	12.245	12.707	13.0483333	101.826	86.436	89.805	92.689
90 E 3	12.981	12.557	13.014	12.8506667	89.369	88.286	92.387	90.014	13.736	11.573	12.905	12.738	96.259	76.852	85.364	86.1583333
			Ra Total	**14.4377593**			**Rz Total**	**97.0878889**			**Ra Total**	**12.4792037**			**Rz Total**	**86.8440185**

Used powder profilometry data

Part	Top (µm)								Bottom (um)							
	Ra1	Ra2	Ra3	Ra avg	Rz1	Rz2	Rz3	Rz avg	Ra1	Ra2	Ra3	Ra avg	Rz1	Rz2	Rz3	Rz avg
0 C 1	15.216	14.753	16.07	15.3463333	96.343	96.459	106.974	99.9253333	13.875	13.199	12.44	13.1713333	92.309	86.719	79.67	86.2326667
0 C 2	13.224	14.011	13.129	13.4546667	90.629	87.832	87.678	88.713	10.539	12.554	12.031	11.708	80.317	79.173	81.407	80.299
0 C 3	15.067	14.324	13.58	14.3236667	100.269	92.408	81.722	91.4663333	12.564	11.691	10.424	11.5596667	85.818	77.288	76.587	79.8976667
0 E 1	15.063	14.041	14.404	14.5026667	97.352	97.542	98.891	97.9283333	10.861	12.413	12.641	11.9716667	80.462	89.132	84.62	84.738
0 E 2	16.28	15.079	17.405	16.2546667	104.483	98.66	124.189	109.110667	13.084	13.425	11.875	12.7946667	92.617	99.028	81.25	90.965
0 E 3	13.716	13.733	14.139	13.8626667	97.351	86.69	100.801	94.9473333	11.379	12.724	11.948	12.017	78.673	85.481	83.652	82.602
45 C 1	15.643	14.728	17.584	15.985	100.044	104.393	116.035	106.824	14.281	12.204	13.69	13.3916667	103.573	94.969	99.585	99.3756667
45 C 2	13.595	14.656	15.369	14.54	97.981	87.422	97.51	94.3043333	12.191	12.652	13.645	12.8293333	91.055	83.578	95.571	90.068
45 C 3	14.436	12.603	14.789	13.9426667	107.013	93.123	100.095	100.077	13.93	13.157	12.676	13.2543333	98.244	93.546	97.982	96.5906667
45 E 1	17.023	17.825	16.767	17.205	114.919	112.264	114.725	113.969333	13.285	13.762	12.682	13.243	90.615	88.062	91.062	89.913
45 E 2	12.933	13.54	14.109	13.5273333	94.104	93.365	95.079	94.1826667	12.929	12.301	13.508	12.9126667	86.822	94.022	101.977	94.2736667
45 E 3	14.294	16.054	14.954	15.1006667	97.093	97.586	102.573	99.084	11.875	12.376	14.507	12.9193333	87.457	83.983	108.272	93.2373333
90 C 1	14.528	16.017	15.507	15.3506667	96.06	110.728	109.766	105.518	14.572	14.075	14.718	14.455	102.452	97.939	99.878	100.089667
90 C 2	14.525	13.592	14.104	14.0736667	94.234	93.045	85.439	90.906	13.486	12.057	13.753	13.0986667	86.881	86.544	89.288	87.571
90 C 3	15.562	13.301	15.247	14.7033333	101.079	101.417	97.394	99.9633333	13.312	12.376	15.486	13.7246667	88.025	89.984	103.495	93.8346667
90 E 1	14.666	16.241	12.704	14.537	101.326	98.478	91.754	97.186	12.401	13.597	19.122	15.04	86.729	93.136	113.045	97.6366667
90 E 2	14.997	14.935	14.85	14.9273333	98.465	91.802	97.399	95.8886667	13.781	11.279	13.51	12.8566667	87.155	78.983	92.112	86.0833333
90 E 3	13.483	13.854	15.033	14.1233333	96.797	91.634	108.386	98.939	13.596	12.014	12.756	12.7886667	91.024	85.691	91.055	89.2566667
			Ra Total	**14.7644815**			**Rz Total**	**98.8296296**			**Ra Total**	**12.9853519**			**Rz Total**	**90.148037**

10.3 Appendix C

These are the documents used by the facilitator and participants in the trial testing.

Facilitator Notes

These notes are designed to help plan and guide the facilitator through the draft protocol smoothly and to ensure that the conversation does not steer too far from the desired topic.

