SURFACE ROUGHNESS OF COBALT CHROMIUM ALLOY FABRICATED WITH SELECTIVE LASER MELTING AND CONVENTIONAL TECHNIQUES

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FACULTY OF DENTISTRY
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RESEARCH REPORT SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTERS OF CLINICAL DENTISTRY IN RESTORATIVE DENTISTRY (PROSTHETIC DENTISTRY)

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ABSTRACT

Introduction: Selective laser melting (SLM) is a new technique in fabricating cobalt chromium denture framework. However, surface properties of cobalt chromium denture framework fabricated using this technique have not been widely investigated. **Aim**: To investigate surface roughness of cobalt chromium alloy for removable partial denture fabricated with SLM technique. **Materials and Method**: Cobalt chromium denture frameworks were fabricated with two techniques (n= 10) ; the conventional lost wax casting (conventional group) and SLM techniques (SLM group). Specimens from conventional group were subjected to sandblasting and electropolishing. No treatment was employed for specimens from SLM group. All specimens were subjected to surface roughness measurement on polished and fitting surfaces using non-contact optical three-dimensional metrology and surface roughness analysis machine (Infinite Focus Real 3D Alicona). **Results**: Statistical analysis showed no significant difference in surface roughness between the specimens from conventional and SLM groups *($p>0.05$).* There was no statistically significant difference in surface roughness between the polished and fitting surfaces of SLM specimens *($p>0.05$).* **Conclusion**: Surface roughness quality of cobalt chromium denture framework fabricated with SLM technique is comparable to that fabricated with the conventional lost wax casting technique. The surface roughness of SLM fabricated cobalt chromium denture frameworks carries the same surface roughness quality between the polished and fitting surfaces.

ABSTRAK

Pengenalan: *Selective laser melting* (SLM) adalah teknik terkini yang digunakan dalam menghasilkan dentur kobalt kromium. Walaubagaimanapun, masih belum banyak kajian yang dihasilkan berkaitan permukaaan dentur yang dihasilkan melalui teknik ini. **Tujuan**: Mengkaji kekasaran permukaan dentur yang dihasilkan melalui teknik SLM. **Bahan dan Kaedah**: Dentur kobalt kromium dihasilkan menggunakan teknik konvensional dan teknik SLM (n= 10). Spesimen konvensional disembur-pasir dan melalui proses *electropolishing*. Tiada rawatan dilakukan untuk spesimen dari kumpulan SLM. Semua spesimen diimbas dengan mesin optikal pembacaan kekasaran permukaan*(Infinite Focus Real 3D Alicona*). **Keputusan**: Tiada perbezaan nyata statistik didapati antara spesimen konvensional dan SLM *($p>0.05$)*. Tiada perbezaan nyata statistik antara permukaan licin dan permukaan adaptasi tisu untuk specimen SLM *($p>0.05$)*. **Kesimpulan**: Kualiti permukaan untuk dentur kobalt kromium yang dihasilkan melalui proses SLM adalah sama dengan dentur yang dihasilkan melalui proses konvensional. Kualiti permukaan dentur kobalt kromium yang dihasilkan melalui proses SLM adalah sama antara permukaan licin dan permukaan adaptasi tisu

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LIST OF SYMBOLS AND ABBREVIATIONS

C. albicans	:	*Candida albicans*
CAD	:	Computer aided design
CAM	:	Computer aided manufacturing
SLM	:	Selective laser melting
SLS	:	Selective laser sintering
STL	:	Standard tessellation language
3D	:	Three dimensional
$\bar{X}$	:	Mean
σ	:	Standard deviation
μ	:	Micron

CHAPTER 1: INTRODUCTION

Prosthodontics is a branch in dentistry concerning prosthetic restoration and substitution of missing intra oral and to some extent extra oral facial structures in order to achieve masticatory function, comfort and aesthetic. Denture has been a viable option for this purpose for decades and has been on the list for prosthodontics treatment options apart from fixed bridge, crown and implant treatment. Modern denture base materials were developed since 1839 from materials like acrylic resin and cast metallic material such as cobalt chromium, nickel chromium based alloys, pure titanium and titanium alloys (Anusavice, 2003).

From conventional method of fabricating cobalt chromium denture base where lost wax casting technique is utilized, advancement in engineering field had allowed computerized and digitized fabrication of cobalt chromium denture framework using selective laser melting (SLM) technique (Budak et al., 2012). This has helped to overcome drawbacks of conventional technique that is labour and time intensive (Koutsoukis, 2015). Owing to the fact that a denture framework is an entity that has close adaptation and interaction with human body and biological tissue, it is only wise that cobalt chromium denture framework fabricated using SLM technique is thoroughly investigated in all aspects before this application is fully adopted in dental fraternity.

Mechanical properties of cobalt chromium denture framework fabricated using SLM technique has been investigated by many previous studies. Alageel et al. (2018) has demonstrated that cobalt chromium denture framework fabricated using SLM technique had more precise fit and exhibited better fracture resistance than those fabricated using conventional cast technique (Alageel et al., 2018). This corresponds to earlier studies in mechanical aspects where it has been demonstrated that cobalt chromium alloy fabricated with SLM method exhibited high strength and better brittleness property (Jevremovic et al., 2012; Kajima et al., 2016).

Besides mechanical property, other aspects that demands investigation are microstructure and surface properties. Surface integrity plays an important role as deficiency in surface integrity could become the initiation point for fatigue cracking, wear, tension and corrosion (Blunt & Jiang, 2003) as well as microbial retention that could lead to oral pathology (Budtz‐Jörgensen, 1974) especially with dentures. Literature confirms abundance of studies that have well demonstrated that surface roughness is associated with plaque and microbial accumulation (Bollen et al., 1996; Liu et al., 2018; Quirynen et al., 1990; Taylor et al., 1998; Verran et al., 1991).

In other studies (Hong et al., 2016; Koutsoukis, 2015; Pupo et al., 2015; Takaichi, May 2013) surface properties of SLM fabricated cobalt chromium have been investigated. With optimum process parameters, it has been confirmed that SLM fabricated cobalt chromium has similar or better properties than the casted counterpart (Koutsoukis, 2015). Takaichi (2013) demonstrated its uniform and fine microstructure, Hong et al. (2016) confirmed similar roughness of the surfaces, as had been shown by Taylor et al. (1998) and Aydin (1991). However, in all these studies the parameters used for surface roughness measurement were in Ra unit.

As optical technology grew and areal surface analysis became more popular (Leach, 2011) a reference for surface roughness for cobalt chromium fabricated with SLM technique in Sa measurement is required in the literature. This study investigates the surface roughness of cobalt chromium denture framework fabricated with SLM technique in Sa measurement.

1.1 Aim and objectives

1.1.1 Aim

This study aimed to investigate the surface roughness of cobalt chromium alloy for removable partial denture fabricated using selective laser melting (SLM) technique.

1.1.2 Objectives

To determine and compare the surface roughness of cobalt-chromium specimens fabricated using SLM and conventional lost wax casting techniques.

i. To compare the surface roughness between the fitting and polished surfaces of cobalt-chromium frameworks fabricated using SLM technique.

CHAPTER 2: LITERATURE REVIEW

2.1 Surface Roughness

Fitting surface of a denture is the surface directly in contact with intraoral mucosa, and is often responsible for harbouring microorganisms such as *Candida albicans (C. albicans*) (Budtz - Jörgensen, 1974). It is generally accepted that *C. albicans* is the main cause of denture stomatitis (Budtz - Jörgensen, 1974). Since it has been demonstrated that higher numbers of these microorganisms is found on the fitting surface of a denture then on the affected mucosa (Davenport, 1970; Olsen, 1974) it is only prudent that surface characteristics of denture frameworks is studied.

Several studies have demonstrated a clear association between plaque accumulation and surface roughness (Bollenl et al., 1997; Quirynen et al., 1990; Taylor et al., 1998). Higher plaque score and thicker plaque formation in rough test samples then that of smooth samples were shown by Quirynen et. al, (1990). Taylor et al. (1998) demonstrated higher microbial retention especially *C. albicans* in acrylic resin and cobalt-chromium surfaces with higher Ra values. This is also reciprocated by a study which showed a small increase in surface roughness resulted in high increase in C. *albicans* adherence (Verran et al., 1991). It has been observed that microroughness of acrylic is a factor of *C. albicans* adherence as compared to macroroughness and it has been suggested that a specific type of roughness enhances retention of a specific species (Taylor et al., 1998).

