# The Development of Design Rules for Selective Laser Melting

Daniel Thomas

Ph.D. Thesis

1 of 2

# The Development of Design Rules for Selective Laser Melting

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This dissertation is being submitted in fulfilment for the requirements for the degree of Doctor of Philosophy for the University of Wales Institute, Cardiff.

October 2009

# Declaration

This dissertation is the result of my independent research. Where it is indebted to the work of others, acknowledgement has been made.

I declare that it has not been accepted for any other degree, nor is it currently being submitted in candidature for any other degree.

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# Abstract

The research reported in this thesis focuses on assisting the design process in respect of end use metallic products produced using the Selective Laser Melting (SLM) technology. The advancements in rapid prototyping technologies such as SLM have enabled the rapid manufacture of end use products directly from Computer Aided Design data. Many companies and researchers are exploring the application of SLM in industry for specific applications, such as the mass customisation of biomedical implants and novel lattice structures. However, bridging SLM from research into mainstream manufacturing is not straightforward, as demanding industry standards and compliance need to be fulfilled.

Rapid manufacturing technologies are often perceived by designers as being able to generate all conceivable geometries. However, SLM is not completely freeform as the inherent process difficulties can distort many part geometries, and designers often lack an understanding of these process issues and their effect of the final SLM product. The aim of this research is to address this lack of design knowledge, by developing a set of design rules to allow for more predictable and reliable results when manufacturing parts with SLM.

This Thesis documents how the design rules were created. Firstly, the geometric limitations of SLM were evaluated through a qualitative cyclic experimental methodology. Part orientation, fundamental geometries and compound design features were explored until self-supporting parts with the optimum part accuracy were achieved. Design rules were then created and evaluated through a series of interviews with industrial and academic design professionals.

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## Glossary of Terms

| | |
|---|---|
| 3D Systems | A USA based company who produce Stereolithography equipment. |
| 3DP | 3-Dimesional Printer |
| 3M ESPE | Specialist supplier of dental products |
| 3M Lava Scan ST Design System | A dental 3d-Scanner that incorporates that assists the design of patient specific dental products |
| 3TRPD | A Rapid Manufacturing / Prototyping bureaux |
| AM | Additive Manufacturing: a name given to all process manufacturing end use parts in layers. |
| ASME | American society of Mechanical Engineers |
| ASTM | American Society for Testing and Materials |
| Boeing | The Boeing Company is a major aerospace and defence corporation |
| CAD | Computer Aided Design |
| Ciba-Geigy | Company that collaborated with 3D-Systems to develop SL resins and the STL file format. |
| CMM | Coordinate Measuring Machine |
| CNC | Computer Numerically Controlled machining. |
| Concept Laser GmbH | A company who produces Laser Cusing Machines |
| DFM | Design for Manufacture |
| DMLS | Direct Metal Laser Sintering (Trade name for EOS GmbH process) |
| DTM | Rapid Prototyping Vendor |
| EOS GmbH | Electro Optical Systems. A German based producer of rapid prototyping machines. |
| F&S | Fockele and Schwartz |
| FDM | Fused Deposition Modelling. An RP process that builds in plastic |
| FEA | Finite Element Analysis |
| IR | Infra-Red |
| Laser Cusing | Trade name for Concept Laser GmbH process |
| LOM | Laminated Object Manufacture. An RP process that builds in paper. |
| LS | Laser Sintering (same as SLS; SLS is a registered trademark of 3-D systems) |
| Magics | STL manipulation software by Materialise. |
| Marcam | CAD / CAM software developer |
| Material File | A file that contains all process parameters on the SLM Realizer. |
| Materialise | A software developer and supplier of rapid prototyping services based in Belgium. |
| Maxillofacial | Surgery to correct a wide spectrum of diseases, injuries and defects in the head, neck, face, jaws and the hard and soft tissues |
| Maxillofacial | Surgical specialty concerned with the diagnosis and treatment of |

| | |
|---|---|
| (surgery) | diseases affecting the mouth, jaws, face and neck. |
| MTT (previously MCP) | A SLM developer and manufacturer |
| NPD | New Product Development |
| Objet | Objet Geometries RP system that manufactures in a photopolymer. |
| ODM | On Demand Manufacturing |
| Orthopaedic | Surgery concerned with conditions involving the musculoskeletal system. |
| Osseointegration | A fixed, bone anchored retention method for attaching external or oral prostheses. |
| PDS | Product Design Specification |
| Photopolymer | A polymer that cures and solidifies when exposed to light |
| Photoshop | Digital image manipulation software by Adobe Systems Inc. |
| RM | Rapid Manufacturing |
| Rolls Royce Aero-Engines | Aerospace engine division of Rolls Royce. |
| RP | Rapid Prototyping. |
| RPD | Removable Partial Denture framework. |
| Sandvik Opsrey | A company that produces gas atomized metallic powders |
| SL | Stereolithography |
| SLA | Stereolithography Apparatus |
| SLA-250 | A 3D Systems Stereolithography machine. |
| SLA-500 | A 3D Systems Stereolithography machine. |
| SLM | Selective Laser Melting. An RP process that builds in metal. By MCP-HEK, Germany. |
| SLS | Selective Laser Sintering. An RP process. |
| STL | Stereolithography file format. Defines 3D volumes in faceted triangles. |
| TGM | Temperature Gradient Mechanism |
| Ti | Titanium metal. |
| UV | Ultraviolet light spectrum. |
| VisCAM | CAD software created by Marcam |

# Chapter 1: Introduction

Product development and manufacturing technologies are all aimed at improving productivity by improving efficiency and product quality through the entire manufacturing process, from concept and detailed design, to quality control and packaging. The introduction of rapid prototyping (RP) technologies gave a new insight to the design and development of a product as visual aesthetic and ergonomic models could be produced with minimum labour and tooling required. Since the introduction of RP systems, technologies have advanced and the availability of manufacturing-grade material has increased. This has resulted in rapid manufacturing (RM) which enables the use of RP systems to produce end use functional parts. RM, which is otherwise known as Additive Manufacturing (AM), is still an emerging manufacturing principle that has led to vast research areas in academia and industry.

Selective Laser Melting (SLM) is a layer additive manufacturing process, which has advanced from Selective Laser Sintering (SLS) into a process potentially capable of manufacturing high-value, low volume, end use parts from an increasing inventory of metals and alloys. Research into SLM has been focused on the physics, metallurgical, and advanced applications of SLM rather than research from a designer's perspective. The gap in knowledge is that there is very little design experience when an SLM part is being designed. Designers are unaware of the limitations and possibilities of the SLM process and therefore, design parts to be made using incompatible design rules from familiar processes such as casting, milling and injection moulding. This has been recognised as a barrier to the growth of additive manufacturing and in particular SLM (Wohlers, 2009).

This research was conducted to address this gap in knowledge, in particular to develop design rules that address the lack of design knowledge and design experience of SLM. The research undertaken has been conducted from a designer's perspective to design within the limitations of SLM through initiating draft design rules. This research has contributed to new knowledge as it is the first research that fully evaluates the geometrical limitations of SLM, and the first to develop design rules that are specific to SLM.

The aim of this research is to develop a first draft of process-specific design rules for SLM. To accomplish the aims of this research, the following objectives were addressed:

- Evaluate the SLM process, and identify the geometric limitations of SLM.
- Perform analysis and synthesis of the experimental results and create a first draft of design rules appropriate for use in design practice.
- Evaluate the design rules to establish their effectiveness and inform their further development.

All research undertaken to address the aims and objectives of this study are described as follows in chapters two to eight. The following chapter describes a review of relevant existing literature.

# Chapter 2: Literature Review

## 2.1 Overview

The following chapter presents an introduction and background to Rapid Prototyping (RP) developments and technologies. This chapter also explains the technology advancements, research and industrial applications that have evolved RP into Rapid Manufacturing (RM). Selected Laser Melting (SLM) has become a key RM process; an introduction to SLM is presented, along with an in-depth review of the existing SLM literature. This review is described in two sections: the first explaining existing research on the processing and physics of the SLM technology, followed by a review of research into applications of SLM. Finally, this chapter provides evidence from existing literature that product designers need to be educated with design rules to advance SLM as a RM process, in order to exploit all possible applications and benefits in high-value product design.

## 2.2 Rapid Prototyping

### 2.2.1 Overview

Rapid Prototyping (RP) is a description given to a variety of technologies that manufacture parts layer-by-layer. Otherwise known as Additive Manufacturing (AM), RP is used to produce physical models with limited functionality directly from three-dimensional Computer Aided Design (CAD) data. RP parts have low functionality and are commonly used as visual aids within product development. However, some RP parts have a limited amount of short-term functionality for more extensive prototype testing depending on the material selection. The materials used within RP are nearly all polymer based, which allows for limited part functionality. Also starch-based materials and paper is used which allows for very little functionality. The ability to manufacture single or multiple physical models has revolutionised product development, enabling the reduction of the product life cycle time in a range of industries from automotive to medical.

### *2.2.2 Principles of Rapid Prototyping*

RP produces parts by the polymerisation, fusing or sintering of materials in predetermined layers without the need for tools, as opposed to subtractive processes where material is removed from stock billet. RP is able to produce geometries that are almost impossible to produce using other machining or moulding processes. The process does not require predetermined tool paths; draft angles or undercuts and internal part details can be designed and produced using RP.

The layers of all RP parts are created by slicing CAD data with specialist software (see Figure 2.1). All RP systems work using this principle; however, the thickness of the layers is dependent on the parameters and the system used. Machines that are used commercially in widespread applications typically use layers from 16µm up to 200µm. In all RP processes the layers are visible on the surface of the part, which influences the surface roughness of the finished part. This is known as the staircase effect and is a relationship between the layer thickness and the orientation of a surface. The thinner each layer is, and the more vertical the orientation of a part wall, the smaller each step will be, which results in the smoothest surface roughness. Also the thinner the layer is the longer the processing time and the higher the part resolution (Jacobs, 1992).

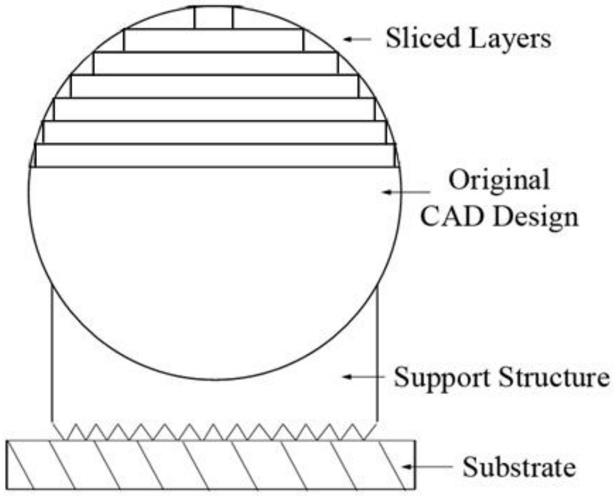



Figure 2.1: Image of the layers of a RP part, and the principle of the support structure

The layers of an RP part are built up one on top of another in the z-axis. As one layer has been processed, the work platform and substrate plate is lowered by one layer thickness in the z-axis and a new layer of material is recoated by using a number of different methods. With resin based systems the parts submerge in the resin by one layer thickness and a traversing edge flattens the resin before the material is processed. With powder based systems a powder is deposited and spread using a traversing edge or a roller, or the part material is deposited through a print cartridge or a nozzle, which only deposits the support and part material required.

The time that it takes to recoat each layer with new material can be equally long, or even longer than the time it takes for the layer to be processed. For this reason the most efficient way to produce RP parts is to build multiple parts together so that the material recoating time remains the same as building just one part. For optimum build efficiency nesting software has become available to orientate and position parts within a virtual representation of the RP system's build envelope so that the maximum amount of parts can be built together. Currently available examples of nesting software include VisCAM RP (Marcam, Denmark), and SmartSpace that is used within Magics (Materialise, Belgium).

Some parts made using RP technologies require a support structure (Figure 2.1) for fixing the part into position on a substrate plate during the build process. This support structure also prevents the part layers from lifting away from its axis as a result of material shrinkage.

All RP systems use a different type of support structure that are designed to be most effective with a specific material or technique that the system uses to build parts. The most commonly used support structures are thin, scaffold-like structures with small pointed teeth for minimising the amount of part contact so that they can be broken away from the part easily using hand tools. Examples of different scaffold support structure designs are shown in Figure 2.2; the supports shown were created in Magics support generation software (Materialise, Belgium).

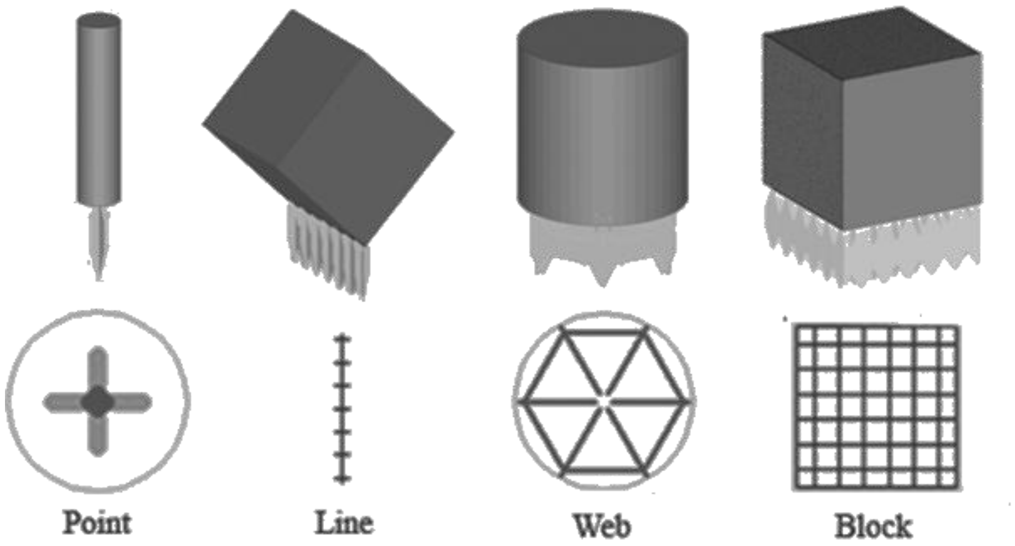



Figure 2.2: Support structures created in Magics support generation software (Materialise, Belgium)

This scaffold-like support style is used in RP systems like Stereolithography (SLA), Selective Laser Sintering (SLS), Selective Laser Melting (SLM) and Fused Deposition

Modelling (FDM). FDM can also produce supports in a soluble material that can be dissolved in a water-based solution after the parts are produced. Three-dimensional printing (3DP) sometimes requires a larger support structure to be used, and in some cases the downward facing surfaces of the parts are completely encased in support material that can be removed by breaking away or using a high-pressure water jet.

### *2.2.3 History*

RP began in the 1980s with the development of Stereolithography (SL), which involved curing photopolymer resins by means of an ultra violet spectrum (UV) laser. This process was patented in 1986 by C. Hull, and together with F. Reed the company known today as 3D Systems was created (Jacobs, 1992). Collaboration between 3D Systems and Ciba-Geigy was formed to develop the SL photopolymer resins and the 3D Stereolithography file format (STL) that is still used to provide data to RP systems today. The first commercially available SLA (Stereolithography Apparatus) was introduced at a show in Detroit in November 1987. Further developments and the increasing recognition of RP resulted in the release of the SLA-250 in 1989, and the SLA-500 in 1990 which allowed the manufacture of larger prototypes (Jacobs, 1992). An example SLA part assembly is shown in Figure 2.3.

Figure 2.3: An example SLA physical prototype part assembly

Research at the University of Texas resulted in the development of the Selective Laser Sintering (SLS) technology, which was followed by the first commercialised SLS in 1992 through a company named DTM. In 2001 DTM were bought out by 3D Systems, which secured 3D Systems place as market leaders within the RP industry. Since SLS was introduced to industry, 3D Systems have been up against several competitors with the largest being EOS GmbH, who has named their system Laser Sintering (LS) because SLS is a registered trade mark of 3D Systems.

The SLS technology works by selectively sintering fine powder materials directly from CAD using an infra-red (IR) laser. SLS mainly processes a number of thermoplastic materials such as nylon (polyamide), glass filled nylon, aluminium filled nylon (alumide) and polystyrene, which means that the parts produced have good mechanical properties and can therefore, be used as functional parts as well as just visual prototypes. Polystyrene models can be used as a sacrificial pattern for investing casting as it leaves very little ash, and the filled polyamide materials have added strength and can be used in rapid tooling applications. An example SLS aircraft part made using EOS Polyamide material is shown in Figure 2.4

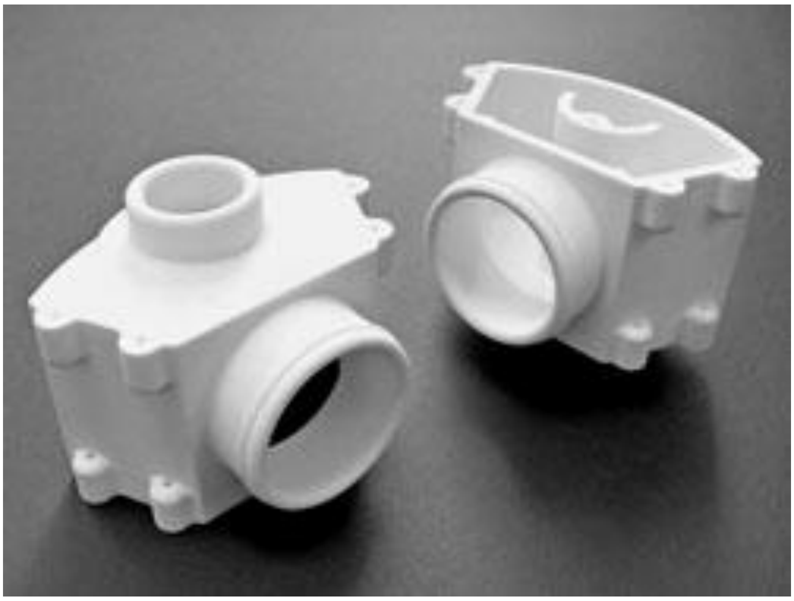


Figure 2.4: SLS aircraft part made using EOS Polyamide material (MWPower, 2007)

The infra-red laser scans the cross sections of each layer, sintering the powder particles and layers together. After the first layer is sintered the substrate drops one layer thickness in the z-axis for more powder to be recoated. The build chamber is preheated and all oxygen is replaced with inert gas such as argon or nitrogen to ensure that there is no oxygen in the sintering process preventing oxides from burning material, and to eliminate the inherent risk of fire caused by handling fine powder.