Aim of the draft protocol

To test the methodology for the semantic differential and two alternative forced choice experiments.

Key points to be covered:

- Two alternative forced choice method
- Semantic differential method
- Participants' opinions

Location

The location should be somewhere free from distractions – therefore it is strongly advised to book a separate room in advance e.g. IPO rooms, LT15, IC group rooms, etc.

Once the room is booked, it can then be set up for testing. A few things to remember:

- The room should have a table and chairs for the participants to carry out the testing.
- The test plates must be labelled and ideally in correct order to save time.
- It may be useful to find a power source before the testing begins (for laptop).

Before Draft Protocol

- Make sure that the participants have signed the ethics form detailing that they can leave at any time and that their participation will be anonymised.
- Ensure that the samples are correctly labelled according to their post processing technique.
- Ensure that the plates are randomised before testing commences.

Two alternative forced choice method

This method includes giving the participants two samples at a time, behind a curtain so the parts are not seen; and asking them to choose which one they prefer. The question will be:

"Choose which plate feels higher in quality?"

Before the test, the plates will be randomised to the order in which the samples will be given to each participant. This is to establish an order of preference and also to see how long the participants can partake in the testing. (Plates will be tested three times – participant will give opinions at the end)

There are 45 pairings to go through the whole selection three times. They will be in this order:

2 5	4 6	5 6
2 6	2 6	3 4
1 2	1 2	2 6
3 5	2 3	4 5
2 3	1 5	1 5
5 6	1 6	4 6
4 6	3 6	1 6
3 4	3 5	2 3
3 6	2 4	1 4
1 6	3 4	1 3
1 3	5 6	2 4
2 4	2 5	2 5
1 5	4 5	1 2
1 4	1 3	3 5
4 5	1 4	3 6

Semantic Differential Testing

This method includes giving the participant a plate, again behind a curtain/screen, and then asking them to rank the part on a pre-written semantic scale sheet. There will be 6 parts to test in this section. The parts have been randomised in this order: 1, 6, 5, 2, 4, 3

Unstructured interview

The unstructured interview will end the draft protocol. This is where the participant is asked to give their opinions on the experiment and this part will be recorded.

The question to be asked is:

"How did you find this testing session, and what are you opinions of it?"

Make sure the language is not led. If the participant does not seem to respond, then talk about drawbacks and improvements.

Post Draft Protocol

Once the draft protocol has finished, it is important to check a few things before you forget:

- Spot check the recording to see if it worked
- Note any themes, hunches, interpretations and ideas
- Clean up any mess left over

Then the recording can be transcribed.

This was the participant questionnaire for the trial test

Testing Questionnaire

Section A

Please answer the following questions about yourself:

What is your gender?

- ☐ Male
- ☐ Female
- ☐ Other
- ☐ Prefer not to say

What is your age?

- ☐ Under 18
- ☐ 18-22
- ☐ 23-29
- ☐ 30-36
- ☐ 37+

Section B

You will now be asked to choose between two parts at a time in a two alternative forced choice experiment, led by the facilitator.

PTO

Section C

Please rate the feel of each part on the semantic scales below:

Part __________________

Rough	1	2	3	4	5	6	7	Not Rough
Soft	1	2	3	4	5	6	7	Hard
Warm	1	2	3	4	5	6	7	Cool
Not Smooth	1	2	3	4	5	6	7	Smooth
High Quality	1	2	3	4	5	6	7	Low Quality
Furry	1	2	3	4	5	6	7	Not Furry

Any further comments:

PTO

Part __________________

Rough	1	2	3	4	5	6	7	Not Rough
Soft	1	2	3	4	5	6	7	Hard
Warm	1	2	3	4	5	6	7	Cool
Not Smooth	1	2	3	4	5	6	7	Smooth
High Quality	1	2	3	4	5	6	7	Low Quality
Furry	1	2	3	4	5	6	7	Not Furry

Any further comments:

PTO

Part ________________

Rough	1	2	3	4	5	6	7	Not Rough
Soft	1	2	3	4	5	6	7	Hard
Warm	1	2	3	4	5	6	7	Cool
Not Smooth	1	2	3	4	5	6	7	Smooth
High Quality	1	2	3	4	5	6	7	Low Quality
Furry	1	2	3	4	5	6	7	Not Furry

Any further comments:

PTO

Part ___________________

Rough	1	2	3	4	5	6	7	Not Rough
Soft	1	2	3	4	5	6	7	Hard
Warm	1	2	3	4	5	6	7	Cool
Not Smooth	1	2	3	4	5	6	7	Smooth
High Quality	1	2	3	4	5	6	7	Low Quality
Furry	1	2	3	4	5	6	7	Not Furry

Any further comments:

PTO

Part ___________________

Rough	1	2	3	4	5	6	7	Not Rough
Soft	1	2	3	4	5	6	7	Hard
Warm	1	2	3	4	5	6	7	Cool
Not Smooth	1	2	3	4	5	6	7	Smooth
High Quality	1	2	3	4	5	6	7	Low Quality
Furry	1	2	3	4	5	6	7	Not Furry

Any further comments:

PTO

Part ___________________

Rough	1	2	3	4	5	6	7	Not Rough
Soft	1	2	3	4	5	6	7	Hard
Warm	1	2	3	4	5	6	7	Cool
Not Smooth	1	2	3	4	5	6	7	Smooth
High Quality	1	2	3	4	5	6	7	Low Quality
Furry	1	2	3	4	5	6	7	Not Furry

Any further comments:

This is the end of section C.

PTO

Section D

You will now be guided through an unstructured interview by the facilitator. Please review the experimental process and feel free to give honest opinions.

10.4 Appendix D

These are the final documents used in the main experiment by both the facilitator and the participants.

Main Experiment Agenda

Introduction

"The point of this study is to gather your opinions and views about the quality of different surfaces."

Hand participant the information sheet and consent form.

"Please read through the information sheet and consent form carefully. If you are happy with them, please feel free to sign."

Take information sheet and consent form back.
Give participant questionnaire booklet.

"Here is the questionnaire booklet that will be used for this experimental process. Please let me know once you have completed section A."

Section A

Questions to be answered in the testing booklet by the participant.

Section B

Two alternative forced choice method. Parts are not seen.

"Imagine the parts you are about to explore are made from a new material for a mobile phone case. In each instance, I would like you to choose which plate feels higher in quality."

"Do you have any questions before we start?"

Order of plates:

7 5		2 5		1 6	
4 1		3 6		3 4	
6 5		3 2		7 1	
7 2		6 5		1 3	
6 3		5 4		3 2	
5 1		2 4		1 4	
4 2		5 1		6 4	
1 2		5 7		2 5	
3 1		2 6		7 4	
3 7		7 4		5 4	
2 5		3 1		2 7	
7 6		3 4		1 2	
7 1		2 7		6 7	
3 4		6 4		5 3	
2 3		7 6		5 6	
4 7		7 3		6 2	
6 1		3 5		3 6	
5 3		2 1		4 2	
5 4		7 1		1 5	
6 2		4 1		5 7	
4 6		6 1		3 7	

Section C

Semantic differential method. Parts are not seen.

"This section is a semantic differential experiment. You will be given one part at a time to study behind a screen and I would like you to rate each plate on the scales in your questionnaire booklet. Please imagine these as the new material for a mobile phone case again."

"You are not allowed to go back and compare the parts, but you may compare the scores you give."

"Do you have any questions?"

Order of plates: 5, 3, 6, 1, 4, 2, 7.

Give the plates back to the participant.

"I would now like you to rank the plates in order of quality behind the screen. Please indicate which are the highest and lowest quality in your opinion."

Note down order.

Section D

Interview. Record using two devices for transcription.

"For the final part of this testing process, I would like to interview you about your opinions. This will be recorded. Just to check that you are still ok with this?"

If ok, turn recording devices on.

These questions are prompters. Skip if the participant answers them by themselves.

"In section B, the section where you were given two parts at a time and had to choose which part was higher in quality, did you find that you were favouring certain parts each time?"

"What was the main factor you used when deciding which was highest in quality?"

Give participant the plates to explore with sight in the order they ranked them in earlier.

"These are the plates that were used today and this is the order of preference that you ranked the parts in in section C. Does seeing the plates now change your opinion?"

"Do you own a case for your own mobile phone? What do you look for when buying it?"

"Would you be tempted to buy a phone case with any of these finishes? Why?"

This is the questionnaire document that was given to the participants in the main experimentation.

Testing Questionnaire

What to expect:

This testing procedure is in place to gather your opinions and views about the *quality* of different surfaces.