Quirynen et al. (1990) suggested that surface roughness above the Ra value of 2 μm drastically increased bacterial retention as compared to smooth test samples with Ra value of 0.12 μm, whereas Bollen et al. (1996) suggested a threshold Ra of 0.2 μm for intraoral hard material is the magic number below which, no further reduction of microbiological load can be observed.

Surface roughness of cobalt chromium denture framework material has not been widely investigated, similarly with that fabricated using SLM technique (Pupo et al., 2015). Whilst microstructural analysis has been the subject of interest for many studies, no study has come up with a specific Sa measurement for surface roughness (Alageel et al., 2018; Koutsoukis, 2015). However, (Swelem et al., 2014) have studied the surface roughness of cobalt chromium denture framework and found that Ra values lies around 2.77 μm for conventionally fabricated framework. However, it is not clear in this study whether the standard treatment of finishing and polishing for cobalt chromium denture framework were applied for the test samples, and whether surface roughness measurements were done on the fitting or the polished surfaces.

In a study looking at different stages of finishing and polishing techniques for cobalt chromium denture framework, the mean Ra values were found to range between 0.14 to 3.50 μm (Aydin, 1991). Smoothest surface with the lowest Ra value was found in the samples treated with (in particular order) sandblasting, followed with hard stone, medium abrasive disk, second sandblasting, electropolishing, hard rubber point, hard felt disk with pumice slurry, and felt disk and soft brush with polishing paste. If the threshold of 2 μm Ra value of surface roughness is used as comparison standard, the least steps needed for cobalt chromium treatment to achieve this were suggested to be sandblasting, hard stone, medium abrasive disk, second sandblasting and electropolishing (Aydin, 1991).

Sandblasting cobalt chromium denture as part of the treatment for the framework however was found to be able to increase Ra values hence bacterial retention. Electropolishing although may improve shiny appearance of cobalt chromium surfaces, does not reinforce Ra values (Taylor et al., 1998). (Jang et al., 2001) demonstrated the Ra values to be in the range of 13.39 ± 4.09 µm , and 0.15 to 2.13 µm by Taylor et al. (1998) .

2.2 Surface Roughness Measurement

Surface has become the area of interest in innumerable studies for a reason that it has been shown that 90% of engineering component failures are initiated by surface. This occurs through mechanisms like fatigue cracking, stress corrosion, wear and erosion. From the point of view of medical and dental fields, the interaction of a surface with biological tissue brings the subject of microbiological organism attachment into the discussion. It is technically not possible for any surface to be manufactured to perfect surface smoothness as every manufacturing component microscopically leaves a surface with texture. This is referred to as surface texture or surface topography consisting of a series of peaks and valleys each possessing their specific size, spacing and shape (Blunt & Jiang, 2003).

Mathematically, the measurement of surface profile can be represented as a height function with lateral displacement that is z(x). On the other hand the mathematical representation of areal surface topography is the height function with displacement across a plane, z(x,y). These inherently describe the nature of surface profiling that is linear, as compared to the areal nature surface topography measurement (Leach, 2011).

Traditionally, the earliest form of surface assessment was made by running fingernails across a surface. Today, this manual technique of tactile assessment still remains as a crude form of surface comparison and evaluation. The earliest instrument developed to enable measurement and quantification of surface finish was the profilometer developed in Germany by Professor Gustaz Schmaltz in the early 20th century. This instrument operates based on the principle of a stylus drawing on a specified line across a selected surface, from which the vertical deviation of the stylus is recorded and measured. This instrument within the same principle of linear profiling was then developed to be electronic, giving rise to wide application in many industries and the parameter for the surface roughness was termed average roughness in Ra measurement (Blunt & Jiang, 2003).

Ra is a value for surface measurement that is universally recognized and most employed. The nature of surface linear profiling that results in Ra measurement however is not a comprehensive representative of a surface roughness measurement especially on a wide range of surface (Whitehouse, 2004).

The academic interest in 3-dimensional characterisation of surfaces blossomed in the 1980s, focusing on the surface parameters that described amplitude properties, spatial properties, and functional properties of a surface (Blunt & Jiang, 2003). This concept was brought into application with the concomitant development of computer system, accompanying supporting software and optical instruments giving rise to an optical instrument that measures the actual surface topography by scanning a beam using the field of view (Leach, 2011).

The development of linear surface profiling to areal surface topography measurement came about to overcome inadequacy in profiling method. Amongst the advantages of the latter apart from it being faster include a more realistic representation of a surface with statistical and less chances of significant features being missed, resulting in a better record of the overall structure of the surface (Leach, 2011).

2.3 Computer Aided Manufacturing

Manufacturing techniques could be categorized into deforming, additive and subtractive manufacturing. Deforming process involves a process that starts from the right amount of material bulk which then deformed into another state by means of forging, stamping, drawing, casting and injection moulding. No material is added or taken away in the process. Subtractive manufacturing involves a larger amount of bulk material that is shaped into a product by turning, milling and grinding where excess material is removed. Additive manufacturing is a relatively new technique in which the production involves addition of material rather than deforming or removal (Kruth, 1991).

The terminologies rapid prototyping, 3D printing, stereolitography, selective laser melting and selective laser sintering (SLS) have been used loosely and interchangeably to describe a technique of manufacturing parts via computerized application. Each of these terms however carries a specific definition of a manufacturing technique.

This technique of computerized designing and additive manufacturing has evolutionized from the first phase where architects and designers used this technology to produce mockups and prototypes, and referred to as "rapid prototyping" for the simplicity and ease of this production technique. Prototype models however are too brittle to be functionally operated (Kruth, 1991) and produced from cost-effective materials like resin and plastic as compared to the actual objects that are made from metals. The second phase entailed where accomplished, functional and finished products started to be mass-produced termed as rapid manufacturing. It is projected that in the future 3D printers will penetrate every office and work desk as how a desktop printer is essential to every home and office (Berman, 2012).

Rapid prototyping is the terminology used to describe accurate production of parts from computer aided design (CAD) model (Pham & Gault, 1998) by addition of layers of material on top of each other until a complete model is produced. The main components in rapid prototyping include computer aided designing, laser or light processing and additive manufacturing (Dickens, 1995).

The production process of additive manufacturing requires input from 3D solid CAD model (Dolenc & Mäkelä, 1994). CAD software is used for computerized designing, from which the CAD model is sliced into thin layers and standard tessellation language (STL) format file of the design is tessellated and exported to the 3D manufacturing machine (Pham & Gault, 1998). It is the information from these thin layers that is used by the 3D manufacturing system to build back the physical model in real material (Dickens, 1995). A 3D manufacturing machine relies on energy sources like light or laser to initiate material to change its phases or polymerize (for some types of material) from liquid or powder to solid state. Solidification of raw material occurs layer by layer as determined by the sliced CAD file.