The build time for sintering each layer and depositing material may be rapid, but the overall process times are increased because of the need to heat the powder which can take around two hours, and then waiting for it to cool down before the parts can be removed from the machines, which can take up to twelve hours. Another drawback of SLS is that

50% of the processed material must be mixed with virgin material after every process cycle because it degrades as a result of the high temperatures required.

The ability to sinter powders using an infra-red laser advanced into the sintering of metal powders in the late 1990s. Specially developed alloys and metals with polymer based binding materials were developed to use SLS for Rapid Tooling. The materials had poor mechanical properties when compared to the traditionally used tool steels and were only suitable for limited small to medium production volumes. The material required post processing to create dense parts. What was known as the "green" part firstly needed to be heated to remove the polymer binder leaving what is called the "brown" part. A secondary material with a lower melting point such as copper or bronze was then infiltrated into the porous part in a furnace, which resulted in dense material parts that were constructed of two materials.

The accuracy of the metal SLS part was difficult to control since stresses were introduced to the parts during each processing stage. A special alloy powder mix material was created by Electrolux (Electrolux, Finland) in conjunction with EOS GmbH that did not develop shrinkage distortions; however, this material was still not comparable to tool steels. The next major development in creating metal parts occurred with the introduction of the fibre laser technology. This allowed the introduction of Selective Laser Melting (SLM) since the fibre laser enabled the direct sintering of manufacturing grade metals that were fully melted into dense parts without the need for post process infiltration (see SLM background in 2.4).

Since 1991, a number of other systems have been commercialised, including Laminated Object Manufacturing (LOM), Fused Deposition Modelling (FDM), and Three-Dimensional Printing (3DP). Today, the availability of RP systems has increased, along with the capabilities and materials that can be produced.   Endless selections of materials that replicate the properties of manufacturing materials has increased the effectiveness of producing physical prototypes in new product development (NPD) (Wohlers, 2009; Jacobs, 1996).

## *2.3 Definition of Rapid Manufacturing (RM)*

Rapid Manufacturing (RM) has been described as the use of a computer aided design (CAD)-based automated additive manufacturing process to construct parts that are used directly as finished products or components (Hopkinson, Hague, *et al.* 2006, p. 1).

Since the turn of the century, research into materials and RP system technologies has advanced, and the production of functional, low volume parts have become available and is becoming an increasingly viable manufacturing process within many industries.  RM is the name given to the use of RP technologies when used to produce end-use components from manufacturing grade materials, unlike RP which has limited functionality and does not produce parts with manufacturing grade materials. During the time of this research the terminology for manufacturing layer by layer is undergoing standardisation within ASTM committee F42 on Additive Layer Technologies.  It appears that the preferred name is Additive Manufacturing (AM), however, this is not finalised therefore RM is used throughout this thesis.  Many companies are investing in RM technologies, and are exploring design possibilities to increase the functionally of high-value components and to decrease the product time to market.  The ability to build end use components directly from CAD without the use of tools and multiple process stages has been the key driver in ongoing developments of RM technologies, as well as the ever-expanding inventory of manufacturing grade materials, for example, Titanium, Aluminium, ABS, and Nylon.

The focus of RP technologies has progressed into research and development of RM technologies and applications. However, the advent of RM is not as simple as it first appears. The transition from RP to RM is still ongoing because there are a number of issues that need to be addressed to bridge RM from research to mainstream manufacturing. When parts were made for prototype purposes with RP, quality control and part repeatability was never needed. Since RM parts have an intended functionality, certification and compliance requirements from industry have been introduced which needs to be addressed for applications of RM to advance. These issues include surface finish, accuracy, part repeatability, material control, process data traceability, speed, and machine/material cost.

The regulations of high-value industries differ from country to country, which is why Titanium SLM implants are implanted in countries other than the UK, and why safety-critical RM parts have not yet taken flight on commercial aeroplanes (Ruffo, 2009). According to Richard Rogers of Rolls Royce Aero-Engines UK (Rolls Royce, UK), through private communication, the potential for RM parts being using within aircraft engines has been recognised. Parts have been used in test rigs but have yet to be tested for full flight capabilities. The decision of introducing RM parts into an engine is based on the potential level of failure and the consequence of that failure. Some failures may be catastrophic and others will have less effect.

There are many successful examples of RM within the medical, automotive and aerospace industries (Wohlers, 2009). On Demand Manufacturing (ODM) is a subsidiary of Boeing based in Oxnard, California, who has undertaken certification to produce flight qualified hardware using SLS. ODM are a certified manufacturer for the F/A-18 fighter jet for which over 14,000 parts have been produced. The manufacturing system used is a 3D-

Systems Sinterstation SLS machine which has also been certified to meet aerospace and material compliance.  The material properties for each production run are tested using tensile test bars that are built along side the parts (Davidson & Glock, 2009)

Designers have very little knowledge of how to design for given RM processes, and existing CAD systems do not allow for the freedom in design and part complexity that is possible with RM.  In fact, RM systems can produce parts with such high detail that commercial CAD packages cannot even cope with the amount of data that needs to be processed.  This is a recognised concern within industry because it prevents designers exploring RM design possibilities and exploiting advantages (Hague *et al*. 2006).

As previously stated, no safety critical parts have been installed on a commercial aircraft, however, the potential for using RM for such parts are being explored, and there are several successful cases of parts being used on non-commercial Formula One race cars, racing catamarans and the Red Bull Air Race performance aircraft as shown as shown in Figure 2.5.  The part shown is an air intake cover that has been rapid manufactured.

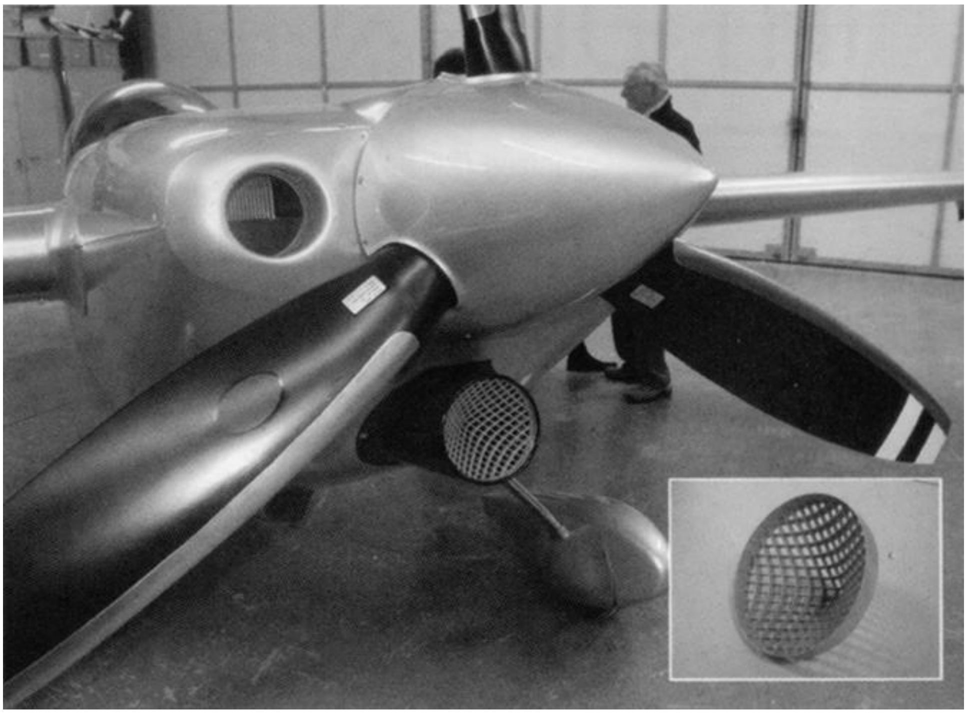


Figure 2.5: Rapid Manufactured air intake on a Red Bull Air Race performance aircraft (Wood, 2009)

Figure 2.6 shows an example RM SLS part made by 3D Systems in the USA for the Oregon State University Formula SAE Team. This part is an engine intake that was made from polyamide, and was lighter and less time consuming to manufacture than their previous manufacturing process of bonding pipes and composite materials. The ability to optimise the design through internal features meant that there was a more efficient use of fuel and air within the part. The part was installed into a race car and used in competition.

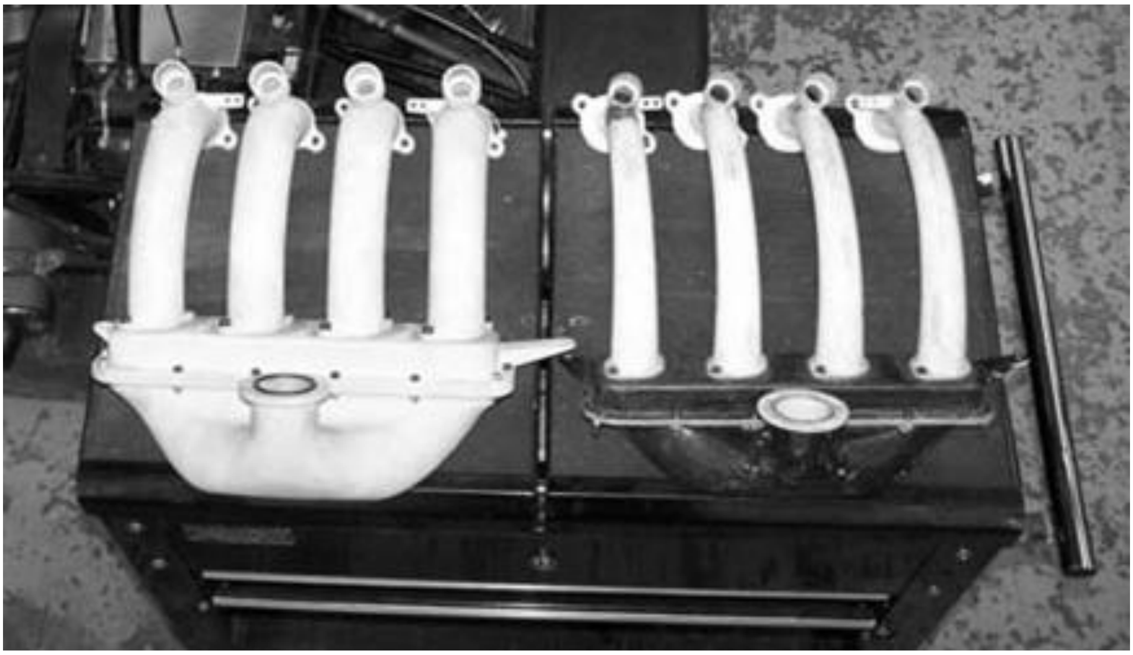


Figure 2.6: On the left is an engine intake made using SLS, and the right shows the same part made using hand made methods (3D Systems, 2009)

## 2.4 Selective Laser Melting (SLM)

### 2.4.1 Overview

Selective Laser Melting (SLM) is a layer additive process that is evolving into a viable RM process. SLM has advanced from Selective Laser Sintering (SLS) since the availability of fibre laser technologies and is constantly developing through vigorous in-house and university-based research. Powder particles can now be fully melted to form dense parts rather than less functional sintered parts as with previous metal SLS. The materials that can be processed using SLM are potentially capable of manufacturing end-use parts with industrially acceptable mechanical properties directly from CAD. Since the developments in materials, hardware, technical knowledge and SLM building techniques, many industries have recognised opportunities for fully functional parts to be manufactured using SLM. Several university spin off companies have been established that rely solely on producing SLM parts, such as dental crowns. Exploiting the use of SLM can allow for the design of components to be optimised to create functionalities beyond the capabilities of any previous technologies. However, for the SLM technology to be placed into a rapid manufacturing (RM) category and for the process to gain greater acknowledgment in industry, many process changes and developments need to be fulfilled and the process needs to prove itself as being a viable, reliable, repeatable and cost-effective manufacturing solution.

### *2.4.2 SLM background*

The first SLM system was introduced by Fockele and Schwarze (F&S) of Germany in 1999. This was a stainless steel powder-based SLM system that was developed in cooperation with the Fraunhofer Institute for Laser Technology (Wohlers, 2009). Later, Fockele and Schwarze teamed up with MCP (now MTT Technologies Group) to be the first to commercially release a direct metal system with the MCP Realizer Selective Laser Melting machine in 2004. This machine was then replaced by the SLM Realizer 250, and in 2005 the SLM Realizer100 higher resolusion machine was released.

Since the release of the MCP Realizer SLM, other machine manufacturers (Trumph, EOS, and Concept Laser) released systems naming their process with the different name of Direct Metal Laser Sintering (DMLS) and Laser Cusing. SLM is the name that has become generic to all processes, and the name used in this research. In 2001 Concept Laser (GmbH) released the M3 Linear, an M1 Cusing, and more recently the M2 Cusing systems for manufacturing reactive materials such as aluminium and titanium alloys. In 2003 EOS released a machine named the EOSINT M 270 direct metal laser sintering (DMLS), which is the most frequently installed machine for direct metal fabrication (Wohlers, 2009). In 2008, 3D systems and MTT announced an agreement to distribute SLM machines in North

America. In 2008/9 MTT revealed new versions of their SLM with a new SLM 250 and SLM 125.

### *2.4.3 Principles of SLM*

The SLM process involves the slicing of CAD data and adding support structures just like all other RP and RM processes. Building SLM parts must be completed in an inert gas atmosphere, replacing all oxygen in the building chamber with inert gases such as Argon. A schematic of the SLM process is shown in Figure 2.7.

The hardware of the SLM machine used in this study functions in a similar way to Selective Laser Sintering systems. The metallic powder material is deposited in a predetermined thickness ranging from 50µm to 75µm across a substrate platform of similar material. A fibre laser then draws each layer of the sliced CAD data fully melting the powder particles together. The substrate platform them drops one layer thickness in the z-axis before the material is recoated, and the process is repeated until the entire build is complete. Newer versions of the SLM system use layer thicknesses starting from 20µm.

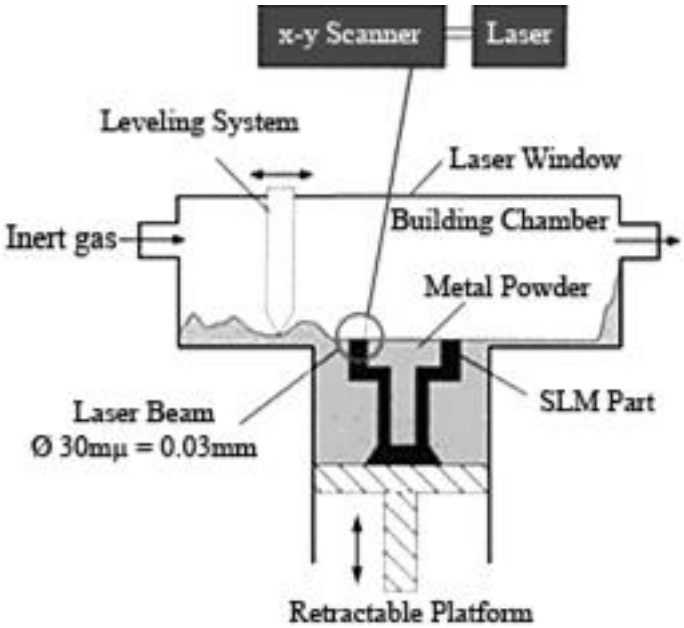



Figure 2.7: Showing a schematic diagram of the SLM process (www.mtt-group.com)

Once the SLM process is complete, the substrate is removed from the build chamber and the supports and parts are removed. The supports need to be carefully designed because they can be difficult to remove as they are the same dense metallic material as the part.

### *2.4.4 Existing SLM research*

SLM is still considered as a new technology, the process is constantly developing due to research into materials, part mechanical properties and process methods. As quoted by Sutcliffe (Nathan, 2006), there is worldwide interest in developing a standard rapid manufacturing process based on selective laser melting. However, very little research has been published on the production of design rules for SLM. The existing SLM research and literature is based on process developments and applications of SLM as an RM technology. Most research was published during the development of the SLM process in collaboration with universities, which resulted in the release of commercial SLM machines. Since the introduction of the SLM Machine, the research focus has shifted from just material and process developments, to research into SLM applications.

In addition to university-based research, the SLM process is now perceived as a viable production-capable process in the biomedical and aerospace markets (Wohlers, 2009). Automotive companies and even Formula One teams are investigating the possibility of incorporating SLM within their production facilities. The suppliers of the SLM technology are constantly making improvements to their process through in-house research and development projects driven from requirements of industrial collaborators. This includes incorporating methods for build data traceability, and increasing the inventory of materials that the machines can process, improving machine performance, and establishing ways to reduce weight on performance products. The in-house research is subject to confidentiality and has caused the amount of published literature to decrease, since the machine suppliers are protecting their potentially valuable intellectual property.