There are four sections to this experimental process:

1. **Section A** contains simple, multiple-choice questions for you to answer about yourself.
2. In **Section B**, you will be asked to compare two parts at a time, placed behind a screen using what is called the “Two alternative forced-choice method”. For each pairing you are given, you must choose which part feels the highest in quality.
3. In **Section C**, you will be given each part separately, still behind a screen, to then rank on a scale against different descriptive words.
4. **Section D** will be an interview to talk to you about your experiences and opinions of the parts you have been analysing. Please feel free to give all opinions, the good and the bad.

Please keep the parts on the table and do not pick them up.

You do not need to wash your hands, as a more natural consumer environment needs to be simulated. It is highly unlikely that you wash your hands as soon as you go into a shop!

If you are unsure of anything, please ask the facilitator. You are free to leave at any point should you wish to.

When you are ready, please turn over the page to start Section A.

Section A

Please answer the following questions about yourself:

What is your gender?

☐ Male

☐ Female

☐ Other

☐ Prefer not to say

What is your age? ……………………

Once you have finished this section, please inform the facilitator and await further instruction.

Section B

You will now be asked to choose between two parts at a time in a two alternative forced choice experiment, led by the facilitator. Please imagine the parts you are about to study are made from a new material for a mobile phone case.

You do not need the questionnaire for this section.

Section C

Please rate each part on the semantic scales below. You are encouraged to write down on anything you notice in the comments box underneath:

<u>Part 1</u>

Cool	1	2	3	4	5	6	7	Warm
Low Quality	1	2	3	4	5	6	7	High Quality
Rough	1	2	3	4	5	6	7	Not Rough
Furry	1	2	3	4	5	6	7	Not Furry
Soft	1	2	3	4	5	6	7	Hard
Smooth	1	2	3	4	5	6	7	Not Smooth

Any further comments:

Please inform the facilitator when you have finished and turn over the page.

Part 2

Smooth	1	2	3	4	5	6	7	Not Smooth
Low Quality	1	2	3	4	5	6	7	High Quality
Not Furry	1	2	3	4	5	6	7	Furry
Hard	1	2	3	4	5	6	7	Soft
Not Rough	1	2	3	4	5	6	7	Rough
Warm	1	2	3	4	5	6	7	Cool

Any further comments:

Please inform the facilitator when you have finished and turn over the page.

Part 3

Smooth	1	2	3	4	5	6	7	Not Smooth
Low Quality	1	2	3	4	5	6	7	High Quality
Furry	1	2	3	4	5	6	7	Not Furry
Cool	1	2	3	4	5	6	7	Warm
Soft	1	2	3	4	5	6	7	Hard
Not Rough	1	2	3	4	5	6	7	Rough

Any further comments:

Please inform the facilitator when you have finished and turn over the page.

Part 4

Hard	1	2	3	4	5	6	7	Soft
Not Smooth	1	2	3	4	5	6	7	Smooth
Low Quality	1	2	3	4	5	6	7	High Quality
Warm	1	2	3	4	5	6	7	Cool
Rough	1	2	3	4	5	6	7	Not Rough
Furry	1	2	3	4	5	6	7	Not Furry

Any further comments:

Please inform the facilitator when you have finished and turn over the page.

Part 5

Smooth	1	2	3	4	5	6	7	Not Smooth
Low Quality	1	2	3	4	5	6	7	High Quality
Warm	1	2	3	4	5	6	7	Cool
Not Furry	1	2	3	4	5	6	7	Furry
Hard	1	2	3	4	5	6	7	Soft
Not Rough	1	2	3	4	5	6	7	Rough

Any further comments:

Please inform the facilitator when you have finished and turn over the page.

Part 6

Warm	1	2	3	4	5	6	7	Cool
Soft	1	2	3	4	5	6	7	Hard
Furry	1	2	3	4	5	6	7	Not Furry
Not Smooth	1	2	3	4	5	6	7	Smooth
High Quality	1	2	3	4	5	6	7	Low Quality
Not Rough	1	2	3	4	5	6	7	Rough

Any further comments:

Please inform the facilitator when you have finished and turn over the page.

Part 7

Smooth	1	2	3	4	5	6	7	Not Smooth
Rough	1	2	3	4	5	6	7	Not Rough
Warm	1	2	3	4	5	6	7	Cool
Not Furry	1	2	3	4	5	6	7	Furry
Hard	1	2	3	4	5	6	7	Soft
High Quality	1	2	3	4	5	6	7	Low Quality

Any further comments:

Once you have finished this section, please inform the facilitator and await further instruction.

Section D

You will now be guided through an interview by the facilitator. Please review the experimental process and feel free to give honest opinions. This is the last section of the testing procedure.