The steps involved in additive manufacturing could be depicted by the following steps (Campbell et al., 2011):-

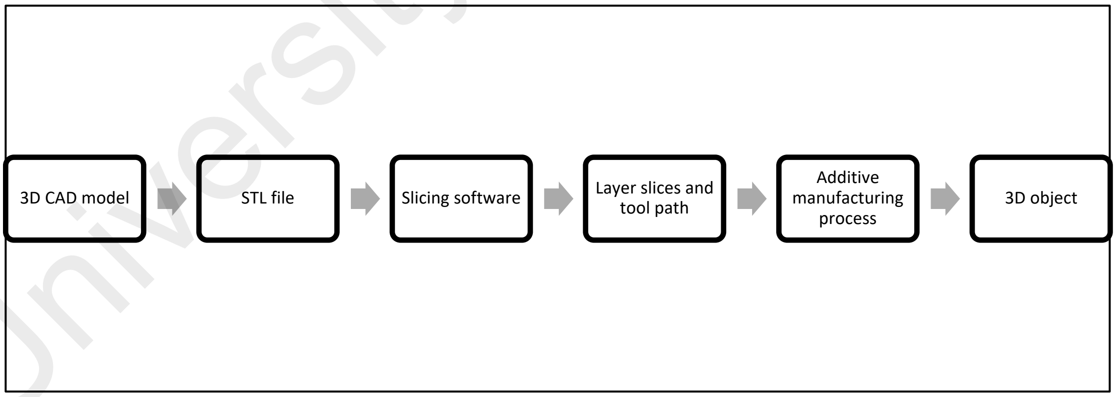


Figure 2.1: Additive manufacturing process

Kruth (1991) classified additive manufacturing based on the raw materials and their states. The following diagram adapted from this paper showcases the classification:-

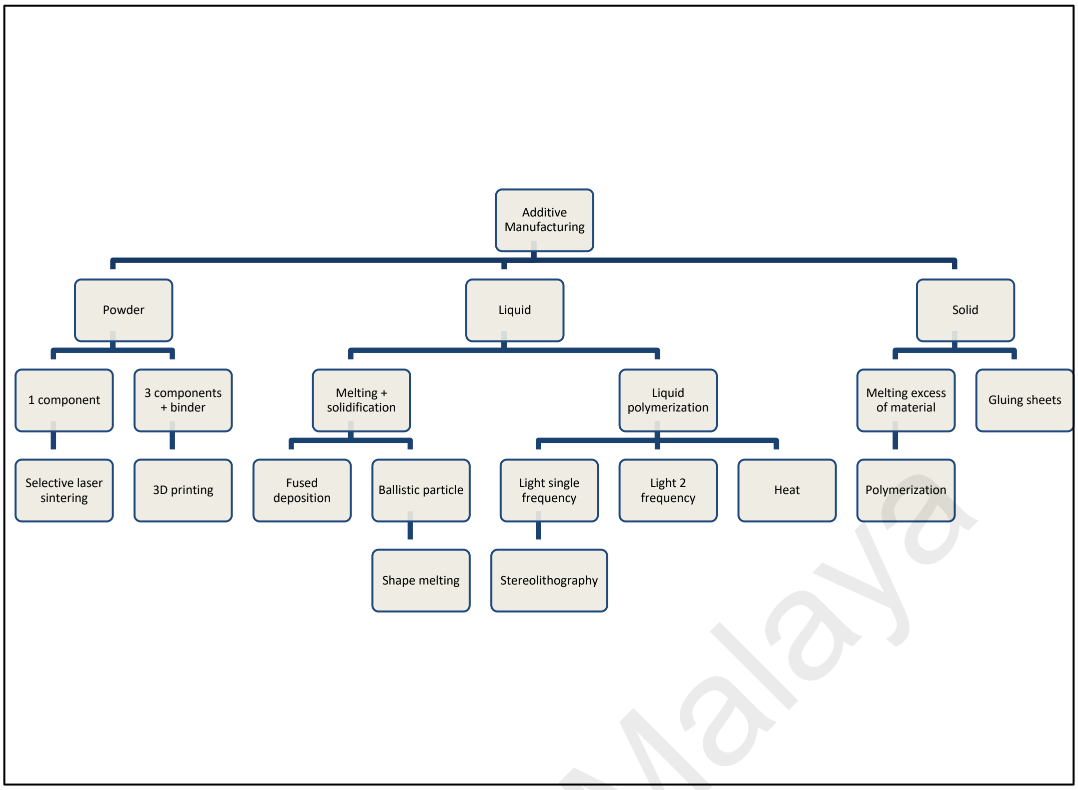


Figure 2.2: Categories for additive manufacturing according to material creation.

Raw materials can exist in 3 forms; solid, powder and liquid. As liquid is deposited during the building process, solidification occurs by the action of heat, laser or light which particularly takes place in stereolithography. Another classification of liquid deposition requires liquidification, deposition and resolidification which can allow materials like metals, plastics and resins to be built. Binding of powder material occurs by melting together of interfacial grains as in selective laser sintering, or addition of binder to glue two grains together. Furthermore, production that involves solid materials requires foils of material to be welded by glue or semi-polymerized foils binded together by photo-polymerization (Kruth, 1991).

Another classification is according to the SLS binding mechanism employed, however one technology might fit into one or more categories. These categories for SLS technology and its derivatives (one of them is selective laser melting or SLM) are also known to be quite arbitrary and the borders are indistinct. The four categories of this classification include solid state sintering, liquid phase sintering or partial melting, chemically induced binding and full melting (Kruth et al., 2005). The following diagram depicts these classification adapted from Kruth (2005) :-

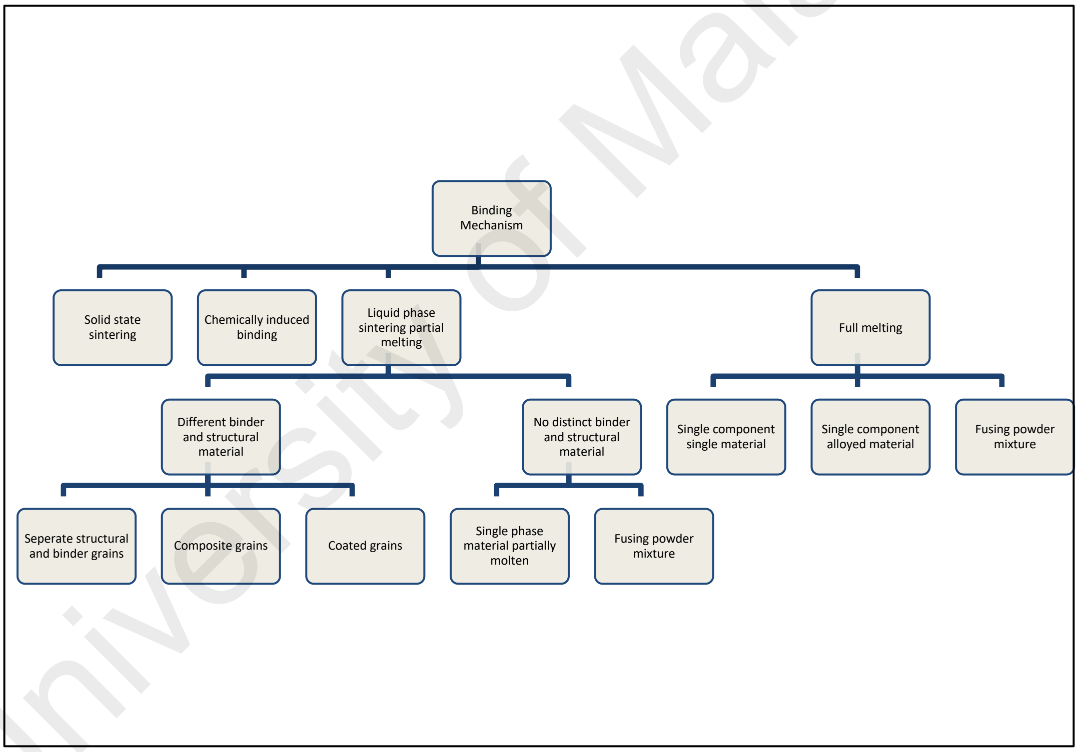


Figure 2.3: Categories of layer additive manufacturing according to binding mechanisms.

Selective laser sintering or SLS is a term used to describe a manufacturing technique that involves successive layering of powder fused together by laser energy until a 3D part is produced (Kruth et al., 2005; Pham & Gault, 1998). Based on a 3D CAD model, every layer is scanned according to its cross section. Successive layers of powder material is laid down in thickness ranging from 20 to 150μm and amalgamated into a 3D object by polymerizing specific areas from thermal energy source commonly supplied by laser beam (Kruth et al., 2005).

In general, additive manufacturing technology offers many advantages over conventional manufacturing. In terms of designing, it is possible to design parts with complex geometries and shapes, variable wall thickness and undercuts, and high strength to weight ratio. An assembly of various parts are able to be consolidated together without having to go through many steps of manufacturing and combining (Atzeni & Salmi, 2012; Campbell et al., 2011; Koutsoukis, 2015). It is also known to be economical and cost effective due to no extra tools required, recyclable and no scrap materials and reduced labour. Besides, products could be customized with every printing, designs could move around the world in STL format and be printed anywhere (Campbell et al., 2011).