### *2.4.5 Process development and materials research*

SLM research is mainly based on engineering principles and identifying the physics behind the SLM process. Researchers using the SLM machine have investigated how to control the melting of the powder, and the physics of the melt-pools generated during the process. Thesis work by Rombouts (2006) investigated a way to expand the number of materials that can be processed in SLM systems. This was done by identifying the physical behaviour of materials during SLM processing, and understanding the processes at a microscopic level. The main quality attributes for SLM parts such as surface roughness, strength, accuracy, hardness, density and residual stresses have to be examined thoroughly when a new process is being qualified for industrial applications (Rehme & Emmelmann, 2005).

Rehme and Emmelmann (2005) stated that the most important part attribute is that they achieve the highest density possible. It appears that the main aim of the parameter and process optimisation research is to control the density of SLM parts, including work by Childs & Hauser (2005) and Wright *et al*. (2006) who were able to control part density by ensuring optimised scan quality characteristics of single melted scan lines, by measuring and eventually controlling the stability of the melt pools and the heating/cooling temperature gradient. An advancement of just building single scan lines and layers was manufacturing whole components whilst controlling the SLM parameters and scan strategies. This research was completed to identify the effects that different parameters and scan strategies had on part geometry, material porosity (Morgan *et al*. 2004), (Kruth *et al*. 2005), and also to identify a method to control the surface roughness of SLM parts (Mumtaz & Hopkinson, 2007).

The control of process parameters in this study was important towards achieving repeatability of the components created during the SLM process. As stated by Kruth *et al.* (2005), fewer product deformations and higher process accuracy can occur when using optimal parameters. According to Rehme and Emmelmann (2005) there are more than 130 process parameters affecting the SLM process, however, only 13 of these parameters are crucial towards gaining an optimum part quality achievable using SLM.

Theoretical calculations of crucial parameters are used to control the amount of energy that is required to fully melt the metal powder being processed. The main parameters controlled are the laser scanning speed, the laser power, layer thickness and hatching distance. Theory suggests that when the values are set for each variable in the equation, the sum should equal the energy density value for the specific processed material. The use of equations for selecting parameters for specific energy density is a limited, inaccurate method, as proven by Tsopanos *et al.* (2005). In many cases the equations used to select process parameters should be used as a guide to the relationship between the parameters. Therefore, it is important that the theoretical calculations are accompanied by practical testing by the user as small process parameter amendments may be required to optimize the parameter values resulting in an optimum quality of part produced by SLM.

All laser/heat based processes are known to induce large amounts of residual stresses due to the temperature gradient that occurs during the process. Residual stress is a recognised drawback that occurs in SLM. According to research by Mercelis *et al.* (2006) and Kruth *et al.* (2004) investigating scanning strategies and how residual stress develops within SLM parts, the stress is caused by the temperature gradient mechanism (TGM) that occurs in every melt-pool as the powder melts. Each melt-pool is heated rapidly and then cooled down rapidly causing the material to expand and shrink. As one scan line is melted all melt-pools cool and shrink separately causing tensile stress between subsequent melt-pools and also scan lines. As the parts build up in the z-axis the thicker the material becomes, which prevents the shrinkage distorting the parts which consequently causes a build-up of stresses that may effect the mechanical and geometrical properties of the part when the parts are removed from the supports, or even at a later date when the parts are used for their intended application.

Evidence shows that the environment of the SLM needs strict control as it reflects on part quality. The SLM build chamber is a sealed compartment, which is filled with an inert gas such as Argon used in SLM Realizer, or Nitrogen /Argon used with Concept and EOS machines. The flow of the inert gas controls the amount of oxygen in the chamber limiting oxidisation during the process. This was demonstrated in an experiment by Badrossamay and Childs (2007) which resulted in the best part density achieved at a 99.9% Argon atmosphere. Oxides that develop on the parts' surfaces prevent sufficient wetting, the wetting (powder melting) behaviour improves by eliminating the oxides from the base metal surface; this is why soldering requires a flux to get rid of any oxides (Rombouts, 2006).

### 2.4.6 Applications and novel geometries

Expanding the inventory of materials that can be processed using SLM will expand SLM applications in industy. Research has progressed from the development of parameter optimisation and SLM physics of 316L stainless steel, into research of more advanced specialist alloy materials such as Inconel, Aluminium, Titanium, Tool steels and Cobalt Chrome. This reseach is driven by application possibilities, such as work by Kruth and Vandenbrouke (2007) who investigated possiblilties of procesing biocompatable metals for medical parts, such as implants and prostheses. Other research into materials included testing the wear behavior of tool steel mould materials using various SLM processes, compared to conventional machining methods (Voet *et al*. 2005).

In the UK, the medical industry currently use SLM to manufacture surgical cutting guides as shown in Figure 2.8 (Bibb & Eggbeer, 2005), the cutting guides allow for more pre-surgery planning to reduce the time of operations. In the dental industry a company named 3TRPD are producing commercially available dental crowns, and bridges with a system named 3T Frameworks (3TRPD, Berkshire). This system incorporates the use of a 3M Lava Scan ST design system (3M EPSE, UK) and EOS M270 (EOS GmbH) to produce a service that promises a turn-around of three days. The possibility of building Removable Partial Denture frameworks (RPD) has been demonstrated by Bibb *et al.* (2006) (see Figure 2.9). This research has shown that it is feasible to produce RPD frameworks from scan data of patient's anatomy, but has not yet proven to be commercially viable. Other higher risk medical devices including Titanium and Cobalt Chrome implants have been implanted outside the UK in the North America (Medical Modelling, USA), Europe, and Australia (Sercombe *et al*. 2008), (Tolochko *et al*. 2002). Standards and compliance in high-value industries have become a constraint in the advancement in applying SLM to medical devices.

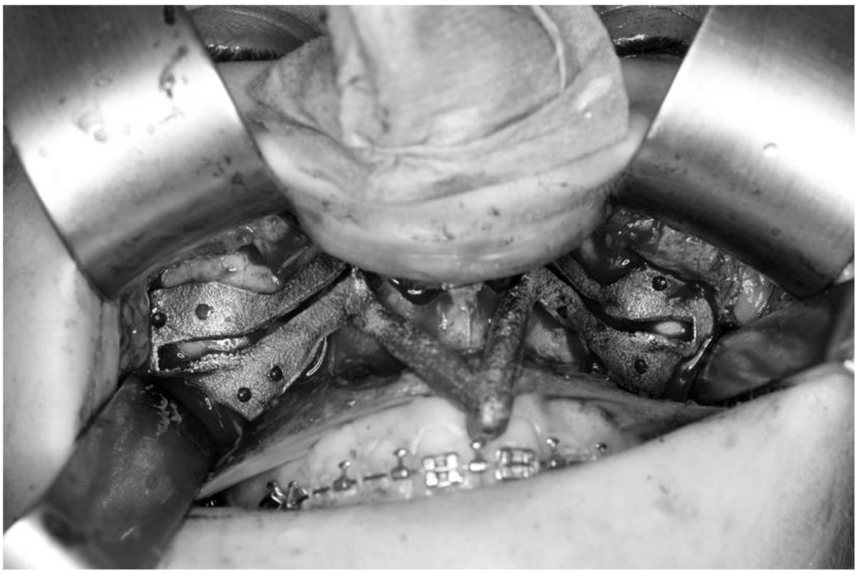


Figure 2.8: Surgical cutting guide fitted to patient during surgery (Bibb & Eggbeer, 2005)

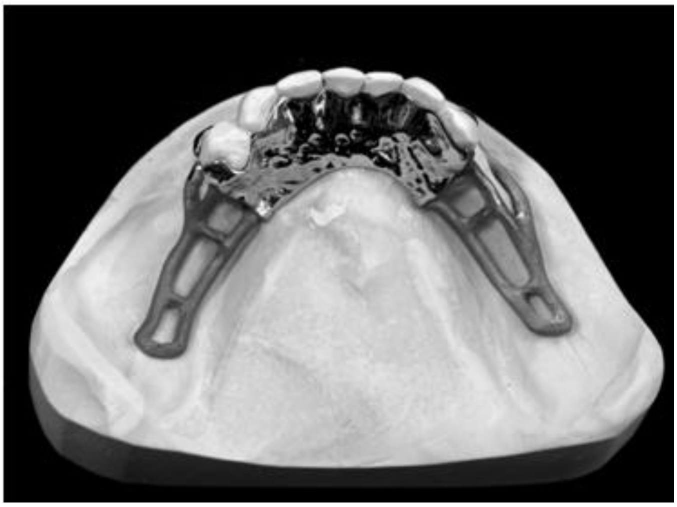


Figure 2.9: RPD framework fitted to patient cast (Bibb *et al*. 2006)

The findings of research into manufacturing implants using SLM is that the surface finish can be manipulated to be selectively porous, and lattice-like structures can be added to areas to promote osseointegration (bonding between the bones and the implant) when implanted. Over 1000 surgeries have completed in the last year with excellent feedback (Ruffo, 2009). In the UK no class 3 medical implants of SLM parts have been carried out because the process has yet to meet the ISO 13485 standard that represents the requirements for a comprehensive management system for the design and manufacture of medical devices. A good example of creating this graded density is reported by Tolochko *et al.* (2002), where both full melting and sintering was used to produce a dental root implant. In this case the laser power was dropped from 100W that produced dense metal, to 60 W to only bond the powder particles together in areas requiring a porous finish (sintering) (see Figure 2.10).

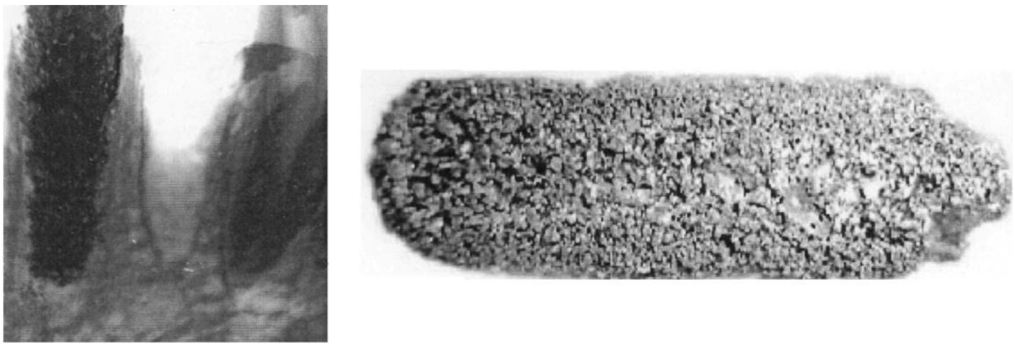


Figure 2.10: (Left) Lower jaw with natural tooth and tooth root cavity for replacement, (Right) Sintered / melted structure of the Ti (cross-section) the laser power is 60W, from Tolochko *et al.* (2002),

Internal geometries can be designed into products that cannot be produced by any other means of manufacturing. Such features have been demonstrated to have lower manufacturing costs and added performance values over conventional processes. A good example is shown by Tsopanos *et al.* (2005) with the manufacture of cross-flow heat exchangers made from stainless steel and copper, and also the manufacture of heat sinks made from Aluminium (Wong *et al*. 2007) (see Figure 2.11). Work by Dotcheva *et al.* (2009) also investigates the design and testing of lattice cellular structures. The research presented in this thesis contributed to the design of the lattice structures and was proven to be valid through expert review. The aim of this research was to investigate the tensile strength of various lattice formations for the possible application within injection mould tooling, and to optimise mould cooling by using cellular internal designs (for full paper see appendix 6).

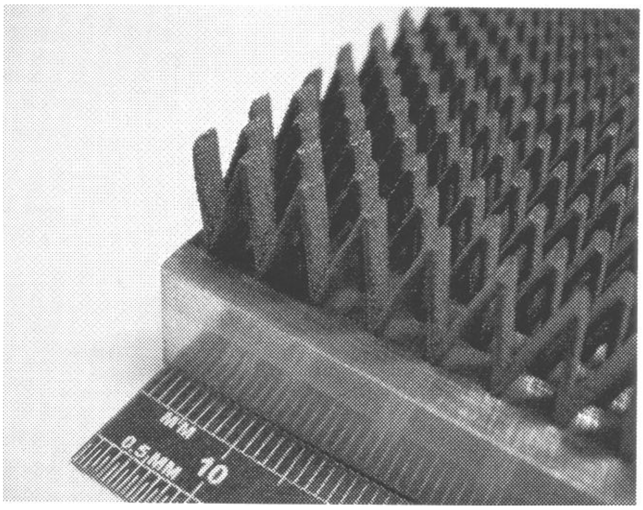



Figure 2.11: Heat sink test parts made using SLM (Wong *et al*. 2007).

One disadvantage of SLM is the significant processing time it takes to melt parts of larger volumes. Research into manufacturing and computer coding novel lattice structures has investigated the possibility of replacing dense volumes of material with lattices that have the same stiffness and strength properties, and will reduce the time and the cost of processing large volume parts (Rehme, Emmelmenn, 2006). The interest in cellular structures has excelled with research efforts being made to identify ways to design and to produce both open and closed structures with a regular and irregular structure (Brooks *et al.* 2005). The lattice structures created by Brooks *et al.* (2005) were lightweight with only 6% of the relative density, and able to absorb energy from compressive loads of over

2.5kN. Possible applications of the lattice structures include heat exchanges (Wong *et al.* 2007), orthopaedic implants (Mullen *et al.* 2009) and ultra-light aerospace components.

The software and computer coding created to develop the lattice structures have become available as a commercial software package and a plug-in to Magics RP preparation software (Materialise, Belgium). However, due to the complexity of the lattice structures computer hardware requires high processing capabilities that are out of reach with larger and more detailed structures. This has resulted in more research into methods of reducing the STL file sizes and creating alternative file formats. Research by Ramin & Harris (2008) and Brooks *et al.* (2005) has investigated automated methods of creating various cellular structures for tissue engineering applications by using an advanced CAD package that does not require additional software like Microsoft Windows because it uses unsecure processing power. The methods used by Ramin & Harris (2008) resulted in a more efficient generation of the complex shapes with up to 75% time saving.

Research into SLM applications, process developments and materials has identified limitations and constraints of the SLM process. However, there is very little research that has been designed to explicitly identify the geometrical boundaries of SLM. All research is focused on the design of more complex geometries such surgical implants, lattice structures and heat transfer devices. Kruth *et al.* (2005) and Rehme and Emmelmann, (2005) both published an investigation into identifying the limitations of the SLM process. The research by Rehme and Emmelmann included the design of simple test pieces to test mechanical propetries of SLM parts. However, the work by Kruth *et al.* (2005), created a benchmark model that was made on five different metal AM processes, ranging from sintering to fully melting the material.

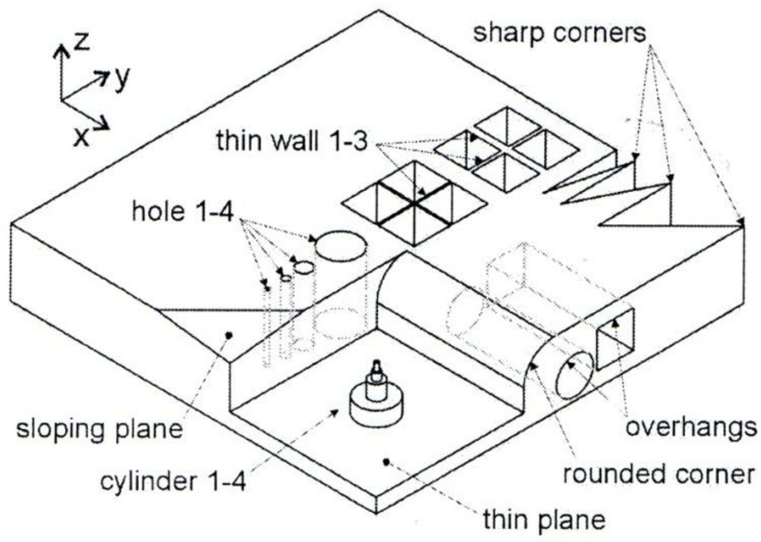



Figure 2.12: Benchmark model created by Kruth *et al.* (2005).

The benchmark model shown in Figure 2.12 is constructed of several geometrical features, these include thin walls, overhangs in holes, self-supporting holes, one angled surface and a large radius. The geometrical featrues were chosen so that the limitations of each process could be identified. To improve the geometries only parameter changes were used, rather than making changes to the geometries. This ensured that all machines were producing parts to their full potential so that the limitations of each process, and potential manufacturing applications could be identified.