10.5 Appendix E

This is some theory on the Freidman test. More information can be found in here: https://statistics.laerd.com/spss-tutorials/friedman-test-using-spss-statistics.php

Friedman test

The Friedman test is used to determine whether c groups have been selected from populations having equal medians.

$$H_0 = M_1 = M_2 = \cdots = M_c$$
$$H_1 = Not\ all\ M_j are\ equal$$

Where: j = 1, 2, …, c

To conduct this test, you replace the data values with the corresponding ranks, so you assign 1 to the smallest value group and rank c to the largest. If any of the groups are tied, you assign them with the mean of the ranks that they would otherwise have been assigned. Thus R_{ij} is the rank (from 1 to c)

Friedman rank test for differences among c medians:

$$F_R = \frac{12}{rc(c+1)} \sum_{j=1}^{c} {R_j}^2 - 3r(c+1)$$

Where

${R_j}^2$ = square of the total of the ranks for group j (j=1, 2, …, c)

r = number of participants

c = number of groups

10.6 Appendix F

Wilcoxon signed-rank test

The theory for this statistical test is very complex. For more detailed information, please refer to Laerd Mathematics:

https://statistics.laerd.com/spss-tutorials/wilcoxon-signed-rank-test-using-spss-statistics.php

Roughness Wilcoxon signed rank table

Tiles	p-value	Perceived quality difference
Natural and shot blasted	1.000	No
Natural and 180 sanded	0.000	Yes
Natural and 400 sanded	0.000	Yes
Natural and 800 sanded	0.000	Yes
Natural and 1200 sanded	0.000	Yes
Natural and PUSh	0.201	No
Shot blasted and 180 sanded	0.000	Yes
Shot blasted and 400 sanded	0.000	Yes
Shot blasted and 800 sanded	0.000	Yes
Shot blasted and 1200 sanded	0.000	Yes
Shot blasted and PUSh	0.010	Yes
180 sanded and 400 sanded	0.187	No
180 sanded and 800 sanded	0.174	No
180 sanded and 1200 sanded	0.047	Yes
180 sanded and PUSh	1.000	No
400 sanded and 800 sanded	1.000	No
400 sanded and 1200 sanded	1.000	No
400 sanded and PUSh	0.000	Yes
800 sanded and 1200 sanded	1.000	No
800 sanded and PUSh	0.000	Yes
1200 sanded and PUSh	0.000	Yes

Hardness Wilcoxon signed rank table

Tiles	p-value	Perceived quality difference
Natural and shot blasted	1.000	No
Natural and 180 sanded	1.000	No
Natural and 400 sanded	1.000	No
Natural and 800 sanded	1.000	No
Natural and 1200 sanded	1.000	No
Natural and PUSh	1.000	No
Shot blasted and 180 sanded	0.130	No
Shot blasted and 400 sanded	0.174	No
Shot blasted and 800 sanded	0.059	No
Shot blasted and 1200 sanded	0.150	No
Shot blasted and PUSh	0.904	No
180 sanded and 400 sanded	1.000	No
180 sanded and 800 sanded	1.000	No
180 sanded and 1200 sanded	1.000	No
180 sanded and PUSh	1.000	No
400 sanded and 800 sanded	1.000	No
400 sanded and 1200 sanded	1.000	No
400 sanded and PUSh	1.000	No
800 sanded and 1200 sanded	1.000	No
800 sanded and PUSh	1.000	No
1200 sanded and PUSh	1.000	No

Temperature Wilcoxon signed rank table

Tiles	p-value	Perceived quality difference
Natural and shot blasted	1.000	No
Natural and 180 sanded	0.375	No
Natural and 400 sanded	0.005	Yes
Natural and 800 sanded	0.000	Yes
Natural and 1200 sanded	0.007	Yes
Natural and PUSh	0.111	No
Shot blasted and 180 sanded	1.000	No
Shot blasted and 400 sanded	0.103	No
Shot blasted and 800 sanded	0.004	Yes
Shot blasted and 1200 sanded	0.130	No
Shot blasted and PUSh	1.000	No
180 sanded and 400 sanded	1.000	No
180 sanded and 800 sanded	0.590	No
180 sanded and 1200 sanded	1.000	No
180 sanded and PUSh	1.000	No
400 sanded and 800 sanded	1.000	No
400 sanded and 1200 sanded	1.000	No
400 sanded and PUSh	1.000	No
800 sanded and 1200 sanded	1.000	No
800 sanded and PUSh	1.000	No
1200 sanded and PUSh	1.000	No