On the other hand, disadvantages associated with additive manufacturing include limitation in available materials, variable dimensional accuracy and surface finish, dependency of mechanical properties on building direction and imitation to size of parts to be produced which is dependent on the building volume of the machine (Atzeni & Salmi, 2012). The application of additive manufacturing takes longer time as compared to injection moulding technique, arguably less environmentally friendly than conventional manufacturing by means of carbon footprint, and limited for mass production (Campbell et al., 2011)

2.4 Selective Laser Melting

A derivative of SLS technology, Selective Laser Melting or SLM has been introduced in the 2000s (Campbell et al., 2011; Kruth et al., 2005), specifically employed for metallic material (Kruth et al., 2005; Noort, 2012), in which process metal powders are completely liquefied by laser beam. Powder material used can be classified into single component single material, single component alloyed powder particles, and fusing powder mixture.

Among the first metal that has been produced this method is titanium, and a cross section of this part has shown that the density is almost 100% (Bremen et al., 2012; Kruth et al., 2005). Range of metal available to be part of SLM manufacturing however is still limited as every metal has particular processing specification to avoid “balling” effect and porosity (Kruth et al., 2005). Introduced to cater for production of hollow and complicated structures in aerospace and automotive industries, currently the application of SLM branches into medical and dental fields (Bremen et al., 2012; Noort, 2012) in which parts with precision and complex geometries are produced thus eliminating part-specific tools in the process of production.

The principles of SLM operation are fundamentally equivalent to that of SLS in which it starts with a 3-dimensional CAD model sliced into layers and transferred to a SLM printing machine. The actual production or 3-dimensional printing of parts starts in the SLM machine where metal powder material is deposited onto a platform in thin slices (10-45µm) that gets melted by a laser source in an inert chamber. As the metal layer is melted and metal grains fused and solidify, the platform is lowered to the next layer according to the sliced CAD design and the next layer of metal is laid down until the part is completely fabricated. In SLM process metal powder is completely melted and this factor accounts for the resulting in high density property of the produced parts (Bremen et al., 2012).

The application of SLM in dentistry has been primarily focused on cobalt-chromium alloys (Koutsoukis, 2015), and due to SLM being a relatively new application in dentistry, more experimental and clinical studies are required to investigate various properties that would account for successful prosthodontic restorations and prostheses.

CHAPTER 3: MATERIALS AND METHODS

3.1 Materials

The materials used for the construction of removable partial denture frameworks consisted of cobalt chromium alloys that were specific for their purpose.

Cobalt chromium metal alloy ingots from Wironit® (Bego, Bremen, Germany) was used in conventional lost wax casting group and cobalt chromium metal alloy powder from SLM MedDent (SLM Solutions Group, AG, Germany) was used for SLM group, both carrying a slightly different composition as shown in the following table:-

Table 3.1: The composition of cobalt chromium alloys in percentage

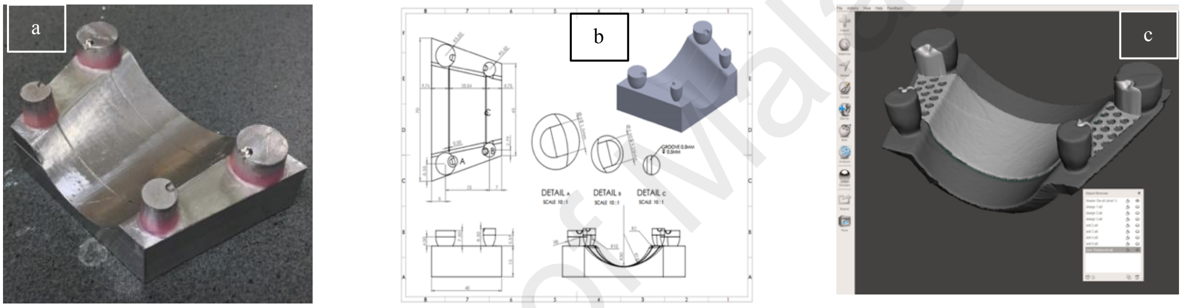
Component / Type	Cobalt	Chromium	Molybdenum	Silicone	Manganese	Carbon	Tungsten
Ingot	64.0	28.5	5.0	1	1.0	< 1	0
Powder	66.8	22.7	4.0	2	0.1	< 1	4.4

Figure 3.1: Bego Wironit® cobalt chromium ingots.

3.2 Sample Preparation

3.2.1 Cobalt chromium denture framework fabricated using SLM technique

A stainless-steel master die (Fig. 3.2a) was fabricated using CAD-CAM with the dimensions as indicated in Figure 3.2b, and was scanned using a desktop 3D scanner (Geomagic Capture®, South Carolina, USA).



Figures 3.2: (a) Stainless-steel master die, (b) schematic design of master die, (c) STL design of master die

The sample design was based on the work by (Alageel et al., 2018; Swelem et al., 2014) in which the experimental specimens that were studied for surface characteristics were constructed to be in removable partial denture design. This would simulate the clinical application of cobalt chromium alloy used in clinical dental setting, as opposed to flat specimens used in vitro.

Figure 3.3: Geomagic Capture 3D Scanner

The scanned data was obtained using the application software (Geomagic Design X, 2016.1.0, United States) and converted into STL file and transported into a CAD software (Autodesk MeshMixer software; version 3.2.37, California). A virtual block out of undercuts were subsequently performed on the master die in the CAD software. The framework design included virtual relieving of both left and right saddle areas by 0.5mm. Meshwork of 0.6mm thickness was designed on each side of the saddles, followed by proximal plates on the proximal areas of the abutments. Occlusal rests were created on abutments, and finally the major connector in the form of a palatal strap of 0.6mm thickness was designed on the palatal area. The finalised design was exported to another CAD software Magics, 3-matic® (Materialise, Belgium), and support structures were designed to be located along the lateral margins of the polished surface of the framework at an angle of 30°.

The resulting STL file of the framework design was then sent to an SLM machine (SLM 280 HL, SLM Solutions GmbH) (Fig. 3.4) for additive manufacturing of the framework, and five removable partial denture framework were fabricated.

Figure 3.4: SLM280 machine

The SLM 280 has a large build envelope, able to support medium to high volume metal additive manufacturing part production, and has a high laser profile offering 400, 700 and 1000W IPG fiber laser to optimize the production process. It has a build rate up to 55 cm3 with laser beam focus range of 80 – 115 µm. The SLM process involves deposition of the cobalt chromium powder onto the powder bed or platform, and the focused laser beam selectively melt and fuses the powder particles together. The geometric information of individual layer is provided by the CAD software in which the STL file of the framework design has been loaded. The process continues as the platform is lowered, another layer of powder is laid down until the part is completed.