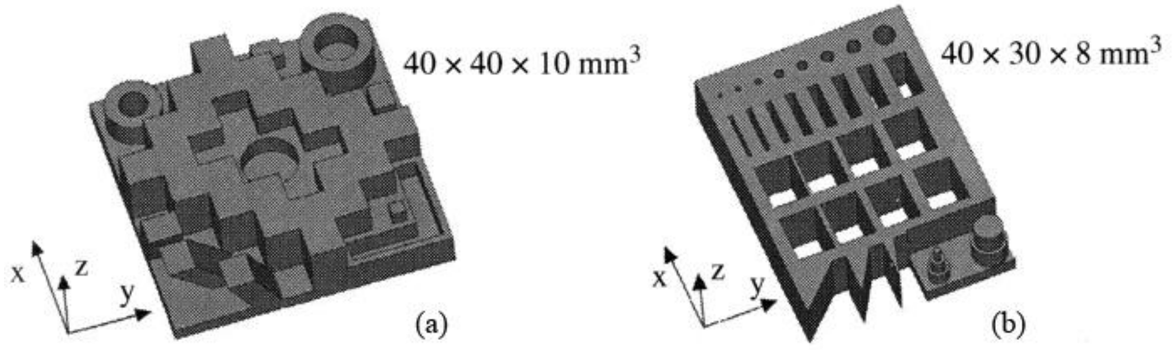



Figure 2.13: Further benchmark test parts designed to identify limitations and measure the accuracy of SLM (Vandenbroucke & Kruth, 2007)

Further studies by Vandenbroucke and Kruth, (2007) developed more benchmark models (Figure 2.13) that tested a larger range of sizes for holes, overhangs and slots. These test parts were built, and measured to identify part accuracy using a Taylor Hobson Form Talysurf surface roughness meter, a tactile probe coordinate measuring machine (CMM) and a optical micro-measurement machine to measure the smallest details. The test pieces designed in Kruth's work were considered in the main experimentation of this study because geometries were created to measure fundamental geometries. This included an investigation of simple orientation and other simple geometries that were the building blocks to more complex constructions. The test pieces did not include a full range of sizes for each design feature, for example only one hole and square was used to investigate overhanging geometries. Another drawback of using Kruth's benchmark designs was that if one feature on each test part failed because it was outside of the limitations of SLM, the entire part would not continue. This would have resulted in no parts to be measured and a excessive use of material. As this study identified the limitations of SLM, it was inevitable that several test parts would fail so that the geometric limitation could be identified, for this reason all design features were designed as individual test parts.

It is clear from work by Kruth (2005), that the accuracy of different machines and different parameters setting results in different geometric limitations. The test parts were not replictated as they were unsuitable as they were too large to build with the aim of changing individual geometry dimensions, and the design of the parts would have been difficult to measure using the apparatus available within this study.

## 2.5 Need for SLM design rules

The advancement of SLM into becoming a robust RM process is held back by process inherent drawbacks such as part accuracy, surface finish, repeatability and material limitations (Hague *et al*. 2004). Since this citation, advancements in technology, part accuracy and surface roughness have occured, but the inherent drawbacks are still apparent, and designers using SLM are still designing for conventional processes. Design freedom is a major driver of RM being accepted as a manufacturing process and could result in reducing the lead time, overall manufacturing costs, and improve part performance (Hague R., 2006). However, very little literature exists that can be used to inform designers of the design limitations and design possibilities that they will be faced with. To obtain repeatability in SLM parts and to control or avoid the process limitations of SLM, it is of high importance to have adequate product design guidelines (Rehme & Emmelmann, 2005).

Many researchers within the RM industry have identified the potential benefits of design rules. However, there is no previous research that has been aimed at addressing the lack of design rules for SLM, or other RM processes. The work that has been completed to date has been based on the physics and applications of SLM in producing novel geometries. Succesful examples of SLM parts have been designed by people who not only know the SLM process but also use and study it day to day. If a product designer were to use SLM as a manufacturing process, there would be no design rules for them to follow which may result in an unsuccsesful part, and a part that could have been optimised further considering the benefits of RM. Without designeers being able to access design guidance for SLM, they will not be familier with the limitations of the process and will therefore be unable to shortlist it as a suitable process for a particular design.

Pullin (2009) reported that none of the design considerations of conventional manufacturing processes apply to RM for part production.  One common theme has been identified from literature by Wohlers (2009), and Pullin and Offen (2008) is that designers in today's inudstry have become adept at creating products that can be manufactured using conventional processes.  Their education and design experience have conditioned them to subconsciously tailor their designs to suit today's common production processes, making it challenging to design outside of normal routine.

Further evidence of designing for the wrong process was quoted through personal communication with Dr. Wilhelm Meiners of the Fraunhofer Institute of Laser Technology (ILT, Germany) - "90% of parts aren't designed for SLM, they are designed for casting or milling.  It is only luck that the other 10% have good geometries for building with SLM. Of the 90%, no parts are designed considering the benefits of RM, therefore, compromising on surfaces is always required".

The limitations of RM need to be openly expressed to prevent any misconceptions of the process prohibiting future growth of the RM industry.  One barrier for RM growth is the lack of design guidelines (Wohlers, 2009).  Wohlers (2009) and Pullin and Offen (2008) reported that design guidelines are needed to encourage designers to explore the advantages of RM, allowing the manufacture of parts with increased functionality and value.  It was suggested that design rules need to outline the limitations of the process, such as minimum wall thicknesses.  It is recognised that when parts are intelligently designed for RM the full benefits are noticeable (Pullin, 2009).

The design of a part determines the number of support structures that need to be used. Out of all the RM processes, SLM has the most difficult supports to remove as they are dense metal.  Support structures are needed to anchor the parts to a substrate, to prevent movement during the process and to prevent surfaces from curling up away from the correct geometry. The use of the support structures in RM are reported as being the main restriction on part geometries, and the support placement is as equalaly important as the part design (Pullin & Offen, 2008).

Burton (2005) has taken a different approach to producing design rules by creating a knowledge transfer tool that enables industrial designers to establish greater understanding of applying design practice to RM processes. This project was established from recognising the need to inform designers of how to design for RM processes. The rules created were principle design guidelines based on a series of design matrices for selecting RM processes and ensuring that designers have considered the features that contributed to the processes selection in the first place. This approach to the design rules was a good method for ensuring that the correct RM process is chosen, and designers exploit the design potential of the RM process. However, no process specific detailed design rules were developed for any RM process (Burton, 2005).

## *2.6 Design rules*

In 1941, a survey by the American Society of Mechanical Engineers (ASME) revealed the need for designers and engineers to have ready access to technical information on material properties for metals. A series of publications were published and in 1958 the first design rules publication was released named "Metals Engineering Processes" which was edited by Roger W. Bolz. Bolz was one of the first to introduce Design for Manufacturing (DFM) principles. The book was used as an aid for designers in enhancing manufacturability of metal parts for a number of metal processing processes (Bralla, 1998).

The use of instructional guidelines advanced into Design for Manufacturing and Assembly (DFMA) principles in the late 1960's by Boothroyd and Dewhurst (Boothroyd *et al.* 2002). The principles were aimed at all stages of design that considers the manufacturing at the design stage of a production. The advantages of applying DFMA principles during product design were a reduction in part count and cost, reduction in manufacturing and assembly times, improved part quality, and product time-to-market, and now that RM has become available, the foreseeable benefits of efficient design are even greater.

Design rules play a major role in the improvement of the efficiency and optimising the quality of parts that the process produces. Some design rules are focused specifically on a product that has been identified as being suitable for the manufacturing process. Since their introduction, design rules have evolved with the advancement of the manufacturing process and are used as an effective way for a designer to select a manufacturing process, and to create optimised designs. Design rules are also used as an effective method to deliver the new process capabilities to designers and engineers so that the process can be fully explored.

Detailed general engineering books such as "The Pocket Ref" (Cromwell Group Holdings Ltd, 2008) and "Zeus Precision" (Zues Precision Charts Ltd, 1995) are pocket books that are used as a reference by designers, tool makers and engineers. These books consist of details such as tapping drill sizes, limits and fits, material, and engineering drawing symbols. The content within the reference books are not focused at any particular manufacturing process and are aimed at being a quick guide and a breakdown of the key points within British Standards that can be applied and work hand in hand with all process specific-design rules.

Existing process-specific design rules are mainly for conventional processes such as casting, injection moulding and aluminium extrusion. The rules are presented both through a printed book format, and data available on the website of companies whose businesses are based on supplying manufacturing services or the manufacturing equipment. The presentation of the process-specific design rules needed to be considered whilst developing the SLM design rules within this study. In particular there are several attributes from existing design rules approaches that show how information may be presented most effectively through a series of illustrations and descriptions. These points are described as follows:

Both two-dimensional and three-dimensional images are used and both are effective in delivering a different depth of detail. The two-dimensional images are more commonly used to illustrate detailed dimensional data and three-dimensional images are used for assembly, less detailed dimensions, product examples and to show more realism to the design feature. See Figure 2.14 for examples taken from aluminium extrusion design rules published by Sapa Ltd (1997) and Groover (2002).

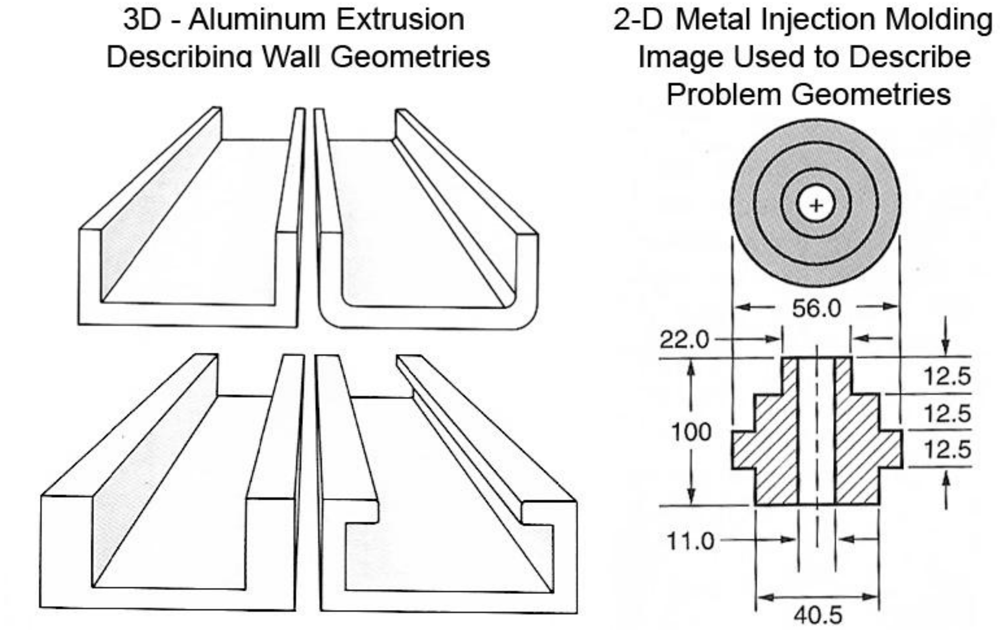



Figure 2.14: Examples of a 3-dimesional image (Sapa Ltd, 1997) and a detailed 2-dimensional Image (Groover, 2002)

Tables in design guidelines are illustrative when there are several dimensional variations of a single geometry. Although tables can appear to be complex some design rules are dependent on them as long as there is an image that corresponds to it, however, in some cases tables do not have an associated image which will be ineffective to someone new to a process, rather than someone who is familiar with the process. An example table and image taken from aluminium extrusion design rules is shown in Figure 2.15. (Spencer, 1994)

**Tolerances on Concavity and Convexity for Extruded Solid and Hollow Sections**

| Width of section *W* | Maximum allowable deviation *D* (see figure) |
|---|---|
| mm | mm |
| Up to and including 25 | 0.125 |
| Over 25 | 0.125 per 25 mm increment in width (e.g. for 150 mm width maximum deviation *D* permitted is 0.75 mm) |

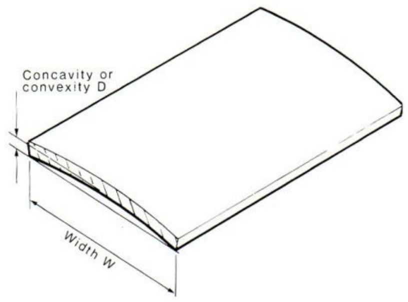



Figure 2.15: Table and Image illustrating dimensional variations of a single design (Spencer, 1994)

All design rules show the possible distortions and part deformations that are inherent to the manufacturing process. These distortions are caused by poor design and showing them is useful to emphasise why the design rules need to be used. An example of a part distortion presentation is shown in Figure 2.16.

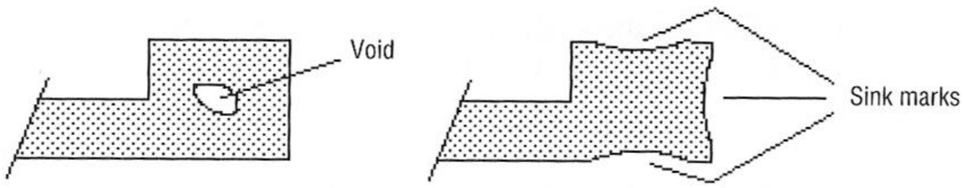



Figure 2.16: Shrinkage that has occurred during Injection Moulding. Both parts shown are the same and there are two possible ways for the distortion to occur (Rees, 1996)

When the distortions are unavoidable they are shown together with a design solution or an alternative design to prevent the distortion occurring. This is shown with an image of a poor design and an image of good design (see Figure 2.17 and Figure 2.18)

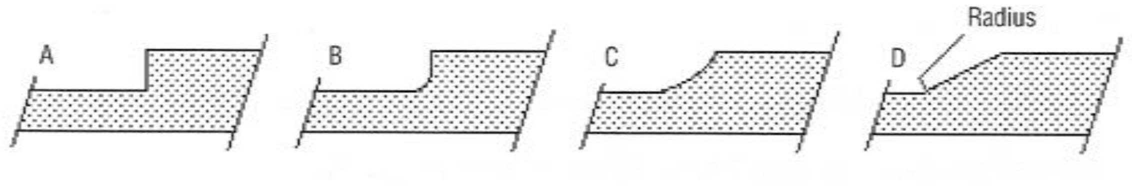



Figure 2.17: This image shows the poor geometry design that caused the distortion (A) and the design improvements to avoid the distortion (B, C & D) (Rees, 1996)

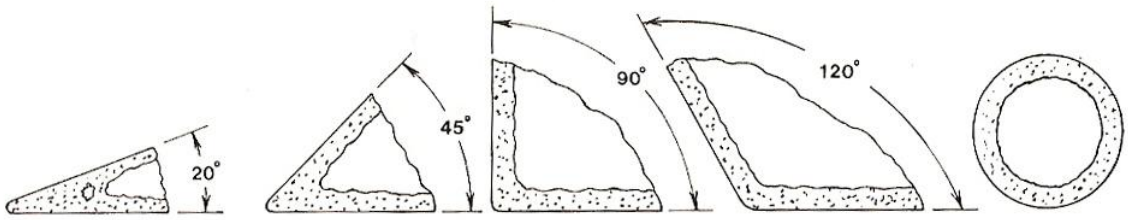



Figure 2.18: Image showing the affect of different corner angles of a rotationally moulded part. Excessive material causes porosity in the material when the angle is too small (Beall, 1998).

An introduction to the manufacturing technology is shown in all design rules. At these stage illustrations of how the process works is presented to set the scene for the content of the design rules. The introduction to the design rules always presents enough information for the designer or engineer to be assured that the process they have chosen is the correct process. When large blocks of text are used without illustrations in the design rules, they are discouraging to read and can be difficult to follow especially when they are concerning geometrical features.

## *2.7 Summary*

The introduction of the RM concept has become an ongoing process since there are many issued involving accuracy, build time, mechanical properties and repeatability that need to be addressed to complete the transition from RP to RM. Within the RM industry, advancements in laser technologies and the ever increasing inventory of manufacturing grade materials has allowed the commercial introduction of SLM.

SLM has become a common research theme in engineering research. The majority of the research is based on the physics, material properties and process improvements of SLM, and in many cases the research is driven by industrial collaborators. Since earlier research efforts, many process improvements have been made because a greater detailed understanding of the process has been gained. However, there has become noticeable competition amongst machine manufacturers which has resulted in much of the research becoming in-house as companies wish to claim intellectual property rights (IP) on their process developments. Also, collaborative research with industry requires confidentiality agreements, which has contributed towards little published research.

Many industries have recognised the benefits and possibilities of applying SLM within their manufacturing process. This has driven research into the development of novel geometries with the aim of enhancing product performance, and exploiting the freedom of design. This includes the development of lattice and cellular structures, to the production of custom fitting implants, although in many cases the concept of building the geometries is proven, but in some cases standards and industry compliance have restricted applied cases of safety-critical SLM parts.

For any new manufacturing process to succeed in its industry the design limitations must be considered to enable designers to exploit the possibilities of the process within its boundaries. The benefits of creating design rules for SLM are recognised as being key to the success of SLM. One major problem is that designers only know how to design for conventional processes, and have little or no understanding of SLM.

Very little research exists that is aimed at identifying the geometrical limitations of SLM with the exception of work by Kruth *et al*. (2005) and (2007). This work gave a good insight to the fundamental geometries that needed investigation. Kruth's research was focused on improving geometrical accuracy through the optimisation of process parameters, as well as identifying simple process limitations. No attempt has been made to develop design rules that are specific to SLM. The only work on developing design rules was aimed at encouraging full exploitation of principle design abilities of general RM processes by using a series of matrices (Burton, 2005). No design rules that are specific to SLM have been created. The following chapter describes the methodologies used to investigate the SLM process, and to develop detailed design rules for SLM.

# Chapter 3: *Methodology*

## *3.1 Introduction*

This chapter describes the research methodology used to generate and evaluate SLM design rules. The aim and objectives of this research led to the methodology being divided into quantitative and qualitative methods. This chapter describes the methodology underlying two phases of research, and the stages that were required to fulfil the research objectives within each phase. Previous literature has identified that no design rules have been created for the SLM process. Therefore, a careful methodology choice was used to gather the data required for developing design rules within this research. The methodology selection was imperative to completing the quantitative and qualitative research effectively. The merits and disadvantages of all appropriate methodologies were reviewed and this chapter describes why the chosen methodologies were used, and why other contending methods were not selected.

## *3.2 Aim and objectives*

The aim of this research was to develop a first draft of process-specific design rules for SLM. To accomplish the aim of this research, the following objectives were set:

- Evaluate the SLM process, and identify the geometric limitations of SLM.
- Perform analysis and synthesis of the experimental results and create a first draft of design rules appropriate for use in design practice.
- Evaluate the design rules to establish their effectiveness and inform their further development.