Smoothness Wilcoxon signed rank table

Tiles	p-value	Perceived quality difference
Natural and shot blasted	1.000	No
Natural and 180 sanded	0.000	Yes
Natural and 400 sanded	0.000	Yes
Natural and 800 sanded	0.000	Yes
Natural and 1200 sanded	0.000	Yes
Natural and PUSh	0.162	No
Shot blasted and 180 sanded	0.000	Yes
Shot blasted and 400 sanded	0.000	Yes
Shot blasted and 800 sanded	0.000	Yes
Shot blasted and 1200 sanded	0.000	Yes
Shot blasted and PUSh	0.082	No
180 sanded and 400 sanded	0.047	Yes
180 sanded and 800 sanded	0.187	No
180 sanded and 1200 sanded	0.005	Yes
180 sanded and PUSh	0.520	No
400 sanded and 800 sanded	1.000	No
400 sanded and 1200 sanded	1.000	No
400 sanded and PUSh	0.000	Yes
800 sanded and 1200 sanded	1.000	No
800 sanded and PUSh	0.000	Yes
1200 sanded and PUSh	0.000	Yes

Quality Wilcoxon signed rank table

Tiles	p-value	Perceived quality difference
Natural and shot blasted	1.000	No
Natural and 180 sanded	0.187	No
Natural and 400 sanded	0.000	Yes
Natural and 800 sanded	0.000	Yes
Natural and 1200 sanded	0.000	Yes
Natural and PUSh	1.000	No
Shot blasted and 180 sanded	0.010	Yes
Shot blasted and 400 sanded	0.000	Yes
Shot blasted and 800 sanded	0.000	Yes
Shot blasted and 1200 sanded	0.000	Yes
Shot blasted and PUSh	0.201	No
180 sanded and 400 sanded	1.000	No
180 sanded and 800 sanded	1.000	No
180 sanded and 1200 sanded	0.111	No
180 sanded and PUSh	1.000	No
400 sanded and 800 sanded	1.000	No
400 sanded and 1200 sanded	1.000	No
400 sanded and PUSh	0.232	No
800 sanded and 1200 sanded	1.000	No
800 sanded and PUSh	0.096	No
1200 sanded and PUSh	0.005	Yes

Furriness Wilcoxon signed rank table

Tiles	p-value	Perceived quality difference
Natural and shot blasted	1.000	No
Natural and 180 sanded	1.000	No
Natural and 400 sanded	0.140	No
Natural and 800 sanded	0.267	No
Natural and 1200 sanded	0.306	No
Natural and PUSh	0.010	Yes
Shot blasted and 180 sanded	1.000	No
Shot blasted and 400 sanded	0.351	No
Shot blasted and 800 sanded	0.628	No
Shot blasted and 1200 sanded	0.711	No
Shot blasted and PUSh	0.031	Yes
180 sanded and 400 sanded	0.187	No
180 sanded and 800 sanded	0.351	No
180 sanded and 1200 sanded	0.401	No
180 sanded and PUSh	0.014	Yes
400 sanded and 800 sanded	1.000	No
400 sanded and 1200 sanded	1.000	No
400 sanded and PUSh	1.000	No
800 sanded and 1200 sanded	1.000	No
800 sanded and PUSh	1.000	No
1200 sanded and PUSh	1.000	No

10.7 Appendix F

Wilcoxon signed rank touch data

Tiles	p-value	Perceived quality difference
Natural and shot blasted	1.000	No
Natural and 180 sanded	0.328	No
Natural and 400 sanded	0.000	Yes
Natural and 800 sanded	0.000	Yes
Natural and 1200 sanded	0.000	Yes
Natural and PUSh	0.628	No
Shot blasted and 180 sanded	0.001	Yes
Shot blasted and 400 sanded	0.000	Yes
Shot blasted and 800 sanded	0.000	Yes
Shot blasted and 1200 sanded	0.000	Yes
Shot blasted and PUSh	0.002	Yes
180 sanded and 400 sanded	0.628	No
180 sanded and 800 sanded	0.711	No
180 sanded and 1200 sanded	0.076	No
180 sanded and PUSh	1.000	No
400 sanded and 800 sanded	1.000	No
400 sanded and 1200 sanded	1.000	No
400 sanded and PUSh	0.328	No
800 sanded and 1200 sanded	1.000	No
800 sanded and PUSh	0.375	No
1200 sanded and PUSh	0.033	Yes