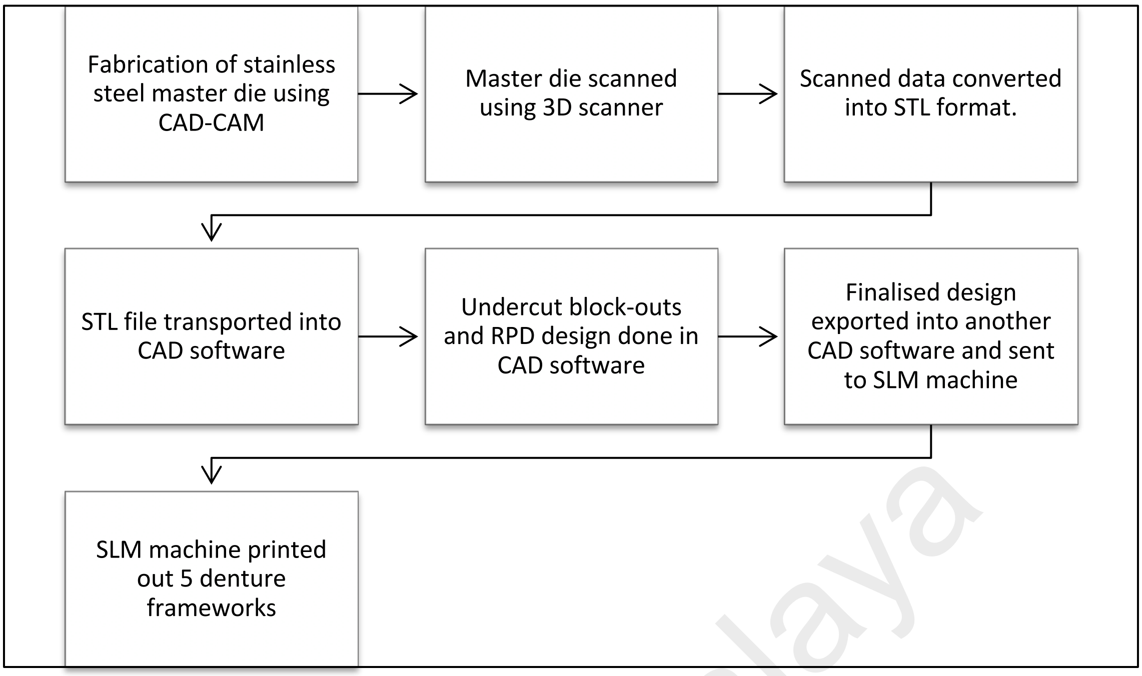


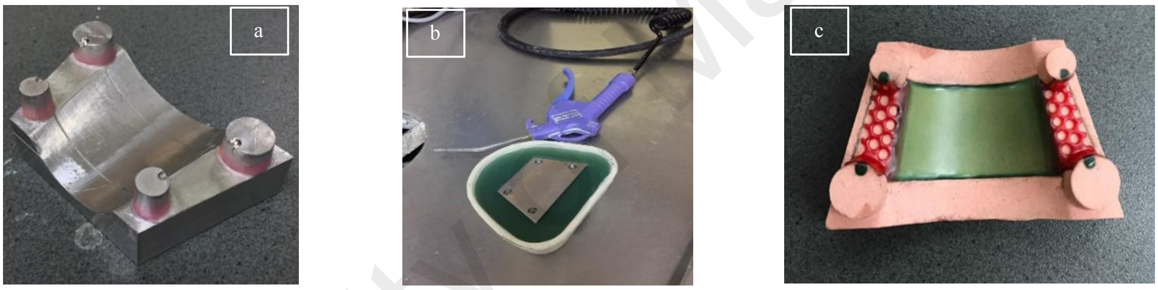
Figure 3.5: Flowchart of fabrication of denture framework with SLM technique

3.2.2 Cobalt chromium denture framework fabricated using conventional lost wax casting technique

Stainless steel master die was prepared for duplication by first blocking out the undercut areas and relieving the saddle areas (Fig. 3.6a). It was performed using block-out wax. Duplication was done with agar (Fig. 3.6b), and upon setting refractory investment material (Wirovest®, Bego, Germany) was poured to produce a refractory model. The investment material was mixed according to the manufacturer's instruction. A hundred grammes of investment powder to 13 ml of liquid (BegoSol® Bego, Germany) was mixed and hand spatulated for 10 seconds and followed by two minutes on the vibrator before the mixture poured into the set agar mould. Duplication was carried out and refractory cast was removed from the agar after 45 minutes. The refractory cast was preheated to 250° C for 30 minutes, soaked in hardening agent and air dried to increase the surface integrity. Five refractory casts were prepared by the same operator.

Wax up of the denture framework was performed on individual cast (Fig. 3.6c). Wax patterns of 0.6 mm thick was laid on the palatal area for the major connector, subsequently followed by the rests and minor connector to connect the major connector to the rests. Meshwork wax was then applied on both saddles and chip-blowed to achieve smooth surface. Three sprues of 2.5 mm diameter were attached to the wax up.

The refractory casts with the wax patterns were then flasked in mould rings and investment material (Wirowest®, Bego, Germany) poured into the ring. It was left to set for more than 30 minutes. Prior to casting, the mould and crucible were placed in the furnace (Bego Fornax 35 EM, Bremer, Germany) for preheating in 250°C for 30-60 minutes. Temperature of the furnace was then raised to final temperature of 1000°C and held for another 30-60 minutes. The cobalt chromium ingots were then placed in the crucible and transferred to the induction casting machine until ingots are partially melted. The mould ring was then transferred from the furnace into the casting machine and casting process started. Once casting was completed, the mould ring was removed from the machine and left to bench cool for two hours. The frameworks were then divested. Five denture frameworks were obtained.



Figures 3.6: (a) Block-outs on master die, (b) duplication in agar, (c) framework wax-up

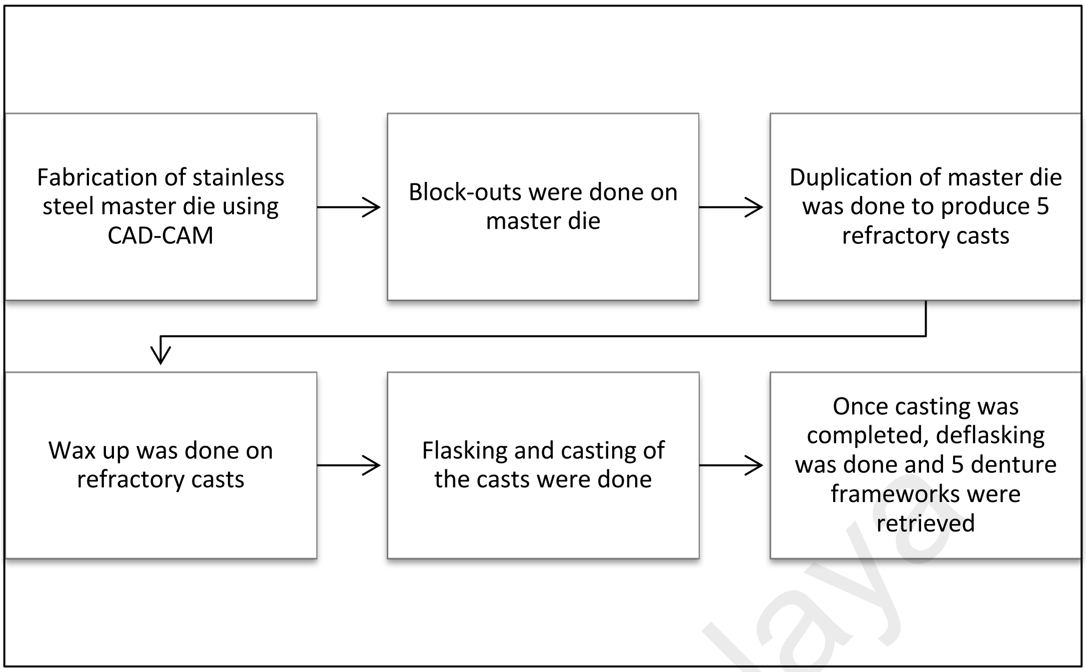


Figure 3.7: Flowchart of fabrication of denture framework with lost wax casting technique

3.2.3 Finishing and polishing of framework specimens

All the framework specimens from both fabrication methods underwent sandblasting and electroplishing with electropolishing liquid (Wirolyt®, Bego, Germany) after excess and sprues were trimmed off with carborundum discs.

3.3 Specimen analysis and data collection

Frameworks were then subjected to surface roughness analysis using a non-contact optical three-dimensional metrology and surface roughness analysis machine (Infinite Focus Real 3D Alicona).