## *3.3 Methodology overview*

The initial literature review was completed before the research methods were selected. After the initial literature review, a continuous literature review was completed over the duration of the research.

The scope of this research entails the creation of design rules for a state-of-the-art new technology. The selected methodology allowed the geometric limitations of SLM to be identified and presented to design professionals as design rules for manufacturing using SLM. To develop the design rules, the research objectives were split into two separate research Phases. The first Phase is quantitative and the second Phase is qualitative. Each Phase is illustrated in the research methodology flowchart in Figure 3.1.

**Phase 1: Quantitative research**

Phase 1 outlines the experimental framework which was the first research objective. As very little previous literature was available for developing the design rules for SLM, the geometric data required for identifying constraints and possibilities of SLM parts needed to be generated within this research to develop the rules. This quantitative approach included pre-experimental SLM machine calibration and SLM process parameter optimisation. The pilot studies and main experimentation required the use of a cyclic research methodology, which allowed iterations of a single experiment, with controlled parameter changes to establish geometrical data of design features. After the completion of pilot studies, definitive measurement and analysis instrumentation were chosen and a series of protocols were produced. Patton (1990) states, "The validity of quantitative research depends on careful instrument construction to be sure that the instrument measures what it supposed to measure". This research phase was used to identify the inherent geometrical limitations of

SLM manufacture and to address the limitations by performing experiments and analysis to produce raw geometrical data.  This raw data was refined in “Phase 2” for developing the design rules that needed to be comprehensive of all common geometries (Phase 2).  Figure 3.1 illustrates the stages within Phase 1 of the research.

**Phase 2: Qualitative Research**

The aim of the second Phase of the research was to develop design rules based on the raw data gathered in Phase 1.  To initiate the design rules, a synthesis of the results from phase 1 was required to ensure that the data could be interpreted and used as design rules.  This synthesis was the critical bridge from Phase 1 to Phase 2 as the success of the design rules was dependent on whether or not the rules were able to be used by design professionals in practice.  Therefore, further developments were required for the rules to be analysed by design professionals and to gain feedback that was used to conclude the design rule development in this research.  (See Figure 3.1)

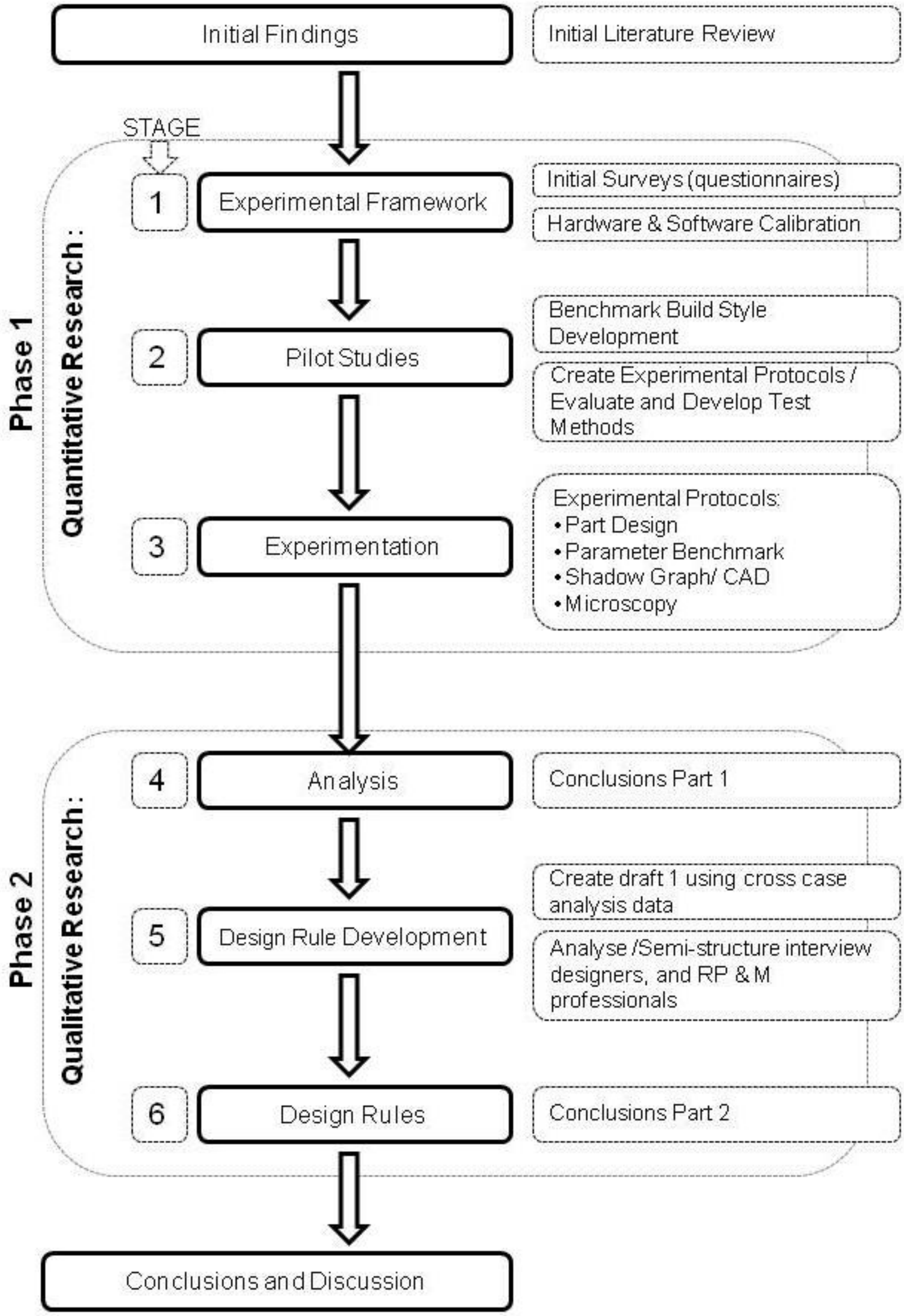



Figure 3.1: Flow chart of research methodology

## *3.4 Phase 1: Quantitative research methods*

### *3.4.1 Selected methods*

As many research methods were available, it was necessary to make a selection that would be most advantageous to the research objectives in Phase 1. The following methods are described in three stages, and were selected to complete Phase 1 of the research as illustrated in Figure 3.1.

#### *3.4.1.1 Stage 1: Initial surveys:*

At the beginning of this research study, less than 15 SLM machines were installed within Europe and very little literature existed. Therefore, questionnaires (see Appendix 1) were an obvious method for finding the answers to issues of interest and concern about SLM in preparation for further research. Questionnaires were presented to the recipients at the SLM User Group Conference in in Paderborn, Germany, during September 2007 to gain an understanding of existing SLM user's knowledge and experiences. The respondent's expertise provided a wealth of knowledge for this initial study, as the recipients included key individuals that developed the first commercial SLM machines. Other recipients' expertise included SLM development research and the commercial use of SLM from universities and sevice bureaus. As suggested by Blaxter *et al.* (2003), the questionnaires were given to and collected from the respondents in person, with many questions open ended. This created an opportunity to gather additional comments and opinion on the overall study. One possible disadvantage of the initial survey is that the research and commercial use of SLM was competitive amongst the respondents, therefore, the depth and accuracy of the responses may have been affected as machine capabilities may have been embellished. The results of the initial surveys were considered in the experimental planning in chapter 4, and the completed questionnaires are in Appendix 2.

#### *3.4.1.2 Stage 2: Pilot studies:*

The aims of the pilot studies were to inform and make quantitative observations about the experimental methods proposed for the main experimentation. These studies were completed at an early stage in the research process (see Figure 3.1). A range of parts with a range of design features where selected for the pilot studies. At this stage of the research the results from building the pilot study test pieces could not be predicted. Therefore, the results provided data that informed the main experimentation of geometries that needed further investigation.

Each pilot study was completed iteratively using elements of Deming's cycle (Deming, 1994) described in Figure 3.2. The advantages of the research cycle became evident, as some pilot study builds failed and were repeated successfully with controlled changes such as orientation. After each pilot test part was made, they were analysed using hand measurement tools, a shadowgraph, and a microscope with a digital camera attachment. The measurements were used to identify the most effective analysis method that provided repeatable and accurate geometrical data, which was then used to create a measurement protocol for all main experimentation. Along with the measurement protocol, the pilot studies were used to create a standard test part design protocol. The parts were designed so that they could be measured effectively using the measurement protocol. To see pilot studies, refer to experimental framework, chapter 4.

#### *3.4.1.3 Stage 3: Main experimentation*

The experimental requirements came from both the research objectives and the pilot study conclusions. Action Research (AR) is a systematic approach to defining, solving and evaluating problems and concerns, as explained by Blaxter (2003). AR is commonly used as a social-science focused method of solving problems, although, the iterative process cycle that is used in AR can be applied across a wider range of research initiatives. Research into the use of AR led to the selection of another systematic method developed by Deming (1994). This methodology is a manufacturing focused design-of-experiments cycle named the "Deming's Cycle for Learning and Improvement". This cycle (Figure 3.2) is described as a "Plan-Do-Study-Act" (PDSA) process and can be used as a technique for performing a test aimed to make improvements in a manufacturing context.

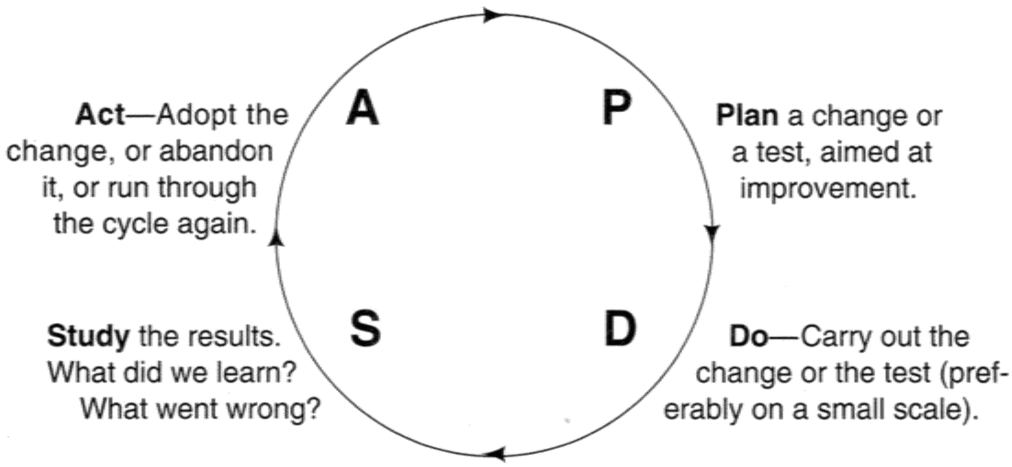



Figure 3.2: Deming's cycle for leaning and improvement (Deming, 1994)

Figure 3.2 illustrates the experimentation cycle as used in this research. This cycle is based on Deming's cycle, and is adapted to ensure that the experimentation would identify limitations. The geometrical feature to be investigated was selected and test parts were created to produce and analyse. The results were then reviewed and the experiment was repeated until the limitations of the geometry in question were identified, and the data could be used to inform following experiments. If further testing was required then the appropriate dimensional values were changed and the cyclic process was repeated until the objectives were met. The results were planned so that the results would inform a start point for the following experiment in the series.

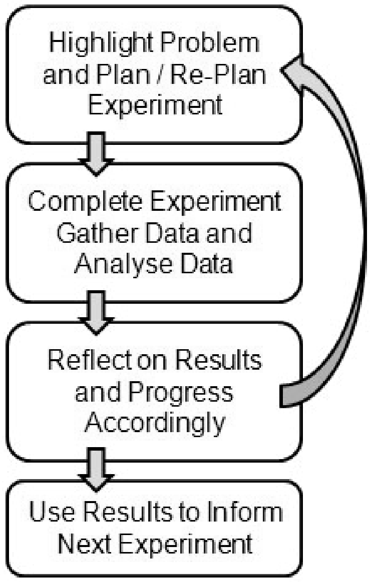



Figure 3.2: Flowchart describing the experimental cycle used in this research

The benefit of the experimental cycle (Figure 3.2) for this research was clear, as the geometrical investigations would need to be addressed step-by-step to record the in-build distortions and measured accuracy, and to make dimensional amendments accordingly. This step is described as "adopt, amend or abandon" by Deming (1994). The parts would be abandoned when the geometrical limitations of each test could be identified and conclusions could be made, or the experiment would be repeated if the results did not identify the geometric limitation of a test part and the results could not inform following experiments. An example of a dimension that was invetigated is shown in Figure 3.4, where the angle labelled "X" is the dimension of which the limitation was investigated. Various values for X were built until the lowest possible value for X was identified.

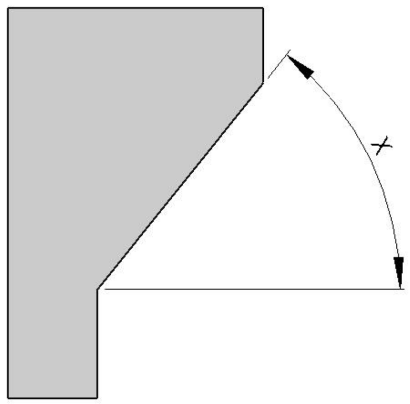



Figure 3.4: Example of a test part. The angle "X" is the limitation to be identified. The angle of the geometry was changed until the lowest value was identified.

This systematic approach to the research encouraged the order of the experiments to be planned so that the data gained in one experiment could be used most effectively to inform a starting point, to plan subsequent experiments in series. The advantage of the Deming's cycle was that it encouraged the data to be evaluated to ensure that it was complete before moving onto a following experiment, which resulted in all results being evaluated in stages to ensure that the research objective was met and the resulting coherent set of data could be used to initiate the design rules.

#### ***3.4.1.4 Other methods considered***

There are many research methodologies available for the first phase of this research. Phase 1 involved three logical stages that were required to complete the research objectives. To select an appropriate methodology for achieving the required study outcome, a range of alternative methodologies were considered before being discounted.

**Large Distribution Surveys:** The intention of large survey distribution would be to identify the existing knowledge of SLM among users. An advantage of using large surveys is that there will be a large number of respondents (Blaxter, 2003). However, very few SLM experts and users existed at the time of the research (there were fewer than 15 machine installations in Europe). Therefore, distributing a large scale survey digitally, or by mail was not possible.

**Case Studies:** As parts of phase 1, the methodology chosen must enable the dimensional limitations of SLM parts to be identified. To do this, a number of planned and carefully designed parts were required to create the data from required geometrical features. Using case studies would require direct observations of SLM parts being made in the field of research or commercial manufacture (Yin, 2003) through field visits to other SLM users across Europe and the UK. As existing SLM parts being manufactured were designed according to design rules of traditional manufacturing processes, the results would be unsuitable and unlikely to be focused on the geometries required to create design rules for Rapid Manufacturing using SLM. Also, many other materials and hardware variations would lead to very little control of process parameters within this research. Using case studies would also require cooperation from many people, which may inncur confidentiality problems. To collate the geometrical data required to develop design rules, Deming's cycle was selected.

**Taguchi Methods:** Taguchi methods (Taguchi, 1986) are a complex quantitative experimental design technique predominantly used in quality management. One obvious benefit of Taguchi methods is that it can be used as a tool for controlling parameters of an investigation so that un-necessary experiments are eliminated (Bendell & Disney, 1989). This method of controlling parameters is described as product variabilty by Taguchi (1986). This is also used to determine the effects of part tolerance deviation on the quality of products, which was considered for highlighting the limitations of the SLM process.

After pilot studies were completed the methodology requirements became clearer. Due to the reletively small number of controlling parameters, it was decided that Taguchi methods were unnecessary and too complex for the scope of this study, as all process control parameters were standardised, and the variable parameters were logical geometrical changes according to the results analysis of each test part. Many of the geometries in this research were built so that the measurement and analysis results would inform the subsequent experiments in series. This alone would limit the number experiments in a less complex way as the experimentation advanced. Many results were expected to be unpredictable and could have more than one reason behind them. The results and conclusions from the pilot studies concluded that Taguchi methods were not needed to control paramters as the more complex parameters would be fixed, so that the geometric limitations of SLM would be the main subject for the study.

## *3.5 Summary of quantitative research undertaken*

This section described the components of the quantitative experimental framework phase (Phase 1), and the methodologies used. Some methodologies were considered, but were not selected as they would not produce the detailed dimensional data required to develop the design rules within Phase 2. The first stage involved creating questionnaires that were presented face-to-face at an SLM User Group Conference in Germany, 2007. The results gave an insight to the current knowledge for designing SLM components. This event was chosen as an appropriate venue, with all SLM expertise grouped together.

The SLM machine’s Hardware and Software were calibrated prior to pilot studies. The pilot studies were used to test the experimental methods and to define measurement, part design and parameter protocols for the main experimentation. Another role of the pilot studies was to inform the experiments of the geometries that needed in-depth investigation. The AR approach to the main experimentation was successful in producing optimised parts in the pilot studies. The main experimentation was strategically chosen in a logical order starting with fundamental geometries, so the results would inform and create a starting point for the following experiment. The success of the experiments was determined when the data created would allow the design rules (Phase 2) to be comprehensive of all common geometries, without any need for further test parts.

## *3.6 Phase 2: Qualitative research methods*

The objectives of phase 2 were to initiate design rules based on the review of SLM limitations, and raw experimental data created in phase 1, and to evaluate the design rules for future developments. The following section describes the methodologies that were considered and selected to complete the objectives, based on a review of their merits and disadvantages.