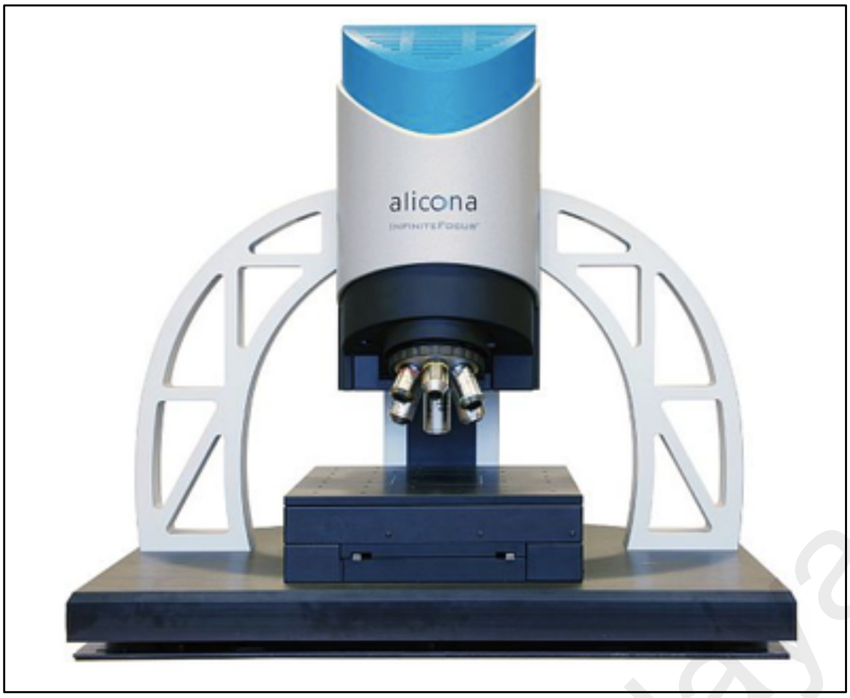
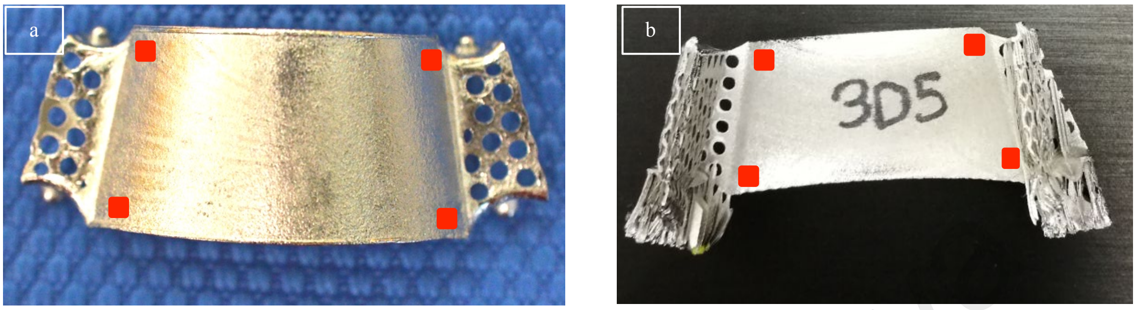


Figure 3.8: Alicona surface roughness measurement machine.

The Infinite Focus Alicona uses focus variation technology that combines optical system with vertical scanning to provide topographical and colour information from the variation of focus. It works by focusing a white light source onto a specimen. The light is reflected into several directions as soon as it hits the specimen, depending on its reflective properties. The reflected rays would then hit an objective lense, gets bundled and gathered by a light sensitive sensor. Algorithms convert the acquired data into a 3-dimensional information with full depth of field, achieved by analysing the variation of focus along the vertical axis. The focus variation technology overcomes the limitations in measurement capabilities in terms of reflectance, enabling various specimens from shiny to diffuse reflecting, from homogenous to compound material and from smooth to rough properties to be analysed.

Surface roughness was determined on four different points on the major connector, on each of the fitting (Figure 3.9a) and polished surfaces (Figure 3.9b) of the denture frameworks.



Figures 3.9: Red squares indicate points chosen for surface roughness measurement. (a) Fitting surface, (b) Polished surface

Measurements were repeated three times for each point. A data set (Fig. 3.10) was produced for every surface texture analysis and Sa value representing surface roughness was taken and recorded in SPSS (SPSS Statistics V21; IBM Corp, US).

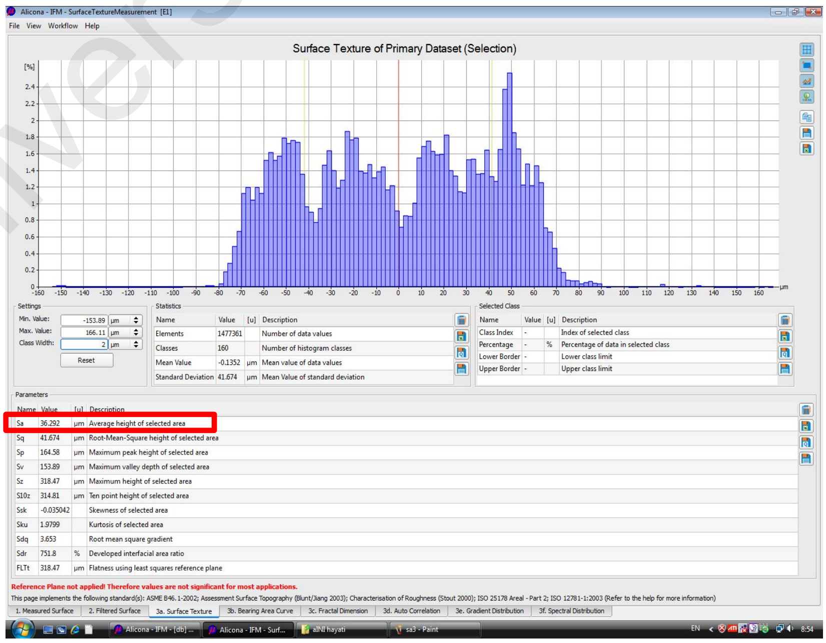


Figure 3.10: Example of data set provided for each surface texture analysis. Red box indicates Sa value for surface roughness measurement.

Statistical analysis was done in SPSS (SPSS Statistics V21; IBM Corp, US), and independent t-test has been used to compare the surface roughness and statistical significance value was set at $p<0.05$.

CHAPTER 4: RESULTS

Normality tests done made for the fitting and polished surfaces of all the specimens (n=10) and Shapiro-Wilk results revealed *p-values* for these specimens lie above the pre-determined significance level of $p<0.05$, therefore it was concluded that the data was normally distributed (Table 4.1)

Table 4.1: *p-values* from normality tests for fitting and polished surfaces of all specimens fabricated with conventional casting and SLM methods.

	Polished surface	Fitting surface
**p-value*	*0.390*	*0.088*

n = 10; SD = standard deviation; *significant difference level was set at *0.05* using t-test

The results of independent t- test are summarized in table 4.2 which revealed no significant difference ($p>0.05$) in roughness of the polished and fitting surfaces between the conventional casting and SLM specimens.

Table 4.2: Mean surface roughness (Sa) values of the fitting and polished surfaces of specimens fabricated by conventional casting and SLM methods (n=5)

SURFACE	**n**	**Surface roughness, Sa (µm) Mean (SD)**		
		Conventional	SLM	*p-value
Polished	5	31.06 (16.32)	30.24 (12.19)	*0.217*
Fitting	5	28.90 (10.57)	29.14 (11.68)	*0.659*
		0.17	*0.45*	

; SD = standard deviation; underlined are *p-values* ; *significance level was set at *0.05* using t-test

Independent sample t-test was also employed to analyse the difference in surface roughness between all specimens fabricated by both methods of conventional casting and SLM regardless of the surface. No significant difference ($p>0.05$) were found. The results are demonstrated in (Table 4.3).

Table 4.3: Mean surface roughness (Sa) values of specimens fabricated by conventional casting and SLM methods regardless of surfaces

Surface roughness, Sa (µm)		
Mean (SD)		
Conventional	SLM	**p-value*
29.97 (13.61)	29.69 (12.15)	*0.50*

*n=10; significance level was set at 0.05 using independent t-test

Independent sample t-test was also employed to analyse the difference in surface roughness between all specimens fabricated by both methods of conventional casting and SLM regardless of the surface. No significant difference ($p>0.05$) were found. The results are demonstrated in Table 4.3.

CHAPTER 5: DISCUSSION

Additive manufacturing particularly selective laser melting technique has been introduced in the fabrication of metal partial denture framework as the next phase after rapid prototyping and stereolithography having brought forth the manufacturing of non-metallic parts from acrylic, resin and plastic materials (Dickens, 1995).

Being a relatively recent application, and realizing the fact that a dental prosthesis interacts with biological environment and tissue, the requirement for denture framework fabricated with this new technique to be investigated is undeniable. A number of research are available in the literature investigating titanium and nickel-chromium based denture framework and dental prostheses (Bartolomeu et al., 2019; Hong et al., 2016; Revilla-León et al., 2018) however the specific focus on surface characteristics of cobalt chromium denture framework fabricated using SLM technique calls for more investigation and publication.

This current study has investigated the surface roughness of cobalt chromium denture framework fabricated with conventional lost wax casting technique and the recently introduced SLM technique in Sa measurement. There was no statistical difference *(p >0.05)* obtained of the roughness between these two types of specimens of the conventional lost wax casting and SLM groups.

Previous studies have shown the surface roughness measurement of conventionally fabricated cobalt-chromium denture frameworks in Ra measurement, to be as low as 0.14 µm (Aydin, 1991) in polished samples and 0.15 µm (Taylor et al., 1998), to as high as 3.50 µm (Aydin, 1991), 13.39 µm (Jang et al., 2001) and and 2.13 µm (Taylor et al., 1998). As for cobalt chromium specimens fabricated with SLM Pupo et al. (2015) demonstrated Ra value of surface roughness to range between 4 to 15 µm with different laser power and scanning space settings. Hong et al. (2016) reported Ra values of 1.3 to 21.5 µm with variable scan line spacing parameters. These values are however not suitable for direct comparison to be made with the findings in this current study for the reason that Ra measurement employs a different procedure of measurement as compared to Sa type of measurement used in this study. Areal method of measurement deals with the average roughness value obtained from a determined area as compared to a line drawn on a surface in linear measurement approach.

According to Whitehouse (2004), due to optical nature of optical measurement that the angle, resolution and depth of focus are not able to be adjusted without affecting each other, surface roughness readings might be affected for very fine surfaces. Optical method might give larger value for surface roughness than the stylus method. These two measurement modalities however should not be treated as correct or wrong, because they behave according to their own physical laws and should be regarded as complementary to each other.

In an study by Vorburger et al. (2007) attempting to investigate the differences between the optical and stylus methods of measuring surface texture, it was found that the average differences between the Ra and Sa measurements were less than or equal to 6 µm. However, the largest discrepancy was up to 75% of the Ra value. Taking this paper as a reference and comparing the mean Sa measurement obtained from this current study to Ra measurement of surface roughness from other studies (Aydin, 1991; Jang et al., 2001; Taylor et al., 1998) it could be inferred that the mean Sa readings of 29.97 µm (conventional) and 29.69 (SLM), to carry the converted Ra readings between 23.97 – 35.97 µm and 23.69 - 35.69 µm respectively. These figures are comparably higher than Ra values surface roughness values obtained from other previous studies (Aydin, 1991; Jang et al., 2001; Swelem et al., 2014; Taylor et al., 1998).

This current study has adopted Sa measurement for surface roughness analysis as compared to Ra measurement that is prominent in literature. Sa measurement is considered a more recent parameter and came into existence with the development of optical devices that is used for surface analysis (Vorburger et al., 2007) and standardization of areal surface texture measurement has been developed by ISO for geometrical product specification.

Studying the analysis of the difference in surface roughness between the same type of surfaces of denture framework between specimens fabricated using conventional and SLM techniques; it was revealed that there was no significant difference obtained *($p > 0.05$)*. No pertinent study was found available in the literature relating the direct comparison of conventionally fabricated cobalt chromium denture framework to those fabricated with SLM technique in specific regards of surface roughness subject. It could be drawn from this current study that both techniques yield comparable surface roughness quality.

Nonetheless, it has to be respected that different process parameters produce different results in respect of laser power, scan rate and scan line spacing (Koutsoukis, 2015; Takaichi, May 2013). It has been discovered that the optimal laser power, scan rate and scan line spacing for smooth surface formation were 200 W, 128.6 mm/s and 100 µm respectively for cobalt chromium alloy by Hong et al. (2016), and 400 W laser power and 450 µm scan spacing by Pupo et al. (2015). In another study, the parameters that has been determined for SLM fabricated nickel chromium alloy were 200 W for laser power, 98.8 mm/s for scan speed and 60 µm for scan spacing (Hong et al., 2018).

The analysis between the polished and fitting surfaces of the SLM specimens has been done with independent sample t-test analysis. It is known that cast cobalt chromium exhibits many microstructural variations (Koutsoukis, 2015; Takaichi, May 2013), therefore it is important to determine if any variation in the surface quality was present within SLM specimens. It was found that the there is no statistical difference $(p > 0.05)$ in the surface roughness between the polished (30.24 µm - $\bar{X}$) and fitting surfaces (29.14 µm - $\bar{X}$) of SLM specimens. This observation corresponds to another study (Takaichi, May 2013) in regards of uniformity of surface quality for cobalt chromium specimens fabricated with SLM technique. It has been demonstrated by optical microscopy images that in SLM cobalt chromium specimens observed in transverse cross section from build direction, fine lamellae elongated to the build direction was noted. This phenomenon is related to process parameters as mentioned above, as differences in input energy results in differential melted and densified zones, resulting in porosity or density of the microstructure (Takaichi, May 2013).

CHAPTER 6: CONCLUSION

Within the limitation of this study, it concluded that the surface roughness quality of cobalt chromium denture framework fabricated with SLM technique is comparable to that fabricated with the conventional lost wax casting technique. The surface roughness of SLM fabricated cobalt chromium denture frameworks carry the same surface roughness quality between the polished and fitting surfaces.

CHAPTER 7: RECOMMENDATIONS

Amongst the limitations of this current study includes lack of Ra measurement of surface roughness obtained for the specimens. This has hindered due comparison to be made between the results from the current study with previous publications. It is recommended that in the future studies, both Sa and Ra measurements are taken into consideration and recorded. This would provide enough information for comparison with previous studies as well as offers new information in Sa measurement that is scarce in the literature.

It is also recommended that scanning electron microscopy (SEM) analysis are taken of the surfaces of the specimens. Other than giving supporting information to the statistical analysis (Aydin, 1991), further information on surface topography would be able to be obtained and it would allow comparison to be made between the surfaces of the specimens fabricated using both methods such as surface porosity and microstructural appearance, as how it has been demonstrated by Alageel et al. (2018) that the polished surface of conventionally fabricated cobalt chromium denture frameworks exhibited grainy surface as opposed to fine microstructure on laser sintered specimens. It is also prominent in many studies in surface roughness where SEM analysis was included as part of the analysis (Alageel et al., 2018; Aydin, 1991; Jang et al., 2001; Taylor et al., 1998).

The employment of microbial analysis would also help to substantiate surface analysis. It has been well demonstrated that a small increase in surface roughness significantly increases bacterial retention as compared to smooth surfaces of less Ra value (Taylor et al., 1998; Verran et al., 1991). The recommendation for microbial analysis such as C. *albicans* assay would further confirm the roughness profile of the specimens.

It would also be prudent for bigger sample size to be studied in future investigations. Bigger sample size will reduce the standard error, hence a better statistical representation of the population can be made.

REFERENCES

Alageel, O., Abdallah, M. N., Alsheghri, A., Song, J., Caron, E., & Tamimi, F. (2018). Removable Partial Denture Alloys Processed By Laser‐Sintering Technique. *Journal Of Biomedical Materials Research Part B: Applied Biomaterials, 106*(3), 1174-1185.

Anusavice, K. J. (2003). Philip's Science Of Dental Materials. 11 St. *Louis: Elsevier Science*, 96.

Atzeni, E., & Salmi, A. (2012). Economics Of Additive Manufacturing For End-Usable Metal Parts. *The International Journal Of Advanced Manufacturing Technology, 62*(9-12), 1147-1155.

Aydin, A. K. (1991). Evaluation Of Finishing And Polishing Techniques On Surface Roughness Of Chromium-Cobalt Castings. *The Journal Of Prosthetic Dentistry, 65*(6), 763-767.