### *3.6.1 Selected methods*

#### *3.6.1.1 Stage 4: Research synthesis*

The quantitative experimental data collected in Phase 1 consisted of dimensional values that relate to the limitations and capabilities of the SLM machine used in this research. The raw experimental data created in phase1 required interpretation into fully explanatory text, tables and diagrams that could be understood by designers in practice. Each iteration of the quantitative experimentation in stage 3 was planned so that the results from each geometry experiment could be interpreted successfully. Each iteration was intended to create results that would inform the initiation of a specific design rule, and in some cases they would inform more than one rule. The presentation of the design rules was based on the merits of previous design rules for traditional manufacturing processes. To see the results of the research synthesis, refer to chapter 6.

#### *3.6.1.2 Stage 5: Semi-structured interviews*

The design rules must inform and give guidance to the designer for when he or she is designing products for Rapid Manufacturing (RM). Therefore the designer's input was crucial in evaluating the effectiveness of the rules. Six design professionals were selected to review the design rules. The candidates were chosen according to their varying background in the design industry (see Table 3.1). This was so that the feedback would not be biased towards a specific design role. These recipients included an industrial designer, medical device designer and a RM practitioner. No more than six respondents were chosen because an insight to the design rules was needed from a small number of in-depth interviews, rather than more respondents who where less involved. Also, six was the number that covered each of the professional roles that were selected and if a duplicate of one role was chosen, bias may have occurred in the results.

| Respondent | Professional Role Within Design |
|---|---|
| Respondent 1 | Product design management research |
| Respondent 2 | Rapid manufacturing development manager |
| Respondent 3 | Senior product design lecturer |
| Respondent 4 | Product development and project manager |
| Respondent 5 | Industrial designer |
| Respondent 6 | Senior industrial design engineer. |

Table 3.1: Showing the varying background in the design industry

A semi-structured interview method was used as it allowed the respondents to provide a fresh commentary on the topic, as suggested by Blaxter *et al.* (2003). Yin (2003) described focused interviews as being conversational, which leads the respondent into providing fresh commentary as long as the questions are not suggestive in any way. This was an important criterion of using focused interviews, as fresh commentary provided new insights and approaches to the design rules that would not otherwise be apparent in questionnaires. The interviews were completed in site visits at the workplace of all six respondents face-to-face so that there were no influences on the responses that would perhaps occur in focus groups. The results were transcribed, and as the design rules analysed were based on geometry illustration, the respondents were given the opportunity to sketch when words could not portray a clear explanation. The results of the interviews are shown in chapter 6. Also, the full transcriptions are shown in Appendix 5.

#### *3.6.1.3 Stage 6: Data analysis*

The results from Stage 5 were analysed. The responses from the semi-structured interviews were analysed and common themes were extracted. The trends in the responses were separated into positive and negative comments. The analysis considered that the results were expected to be subjective and biased towards the different job roles of each designer. Differences between responses were identified for contribution to a thesis conclusion and discussion of future work to progress the design rules development. To see full data analyses refer to chapter 6.

### *3.6.2 Other methods considered*

**Questionnaires:** Questionnaires were considered to review the first draft of the rules and to develop a preliminary set of design rules. This methodology was not used as a conversational feedback method was required to provide a fresh and detailed depth of response. The length of the initiated design rules were too long for it to be reviewed based on a questionnaire. The respondents needed to work through the design rule document with the interviewer for more comprehensive feedback, and to give the interviewees opportunity to expand and clarify on their responses.

**Focus Groups:** Using focus groups as a qualitative, observational feedback method was considered to establish their effectiveness and inform their future developments. A focus group may have caused the respondent response's to be influenced by another respondent. Focus groups were used successfully by Burton (2005), to test principle design guidelines of RM. Participants were asked to apply a suggested design approach to the design a given product for fabrication via rapid manufacturing. The results proved the effectiveness of the guidelines to promote the use, and to exploit the advantages of RM. The design rules created in this research were detailed and specific to SLM. This research is the first attempt of creating any process-specific design rules, the testing required feedback of designer's interpretation, understanding of the content and the presentation methods. Focus groups would be more suited to testing future developments of the design rules. By testing the rules by using focus groups and a design exercise as in Burton's work (2005), would only test how complex designing for SLM would be, and test the design abilities of the participants instead of gaining expert opinion on the rules themselves.

## *3.7 Summary of qualitative research undertaken*

This section describes the stages that were within Phase 2 of the research. Phase 2 was completed in three stages of qualitative research. The first stage was to interpret the raw data created in Phase 1, into an illustrative format that can be used in design practice. Once the design rules were created they were analysed in context by design professionals. Semi-structured interviews were used to interview designers, and the interview structure was planned with a series of questions that were used as prompts to ensure that the conversational interviews remained focused. The final stage of Phase 2 was to analyse the semi-structured interview responses. The results from this analysis created part of the research conclusions, and identified areas for future development of the design rules.

## *3.8 Research novelty*

The success of more conventional manufacturing processes, such as casting, extrusion and injection moulding, relies on designers understanding the limitations and capabilities of the process (Tres, 1998). Research on the development of design rules for RP and RM technologies is limited. More specifically, no design rules have been developed for SLM since the first machine was introduced in the UK (MTT-Group) in 2003. However, the need for SLM design rules has been recognised in previous literature as being a requirement for bridging RP into RM (Pullin & Offen, 2008) and (Wohlers, 2009). As stated in the literature review all previous SLM literature is based on metallurgical engineering principles, novel lattice structures and biomedical implants. Meanwhile, the application of SLM for the design and manufacture of less complex, common geometries has been neglected.

The research undertaken here is the first step in developing process-specific design rules for SLM. Instead of using physics-based research to overcome the inherent geometrical discrepancies of SLM, the issues relating to design for rapid manufacture using SLM will be addressed through identifying geometric constraints and creating rules to maximise SLM part quality using existing commercially available SLM machines.

The following chapter describes the quantitative experimental framework, described as Phase 1 in the methodology. The experimental framework chapter illustrates the preparation and planning of the main experimentation, including machine calibration, pilot studies and the development of experimental protocols.  This chapter is concluded by the rationale and explanation of the main experiments.

# Chapter 4: Experimental Framework

## 4.1 Introduction

The experimental framework is the quantitative phase of this research. This chapter describes the pre-experimental planning, such as software and hardware set-up, and includes a description of the pilot studies, and how the pilot studies informed experimental protocols, and the main experimentation. Finally, this chapter describes the rationale behind each individual experiment and how the experimental protocols made the experiments a success. The experimental framework is illustrated in the methodology (Chapter 3, Figure 3.1). The parameter and apparatus optimisation, together with other elements of the experimental framework were exposed to peer review. This was done by presenting at conferences to get expert peer review feedback. The expert reviews confirmed that the research proposed was valid (See Thomas & Bibb, (2007) in appendix 6)

## 4.2 Apparatus and parameter optimisation

Any discrepancies in machine accuracy will reflect on the results of any experimentation and give a poor accuracy and validity of the experimental results. To ensure the apparatus used throughout the experiments were used in an optimal state before any test parts were built, all hardware and software were calibrated. The calibration of the SLM also included the benchmarking of process parameters which remained consistent throughout the study (see appendix 6).

## 4.3 Pilot studies

The following pilot studies were completed to establish a clearer understanding of further experimentation requirements. The results of the pilot studies contributed to the planning of experiments and confirmed the appropriateness of the experimental methods. The test parts chosen were selected based on opportunities from other research and actual medical cases. Other small designs were created with the intension to promote and identify geometrical deformation.

### 4.3.1 Pilot study 1 – surgical guide

This medical device was a patient specific surgical cutting guide used to guide cutting tools during maxillofacial surgery. This device lowers the risk of human error and decreases time in theatre and it can be tested on a Stereolithography (SLA) model of the patient before surgery (Bibb & Eggbeer, 2005). The build orientation was chosen so that the surfaces that would be in contact with the patient were built upright and therefore had the best surface finish (See Figure 4.1).

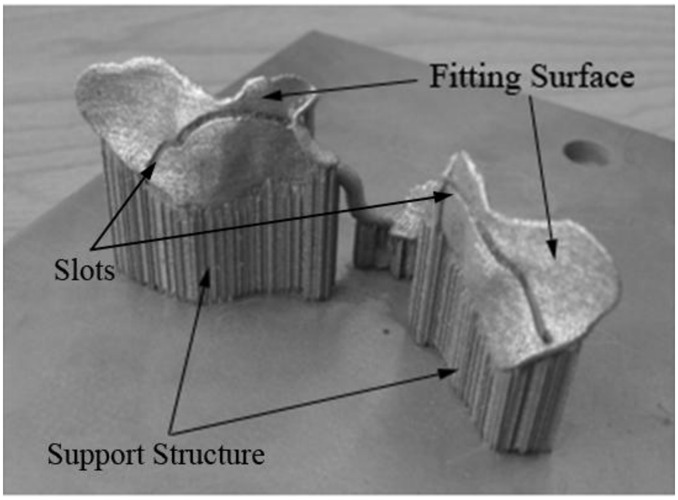



Figure 4.1: Surgical guide still supported on substrate plate.

Small supports were used in the slots shown labelled in Figure 4.1. The supports were difficult to remove as the slot was narrow and the overall geometry could easily distort. After the supports were removed the surgical guide did not fit when tested against the SLA skull model. The poor fit of the device was the result of the force required to remove the supports causing the device to bend at the thinnest wall sections until it eventually fractured (shown in Figure 4.2).

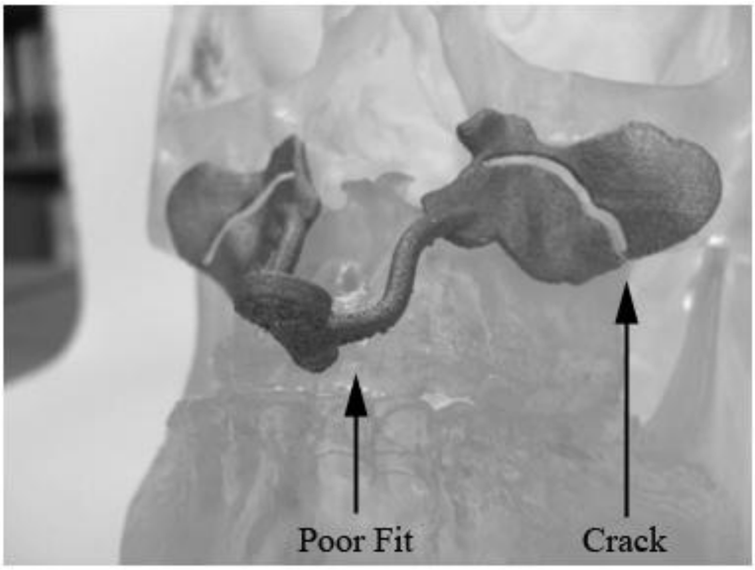



Figure 4.2: Surgical guide fitted on SLA model of patient's skull

This device was redesigned with a stiffening bar that would not change the functionality, fitting, or get in the way of the surgeon's work. The thin wall sections that fractured were also designed thicker so that the chance of part distortion was minimised. Once the revised device was built again, it fitted perfectly against the SLA model when removed from the substrate plate. Although, it was difficult to remove supports from the two cutting slots. A small file and electric hand tool were eventually used to remove the supports. The design modifications are shown in Figure 4.3.

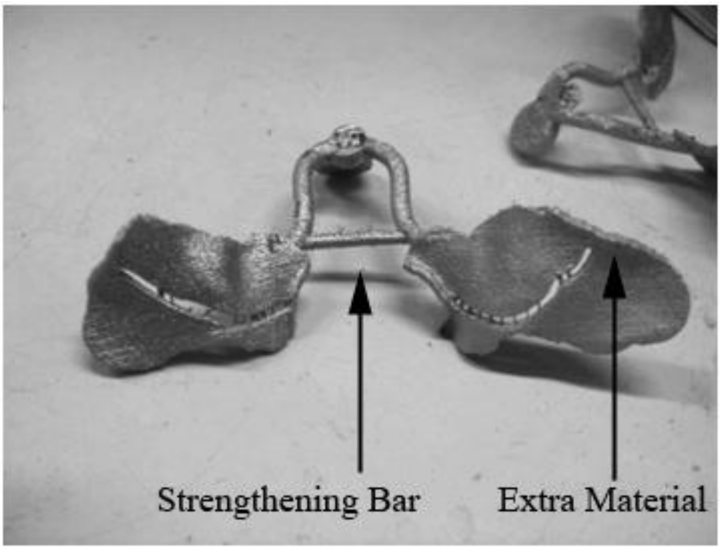



Figure 4.3: The modified Surgical Guide.

During surgery this device fitted very well against the patient. The slot was designed so that there was enough clearance for the cutter to fit without any obstructions. However, the supports were difficult to remove and during surgery the slot was found to be 0.5 mm too narrow, interfering with the surgical cutter. This was caused by the down-facing surfaces at the top of the slot building oversize. This occurred because down facing surfaces are poor where added material adheres to the surface in between the supports.

### *4.3.2 Pilot study 2 – unspecified medical device*

Once this device had been built using SLM, it was difficult to remove from the substrate plate without damaging the part because of the support structures shown in Figure 4.4. After the supports were removed, it was clear that the geometry had distorted.

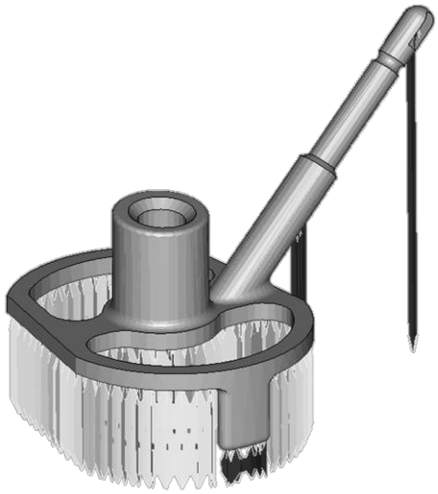


Figure 4.4: Illustration of the medical device with supports

It was clear that the down-facing surfaces had a very poor surface finish (Figure 4.5). The rod section that is protruding from the part was meant to be round in shape but completed oval. Figure 4.6 shows a small step on the rod section was no longer visible on the down-facing surface of the diameter. It had become obvious that support structures are very difficult to remove from small intricate components. In this case extra care on support removal was taken but the part was still damaged.

Figure 4.5: Illustration of the poor surfaces roughness on the down-facing surfaces

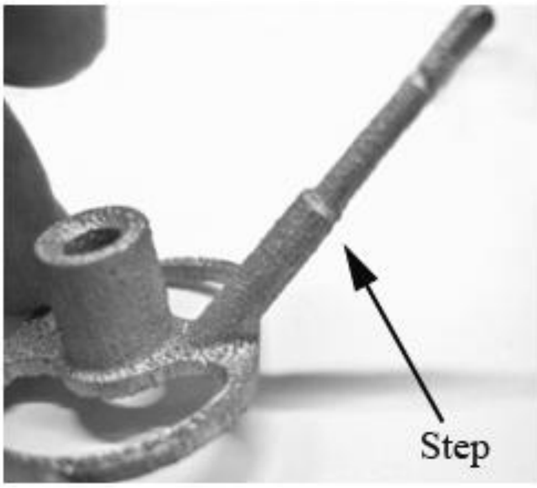



Figure 4.6: Side view of the poor step resolution.

The part was rebuilt at a different orientation to increase the angles of the down-facing surfaces (Figure 4.7). The new orientation allowed the part to be removed from the substrate plate more easily, without any part deformation.

Figure 4.7: Surgical device built for a second time, the parts are shown on the substrate plate still supported.

The surface quality on the rod had improved since the first attempt. The step in the rod was well defined and the profile shape of the rod was round (see Figure 4.8). The flat down-facing surfaces still had a poor surface roughness.

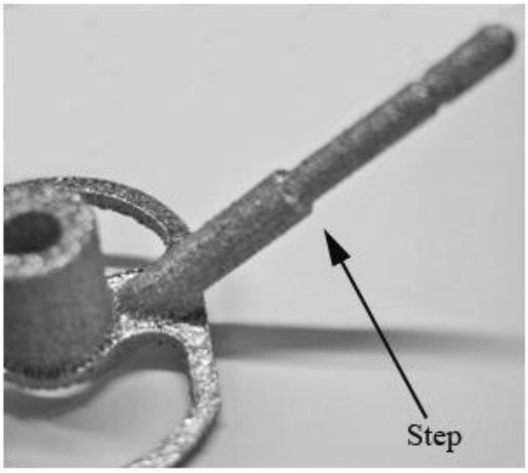



Figure 4.8: Image of the surgical device with the step on the rod improved

### *4.3.3 Pilot study 3 – mixed geometry test part*

This part (Figure 4.9) was constructed with multiple, simple design features, from thin walls, to inclusive angles and holes. This part was designed specifically for testing machine settings, and to identify geometric limitations.

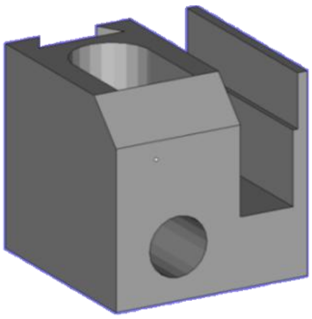


Figure 4.9: Image of the mixed geometry test part

Support structures were used inside of the hole, and at the base of the part to attach the part to the substrate plate.  The base supports were difficult to remove, they needed to be crushed in a bench vice until they separated from the part.  The hole supports were easily removed with a small pin punch.  However, there was evidence that material had melted down in between the supporting teeth, leaving a rough surface at the top of the holes.  This proves that the supports do not improve the surface roughness at distorted areas (see Figure 4.10)

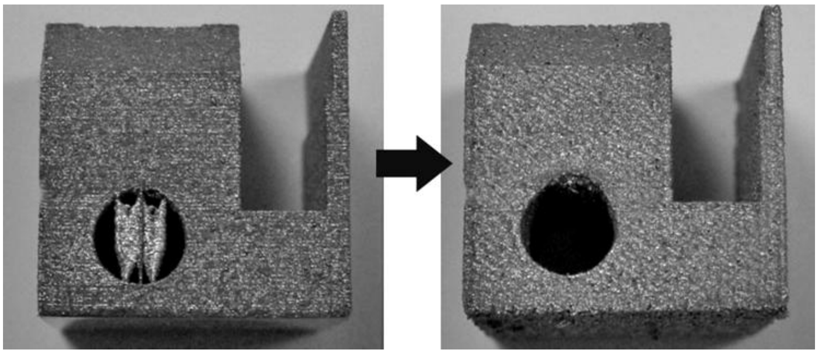


Figure 4.10:  Picture of the hole before (left) and after (right) the support removal

The surface roughness of these walls are all the same, except on one surface a small sink mark was present alongside the length of hole (See Figure 4.11).  The top surface roughness was not as smooth as the side walls.


Figure 4.11:  Image showing the sink marks along the side of the hole

Digital Microscopy was used to see a magnified image of the part features. The images are shown below in Figure 4.12 (a, b, c, and d).  The images show more detail of the part features.

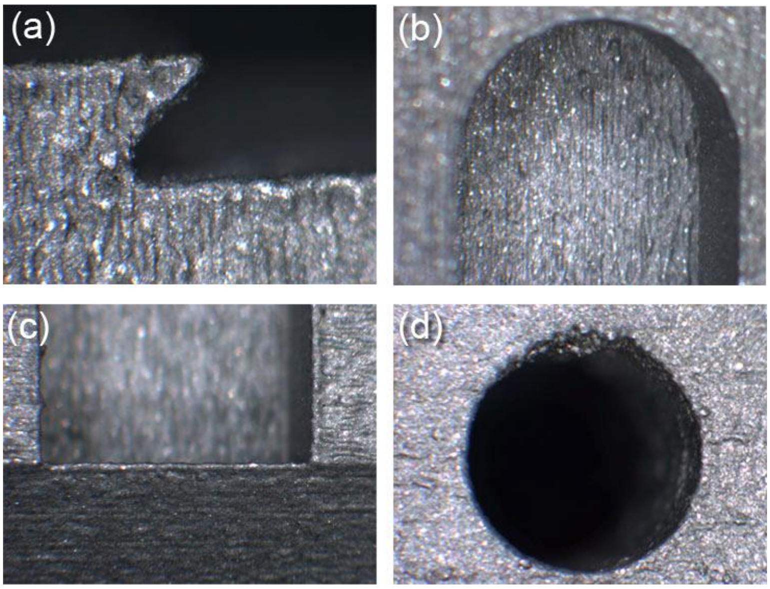



Figure 4.12:  Microscope images of mixed geometry test part

It was not possible to use the microscope to measure the features as they were photographed in true perspective.  However, the detail provided by the microscope pictures was very high and showed a clear picture of the deformations on the test part.  The 45° inclusive corners shown in Figure 4.12(a) were not sharp as they were in the CAD data and the surface roughness at the top of the hole was clear in Figure 4.12(d).

### *4.3.4 Pilot study 4 – holes*

Previous pilot studies identified down-facing surfaces and support structures cause many problems with the geometry of a part.  This test part was designed to identify what happens to round holes when they are built in a non self-supporting position without supports.

A 5mm thick bar with holes of 1mm to 10mm diameter (see Figure 4.13) were built in both the x and y-axis. The only support structure that was used was to anchor the whole part to the substrate plate. The bars were built in both the x-axis and y-axis.

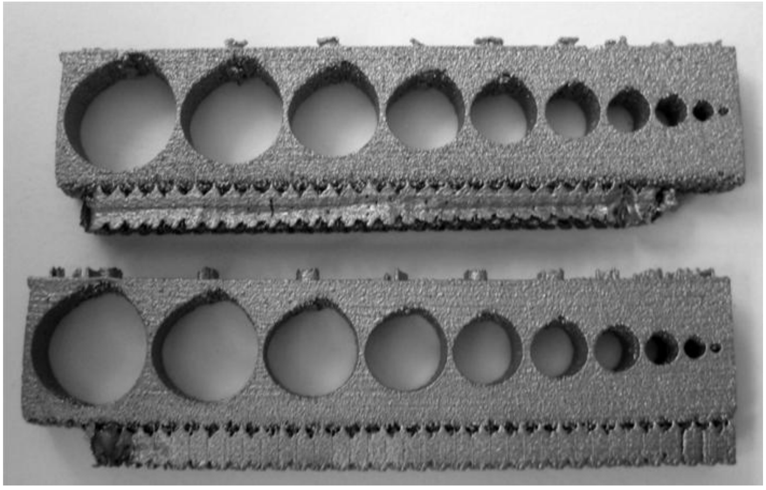


Figure 4.13: Illustration of completed test parts.

The results showed that as hole size increased the material began to curl away from the powder of the bed (Figure 4.14). This deformation is best described as part curl. Up to 7 mm diameter, the amount of part curl was very small and did not seem to interfere with the powder recoating system. From 8 mm and above the curl increased and fouled the recoating system as new powder layers were dropped.

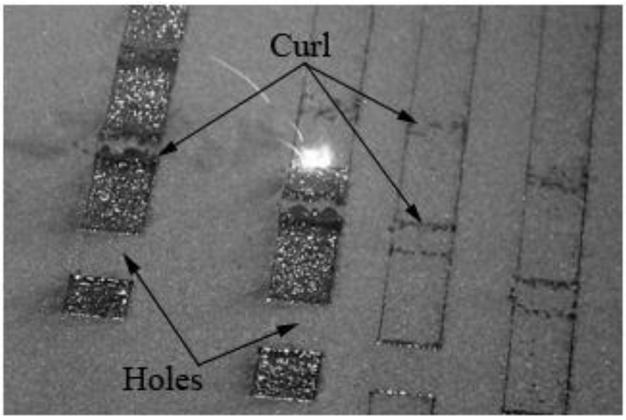



Figure 4.14: Illustration of the curl occurring on holes, the gaps in the melt are where the hole centre is.

It was difficult to see this by eye, therefore the pilot test pieces were viewed through a shadowgraph at 20 times magnification with scaled printouts overlaid onto the projected shadow. It was clear that the circularity of the holes decreased as hole size increased, and the holes were not symmetrical as the geometry had distorted towards areas of dense material. This can be seen at the largest hole in Figure 4.15. Figure 4.15 also shows that the tops of the holes are not round as the material has sagged into the hole.

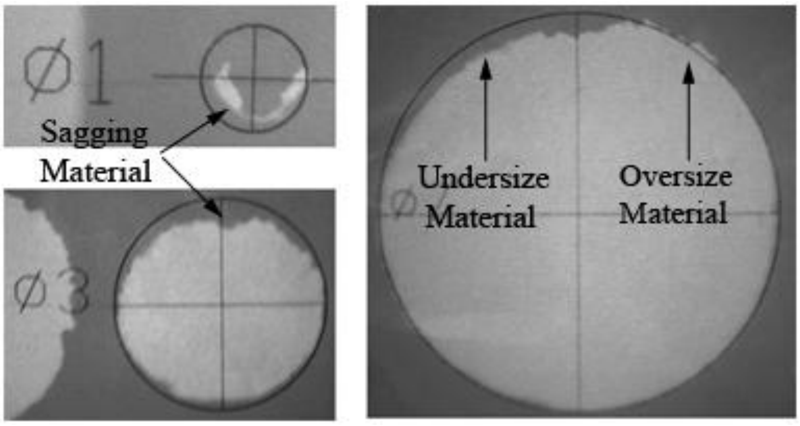



Figure 4.15: Shadowgraph images of round hole pilot test pieces

The shadowgraph images provided good visual evidence of the deformation that occurs in round holes. The perspective of the 3D component does not show on the shadowgraph images, which allows a 2D profile image of the hole cross section.

### *4.3.5 Pilot studies – summary*

The pilot studies were essential in identifying geometric distortions for further investigation. Not all distortions could be highlighted as they were unknown at this stage in the research. The experimental methods were successfully used during pilot study 1 and 2. The experiments were revised and repeated with appropriate design changes, until the parts were built successfully.

Part deformations were identified throughout all of the pilot studies. These deformations were specific to the geometrical features that were built, and were the underpinning data used to plan the investigations for further experimentation. The vulnerable geometric deformations were identified as follows:

- Down-facing flat surfaces
- Down-facing surfaces that are at an angle
- Round holes built at an upright orientation

The deformations that have been identified will have an affect on a wider range of geometries. For example, the inability to build holes will also reflect on radii at the same orientation, as they are essentially quarter of a hole.

Measurement methods used in the pilot studies were used not only to identify poor geometries, but were also used to asses the measurement method and the results that can be achieved. The microscopy produced high quality detailed images of the deformations that occurred in pilot study 3. The microscope images were in perspective and could not be used for measuring. The shadowgraph images created an accurate two-dimensional representation of the hole cross sections as shown in pilot study 4. The two-dimensional images were compared against the original geometry using transparent paper so that parts could be measured, and deformation could be identified.

The pilot studies gave a good understanding of further experimentation requirements. Measurement and build styles were piloted to highlight key areas of importance and for creating experimental protocols.

## 4.4 Experimental protocols: process and design

The experiment protocols were created from previous knowledge gained in the pilot studies, previous literature and general SLM user experience. The protocols were required for all experimentation to create a consistent and fair approach to the research. All fixed and variable parameters are described in the following protocols, along with the test part design, SLM process procedures and methods of measurement and analysis.

### 4.4.1 Machine and process parameters

All SLM hardware parameters were preset before the experimentation. The controllable parameters were set according to previous literature, parameter optimisation experiments and guidance from SLM suppliers. The final parameters were validated by comparing identical parts made on the SLM machine used throughout this study (see Figure 4.16), and an SLM machine based at MTT (Staffordshire, UK). All parameters are presented in the "material file", which is in the coded data file that the SLM machine reads (Refer to appendix 1 to see the material file used). All parameters were as follows:

Figure 4.16: Image of the SLM Realizer system used in this study

- SLM Machine: MCP (now MTT) Realizer Selective Laser Melting (Figure 4.16)

- Laser System: Ytterbium Fibre
- Scanning System : Analogue
- Point Distance = 0.08 mm (the point distance divided by the exposure time equals the scan speeds)
- Scan Speeds: Boundary solid = 0.1m/s (with 1 exposure)
- Hatch solid = 0.12m/s (with 1 exposure)
- Skin Hatch = 0.1m/s (with 0 exposures
- Fill Contour Solid = 0.1m/s (with 1 exposure)
- Support = 0.13m/s (with 1 exposure)
- Hatch Distance (x and y) = 1.3 mm
- Inert gas used = Pure Shield Argon (supplied by BOC)
- Oxygen Level = < 0.5%
- Laser Focus: Smallest Laser Spot (2650µm, this value is different for all machines)
- Laser Spot Size = 0.08µm
- Laser Power: Full Power 100 Watts
- Chamber Pressure: 0.6 bar ± 0.2 bar
- Material: 316L Stainless Steel supplied by Sandvik Osprey (Neath, UK), maximum particle size- 45µm

### *4.4.2 Experimental conditions*

The SLM machine was deliberately positioned in typical machine shop to create a normal working environment for the experimentation. Therefore, certain elements including the ambient temperature and humidity of the working environment were not controlled. Procedures were established to control certain elements to add uniformity to the work.

The powder was hand filtered and also stored in the machine in the uncontrolled normal working environment.  This meant that it could absorb moisture from humidity and become dirty from hand filtering, resulting in the powder loosing its flowablility and consistency.  Virgin powder in direct from Sandvik Osprey (Neath, UK) was used at the start of the experiments and then maintained so that the condition remained the same throughout the experiments.  The powder was removed from the machine once every four weeks and baked in an oven at 200°C for two to three hours, this ensured that oil and general dirt form hand filtering was burned off, and any moisture build up from the environment was removed.  The SLM build chamber was cleaned using an alcohol solution between each experiment in further attempt to maintain the powder.

### *4.4.3 Test part design*

A 5mm maximum part thickness was used for all experiments that investigated design features.  Pilot study 4 proved that a 5 mm thickness is sufficient for identifying geometric deficiencies by eye, and by using a shadowgraph.  A thicker part design would impair the measurement of a shadow image, because the outline of the shadow will include more material which may hide small deficiencies.  No parts smaller than 5mm in depth were used to reduce the risk of bending/damaging the part during removal from the substrate plate.  See Figure 4.17.

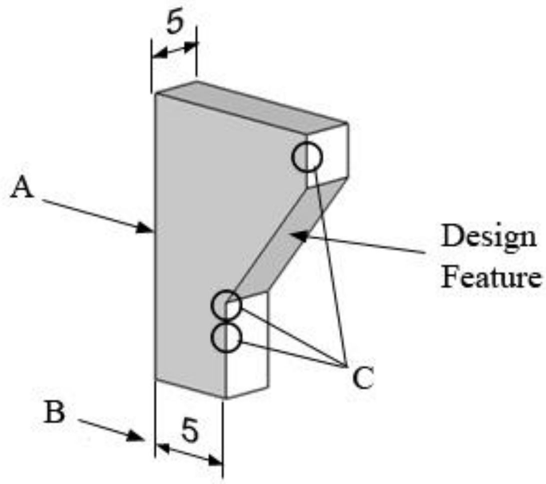



Figure 4.17: Illustration of the test part design

The design details labelled A, B and C in Figure 4.17 is described as follows:

- Label A: This surface was only used align the part into a squared position when measured using the shadowgraph protocol.
- Label B: This dimension was used to ensure that the calibration of the SLM was consistent throughout the experimentation. The data was not recorded.
- Label C: These points were used to align the printout against the test part.

Vandenbroucke & Kruth, (2007) created test pieces to identify simple geometric limitations. The test pieces were large and were constructed of many different geometries. In this research a comprehensive range of common geometries were tested. The cyclic experimentation methods used encouraged the use of of small individual test pieces, designed to allow part geometry iterations and design changes, and to use as little material as possible to save on cost and to minimise build time.

### *4.4.4 Support generation and removal*

All test parts were supported using one block support structure for anchoring the test pieces to the substrate plate. The supports were designed using Magics software version 11.1 (Materialise) (See Figure 4.18). The use of the support structures has been reported as the the main restriction that RM imposes on part geometries and consequently support placement is as important as the part design (Pullin & Offen, 2008). No structures were used to support the design features being investigated, this is because if they were used the geometry would have poor surfaces. Therefore, specific features were included in the design of the test parts to support the main parts without interfering with the surfaces being investigated. This enabled the self-supporting dimensions to be indentified. The supports were removed from the test parts using a vice, pliers and a hammer and chisel. They were not removed from the parts if the part was likely to be damaged.

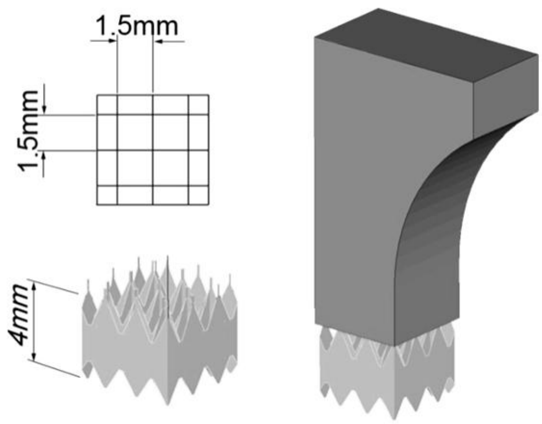



Figure 4.18: Illustration of block supports created in Magics Software (Materialise, Belguim)

Table 4.1 and Figure 4.19 describe the support teeth dimensions used. The dimensions allow for strong anchorage during the build, and enough leverage and room for support removal using hand tools.

| | Upper Teeth | Lower Teeth |
|---|---|---|
| Height | 2 mm | 1.5 mm |
| Top Length | 0.15 mm | 0.15 mm |
| Base Length | 1.5 mm | 1.5 mm |
| Base Interval | 0.2 mm | 0.2 mm |

Table 4.1: This table shows the dimensions used for the block supports.

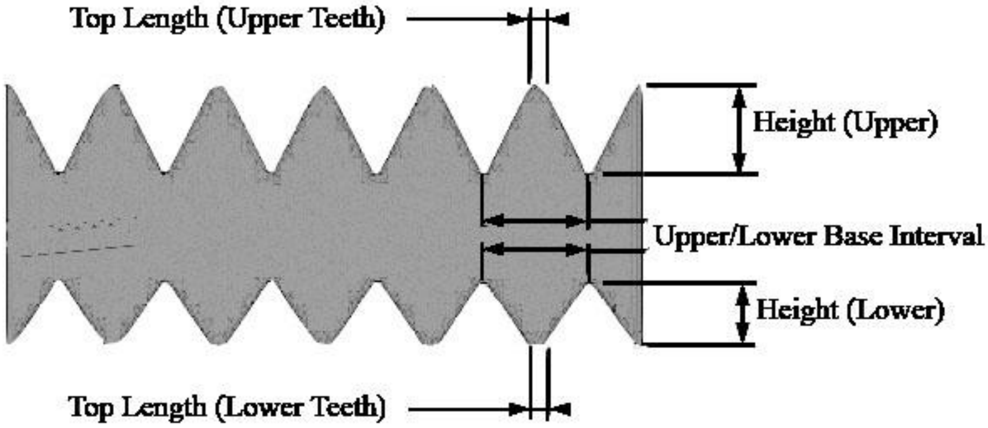



Figure 4.19: Illustration of the support structure variables

### *4.4.5 Post processing: grit blasting*

This was completed using a grit blasting machine to remove small partially melted powder particles that were loosely attached to part surfaces. This ensured that no anomalies jeopardised the quality of the measuring methods. Grit blasting is a common and quick finishing process and was also used in other SLM research by Vandenbroucke & Kruth, (2007) before measuring test parts.