Bartolomeu, F., Costa, M., Gomes, J., Alves, N., Abreu, C., Silva, F., & Miranda, G. (2019). Implant Surface Design For Improved Implant Stability–A Study On Ti6Al4V Dense And Cellular Structures Produced By Selective Laser Melting. *Tribology International, 129*, 272-282.

Berman, B. (2012). 3-D Printing: The New Industrial Revolution. *Business Horizons, 55*(2), 155-162.

Blunt, L., & Jiang, X. (2003). *Advanced Techniques For Assessment Surface Topography: Development Of A Basis For 3D Surface Texture Standards" Surfstand"*: Elsevier.

Bollen, C. M., Papaioanno, W., Van Eldere, J., Schepers, E., Quirynen, M., & Van Steenberghe, D. (1996). The Influence Of Abutment Surface Roughness On Plaque Accumulation And Peri‐Implant Mucositis. *Clinical Oral Implants Research, 7*(3), 201-211.

Bollenl, C. M., Lambrechts, P., & Quirynen, M. (1997). Comparison Of Surface Roughness Of Oral Hard Materials To The Threshold Surface Roughness For Bacterial Plaque Retention: A Review Of The Literature. *Dental Materials, 13*(4), 258-269.

Bremen, S., Meiners, W., & Diatlov, A. (2012). Selective Laser Melting: A Manufacturing Technology For The Future? *Laser Technik Journal, 9*(2), 33-38.

Budak, I., Kosec, B., & Sokovic, M. (2012). Application Of Contemporary Engineering Techniques And Technologies In The Field Of Dental Prosthetics. *Journal Of Achievements In Materials And Manufacturing Engineering, 54*(2), 233-241.

Budtz‐Jörgensen, E. (1974). The Significance Of Candida Albicans In Denture Stomatitis. *European Journal Of Oral Sciences, 82*(2), 151-190.

Campbell, T., Williams, C., Ivanova, O., & Garrett, B. (2011). Could 3D Printing Change The World. *Technologies, Potential, And Implications Of Additive Manufacturing, Atlantic Council, Washington, DC*, 3.

Davenport, J. (1970). The Oral Distribution Of Candida In Denture Stomatitis. *Brit. Dent. J., 129*(4), 151-156.

Dickens, P. (1995). Research Developments In Rapid Prototyping. *Proceedings Of The Institution Of Mechanical Engineers, Part B: Journal Of Engineering Manufacture, 209*(4), 261-266.

Dolenc, A., & Mäkelä, I. (1994). Slicing Procedures For Layered Manufacturing Techniques. *Computer-Aided Design, 26*(2), 119-126.

Hong, M.-H., Min, B. K., & Kwon, T.-Y. (2016). The Influence Of Process Parameters On The Surface Roughness Of A 3D-Printed Co–Cr Dental Alloy Produced Via Selective Laser Melting. *Applied Sciences, 6*(12), 401.

Hong, M.-H., Son, J. S., & Kwon, T.-Y. (2018). Surface Roughness Of A 3D-Printed Ni–Cr Alloy Produced By Selective Laser Melting: Effect Of Process Parameters. *Journal Of Nanoscience And Nanotechnology, 18*(3), 2037-2040.

Jang, K.-S., Youn, S.-J., & Kim, Y.-S. (2001). Comparison Of Castability And Surface Roughness Of Commercially Pure Titanium And Cobalt-Chromium Denture Frameworks. *The Journal Of Prosthetic Dentistry, 86*(1), 93-98.

Jevremovic, D., Puskar, T., Kosec, B., Vukelic, Đ., Budak, I., Aleksandrovic, S., . . . Williams, R. (2012). The Analysis Of The Mechanical Properties Of F75 Co-Cr Alloy For Use In Selective Laser Melting (SLM) Manufacturing Of Removable Partial Dentures (RPD). *Metalurgija-Zagreb, 51*(2), 171.

Kajima, Y., Takaichi, A., Nakamoto, T., Kimura, T., Yogo, Y., Ashida, M., . . . Hanawa, T. (2016). Fatigue Strength Of Co–Cr–Mo Alloy Clasps Prepared By Selective Laser Melting. *Journal Of The Mechanical Behavior Of Biomedical Materials, 59*, 446-458.

Koutsoukis. (2015). Selective Laser Melting Technique Of Co-Cr Dental Alloys: Areview Of Structure And Properties And Comparative Analysis With Other Available Techniques.

Kruth, J.-P. (1991). Material Incress Manufacturing By Rapid Prototyping Techniques. *CIRP Annals, 40*(2), 603-614.

Kruth, J.-P., Mercelis, P., Van Vaerenbergh, J., Froyen, L., & Rombouts, M. (2005). Binding Mechanisms In Selective Laser Sintering And Selective Laser Melting. *Rapid Prototyping Journal, 11*(1), 26-36.

Leach, R. (2011). *Optical Measurement Of Surface Topography* (Vol. 14): Springer.

Liu, B., Kuai, Z., Li, Z., Tong, J., Bai, P., Li, B., & Nie, Y. (2018). Performance Consistency Of Alsi10mg Alloy Manufactured By Simulating Multi Laser Beam

Selective Laser Melting (SLM): Microstructures And Mechanical Properties. *Materials, 11*(12), 2354.

Noort, R. V. (2012). The Future Of Dental Devices Is Digital. *Dental Materials, 28*(1), 3-12.

Olsen, I. (1974). Denture Stomatitis Occurrence And Distribution Of Fungi. *Acta Odontologica Scandinavica, 32*(5), 329-333.

Pham, D. T., & Gault, R. S. (1998). A Comparison Of Rapid Prototyping Technologies. *International Journal Of Machine Tools And Manufacture, 38*(10-11), 1257-1287.

Pupo, Y., Monroy, K. P., & Ciurana, J. (2015). Influence Of Process Parameters On Surface Quality Of Cocrmo Produced By Selective Laser Melting. *The International Journal Of Advanced Manufacturing Technology, 80*(5-8), 985-995.

Quirynen, M., Marechal, M., Busscher, H., Weerkamp, A., Darius, P., & Van Steenberghe, D. (1990). The Influence Of Surface Free Energy And Surface Roughness On Early Plaque Formation: An In Vivo Study In Man. *Journal Of Clinical Periodontology, 17*(3), 138-144.

Revilla-León, M., Ceballos, L., Martínez-Klemm, I., & Özcan, M. (2018). Discrepancy Of Complete-Arch Titanium Frameworks Manufactured Using Selective Laser Melting And Electron Beam Melting Additive Manufacturing Technologies. *The Journal Of Prosthetic Dentistry, 120*(6), 942-947.

Swelem, A. A., Abdelnabi, M. H., Al-Dharrab, A. A., & Abdelmaguid, H. F. (2014). Surface Roughness And Internal Porosity Of Partial Removable Dental Prosthesis Frameworks Fabricated From Conventional Wax And Light-Polymerized Patterns: A Comparative Study. *The Journal Of Prosthetic Dentistry, 111*(4), 335-341.

Takaichi. (May 2013). Microstructures And Mechanical Properties Of Co–29Cr–6Mo Alloy Fabricated By Selective Laser Melting Process For Dental Applications. *Journal Of The Mechanical Behavior Of Biomedical Materials, 21*, 67-76.

Taylor, R., Maryan, C., & Verran, J. (1998). Retention Of Oral Microorganisms On Cobalt-Chromium Alloy And Dental Acrylic Resin With Different Surface Finishes. *The Journal Of Prosthetic Dentistry, 80*(5), 592-597.

Verran, J., Lees, G., & Shakespeare, A. P. (1991). The Effect Of Surface Roughness On The Adhesion Of Candida Albicans To Acrylic. *Biofouling, 3*(3), 183-191.

Vorburger, T. V., Rhee, H.-G., Renegar, T. B., Song, J.-F., & Zheng, A. (2007). Comparison Of Optical And Stylus Methods For Measurement Of Surface Texture. *The International Journal Of Advanced Manufacturing Technology, 33*(1-2), 110-118.

Whitehouse, D. J. (2004). *Surfaces And Their Measurement*: Elsevier.