### *4.4.6 Post processing: machining*

Post process machining was used on one experiment only, to investigate stock on material. The machining was performed on a CNC Vertical Milling Machine using a standard machinist's vice and parallel bars to ensure that the parts were square to the cutting axis.

## *4.5 Experimental protocols: measurement and analysis*

After completion of the pilot studies, definitive measurement protocols were created. Various inspection and quality control methods were examined before deciding on the most suitable methods. The following protocols explain the measurement and analysis apparatus and techniques used during this study.

### *4.5.1 Considered methods unused:*

#### *4.5.1.1 Coordinate Measuring Machine (CMM):*

CMM is a useful measuring technology that is more suited for measuring complex geometries that have been made using more traditional manufacturing methods such as milling, pressing and injection moulding. Using CMM on small SLM components would be very time consuming and outside the available budget for the overall research. CMM would also be unduly affected by local poor or uneven surface roughness. However, this approach has been used successfully on a small number of test parts by Vandenbroucke & Kruth (2007) to measure the accuracy of simple SLM test parts.

#### *4.5.1.2 3D Scanning:*

3D scanning is a commonly used as a reverse engineering tool for making virtual replicas of 3D objects. This technology is also used for measuring components in production and creating FEA analysis of stresses and other deformations that develop during manufacturing. To use 3D scanning to measure the test pieces anticipated in this study would be extremely time consuming and expensive. Optical scanning would produce thousands of data points resulting in masses of unnecessary data. Surface roughness and reflectivity would also result in a large amount of noise in optically scanned data that would lead to inaccuracies. The high accuracies would not be of benefit to the results as many test parts were non-complex in design and had surface roughness that would require a specialist surface profile scanner.

### *4.5.2 Selected measurement protocols:*

#### *4.5.2.1 Microscopy:*

Microscopy was used in the pilot studies to create detailed images of part features. The images were taken using a digital camera add-on to an optical microscope. Whilst it is possible to take measurements of part features, the level of accuracy at the magnification used was more than required, this would have been very time consuming and would have required the use of an expensive travelling microscope. Perspective issues made it impossible to create reference points for accurate measurements. However, the images taken with the microscope proved very useful and gave a clear visual representation of part surface quality. Microscopy was used in this study at an early stage to depict and explain part deformation that would occur throughout all tests.

#### 4.5.2.2 *Shadowgraph imagery:*

The shadowgraph (Figure 4.20) creates a 2D representation of a 3D part at magnification. At first the parts were measured using the shadowgraph's optical measurement system. This took a long time to measure a small number of parts as many surfaces of the pilot parts were rough, making it difficult select a reference point to measure to.

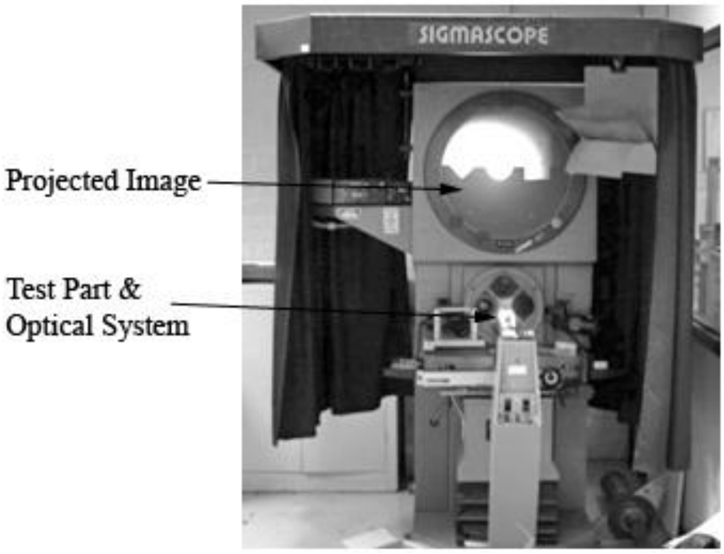



Figure 4.20: Image of the shadowgraph machine used.

The final method was to do all measuring in CAD software and just use the shadowgraph to capture the shadow image. Scaled (10x Magnification) images of the test parts were printed onto 90 GSM semi-transparent paper, including the part number. When the parts were placed squarely onto the shadowgraph using a small vice, the printed image was lined up against a known reference point and a photograph was taken. A long focal length was used to ensure that no barrelling effect developed in the photo. The photo was then imported onto the appropriate plane of the original CAD geometry in the software. The image was then scaled against the printed image in the photo, and the outer lines of the CAD image were offset to the extremities of the deformation. Dimensions were then added to the CAD image and the results were recorded. The measurement process is shown in Figure 4.21.

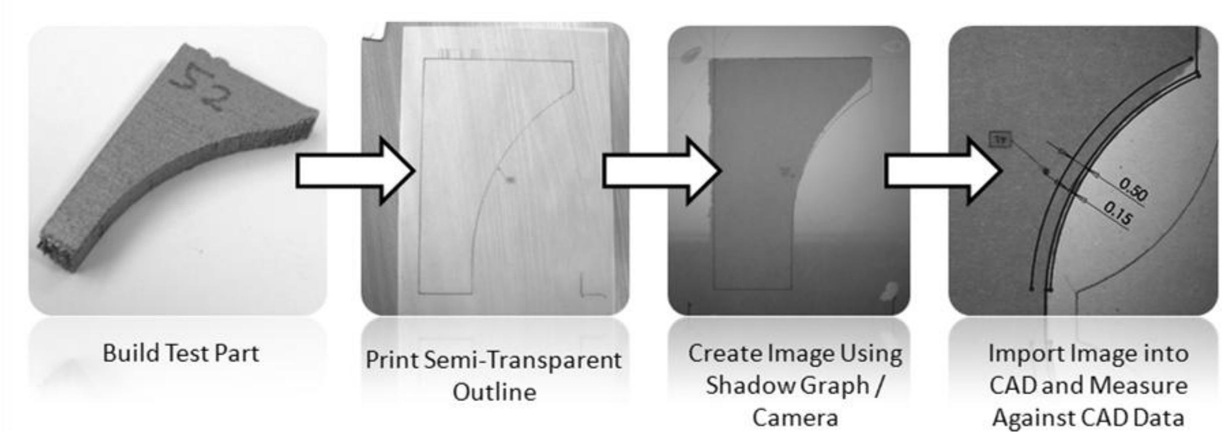



Figure 4.21: Illustration of the Shadowgraph/CAD measuring process

The cross section of the parts in shadow images shows projections of all uneven part discrepancies along a part surface. Measuring geometries with un-even surfaces with instruments that make contact with the part will not give the same measurements each time due to the surface roughness that was expected of some of the least accurate test parts. Therefore the shadowgraph images were appropriate for identifying the extents of all material deviations on a surface.

The shadowgraph used was a Sigmascope HF 500. Calibration of the Shadowgraph was completed within Arvin Meritor under their ISO 9001 quality management accreditation.

#### *4.5.2.3 Surface roughness:*

The surface roughness of the SLM test parts were measured using a surface roughness gauge (Taylor Hobson Sutronic 3p) as shown in Figure 4.22.

Figure 4.22: Taylor Hobson Sutronic 3p surface roughness gauge

The surface roughness gauge is an appropriate and simple method of measuring the mean roughness (Ra) of SLM parts. A stylus is used to traverse a sample distance across the part surface, and will display a digital readout of the Ra value.

## *4.6 Quantifying part deformation during the build process*

### *4.6.1 De-lamination*

Some part deformation happens during the SLM build that prevents the part building process from completing. De-lamination (Figure 4.23) takes place when subsequent layers do not melt together. As the metal cools, the material shrinks which causes it to lift away from the power surface if it has not fully bonded with the layer below. This is caused by poor parameter selection. However, all parameters were benchmarked to minimise the risk of this happening. This work was published in Thomas and Bibb (2007).

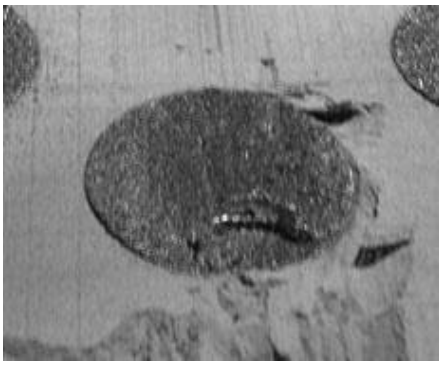


Figure 4.23: Photo of de-lamination where the layers haven't merged

### *4.6.2 Curl*

A common cause of part distortion is curl (see Figure 4.23), which occurs when the harsh temperature gradient melts and solidifies the powder in areas where the material is not self-supporting and has no underlying dense material. In this study, curl was expected because few supports were used. The amount of curl that occurs during the build was quantified using the scoring system shown in Table 4.2 and is also illustrated in Figure 4.24.

| Curl Level | Curl Amount | Explanation |
|---|---|---|
| 0 | No curl | No Curl |
| 1 | Up to 1 layer thickness (<0.075mm) | Slight visible curl, no threat to build finishing safely |
| 2 | More than 1 layer thickness (>0.075mm) | Bad curl, build safety is at risk |
| 3 | Curl increased at least 2layers every layer | Fail, serious curl which is guaranteed to impair the powder re-coater |

Table 4.2: This table shows the scores given for curl, and the reason why that score was given.

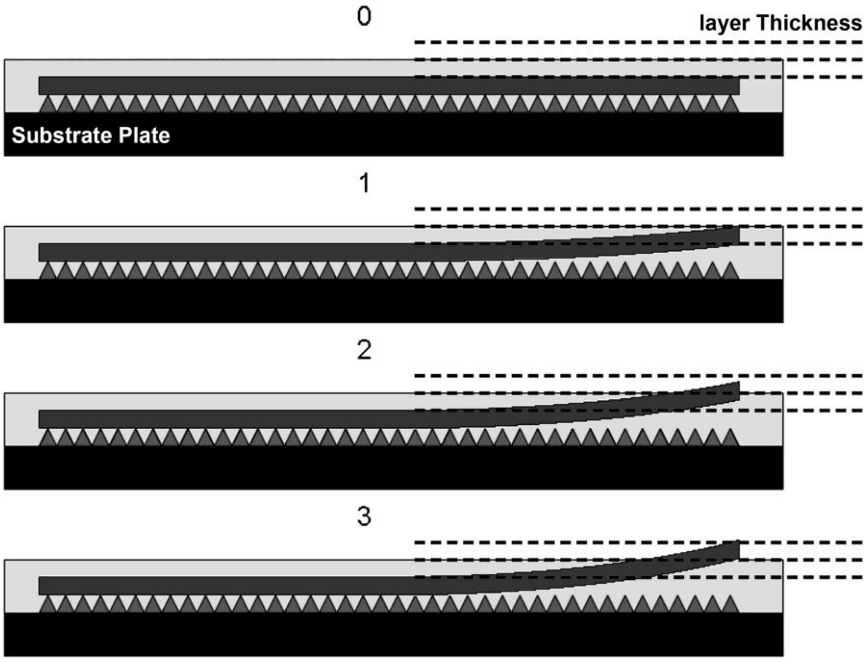



Figure 4.24 : Illustrtaion of curl values 0 to 3, the dotted lines replesent the layers and tringles represent support structures.

## *4.7 Summary*

Once the research methodologies were established all hardware and software used in the experimentation were optimised and calibrated, and a series of pilot studies were completed. During these pilot studies a series of measurement methods and part designs were tested. The outcomes of the calibration and pilot studies contributed to the development of definitive experimental protocols that ensured all experimental parameters, test part designs and analysis techniques were controlled within set boundaries. The experimentation that was completed to establish raw experimental data to inform the design rule development follows.

## 4.8 Experimentation overview

The experimental overview describes all quantitative experiments that were planned and completed to inform the design rules. Each experiment was required to produce dimensional data of specific design features, including part accuracy and dimensional limitations. The geometrical features that were investigated were planned based on non-complex design features that are fundamental in the construction of more complex shapes. It has been established that if support structures are used, it is because the geometry is designed outside of the limitations of SLM. Therefore, each experiment was planned to identify the dimensions of several geometries that allowed them to build without the use of supports. Initial questionnaires were carried out to identify existing SLM users' knowledge on design limitations of SLM. The results of the questionnaires were considered when developing the experiments required to develop fundamental results for the design rules. The process was iterative following Deming's plan, do, study, act approach. The results of one experiment were used to inform the design of the following experiment.

### 4.8.1 Supports and orientation

The selection of a support structure is closely linked to selecting a part orientation in preparation for building using SLM. The number of supports can be dependent on the orientation of a specific geometry. If a geometry can be orientated so that 90% of the surfaces are self supporting, then only 10% of the geometry will need to be supported. It is impossible to eliminate the use of supports entirely as they are needed to anchor the parts to a substrate during a build. However, if a designer considers orientation and support at an early stage the amount of support and the accuracy of SLM parts will greatly improve.

All test pieces were designed to identify self-supporting geometries, which were used to show what needs support and what does not. The geometry of all future designs was unknown. Therefore, the optimum support and orientation cannot be suggested and each SLM part would need to be treated case-by-case. Through the experience gained in the main experiments it became possible to suggest considerations for support and orientation within the design rules.

### *4.8.2 Experiment 1: Simple orientation*

The aim of this experiment is to identify the lowest self-supporting orientation of a simple flat surface that can be built using SLM. Simple cuboids were designed and supported on one surface only and were orientated at 90° to 25° at both x and y-axis directions. The test parts where designed so that the surface roughness could be measured on all surfaces in the following experiment.

### *4.8.3 Experiment 2: Surface roughness*

The aim of this study is to identify if there is a correlation between part build orientation and the surface roughness. The first experiment was completed to identify the minimum self supporting orientation of a surface. This experiment was designed using the test parts from experiment 1 to identify what happens to the surface roughness average (Ra) as self supporting orientations angle changed.

### *4.8.4 Experiment 3: Ledges*

This experiment was designed to identify the effect of building ledges that are parallel to the substrate plate. It is not possible to build a surface parallel and facing the substrate plate unless supports are used. This experiment investigated if there was a size restriction to when supports need to be introduced. Simple geometries were designed with overhanging ledges of 0.5mm to 5mm in increments of 0.5mm.

#### *4.8.5 Experiment 4: Angular overhangs (chamfers)*

A chamfer is a common design geometry typically used for bevelling corners and eliminating unnecessary sharp corners. Experiment 1 explored building simple flat cuboids at various orientations. The results from these experiments were used to design several test parts with chamfers of 45°, 50°, 55°, 60° and 65°. The accuracy of the chamfered surface was measured in this experiment.

#### *4.8.6 Experiment 5: Convex radii*

Convex radii are fundamental in the construction of holes and channels and they are commonly used to blend sharp external corners and in the construction of more complex curved surfaces. A typical convex radii curve has a varied tangent that causes the base of the radii curve to become overhanging. This experiment investigated the effect on part accuracy when making both tangential and partially tangential radii, and identified the critical dimensions of radii that need to be considered to make self-supporting radii. The results of the orientation experiments were used to plan and analyse this experiment.

#### *4.8.7 Experiment 6: Concave radii*

This experiment was designed to indentify the limitations of building concave radii in the same way as experiment 5. The tangent of a concave radius varies and is smallest at the top of the radius curve. Results from the orientation experiments were used to plan this experiment also. The results of this experiment were used to develop design rules for self-supporting radii.

#### *4.8.8 Experiment 7: Holes and channels*

The objective of this experiment was to highlight the geometric constraints of holes. It was identified that round holes collapse at the top of the hole when built with or without supports, and holes could not be built larger than 7mm diameter without supports. The intentions were to develop new designs and to modify simple round holes so that they can be produced reliably and accurately without requiring support structures.

#### *4.8.9 Experiment 8: Tapping and reaming self-supporting holes*

Previous experimentation has proven the difficulty involved with making simple round holes in an unsupported position. This experiment is aimed at identifying the best possible way of adding an internal thread and reaming self-supported holes (experiment 7). Threads are common to the design of components in assemblies and reamed holes are commonly used to as an accurate location hole for mating components

#### *4.8.10 Experiment 9: Minimum slot and wall thickness*

The aim of this experiment is to determine the smallest slot and the thinnest wall thickness that can be built using the SLM machine used in this research. Test parts were designed with an array of slot sizes to identify the smallest slot possible and a wall was built with a single pass of the laser. This wall was the thinnest possible wall that could be built with the SLM used in the research.

### *4.8.11 Experiment 10: Shrinkage*

Shrinkage and similar deformations are common with more conventional processes like injection moulding. A small amount of shrinkage appears on the outer walls of SLM parts, this was first identified in the pilot studies. The aim of this experiment was to identify when shrinkage occurs, and how to eliminate it through avoiding vulnerable geometries. Test parts were designed to promote the shrinkage so that its development could be monitored. Previous test parts from all experiments were also analysed to identify links between accuracy and shrinkage.

### *4.8.12 Experiment 11: Stock on material / sacrificial geometry*

Stock on material is the name given to adding extra material to specified surfaces of a design so that post processing can be completed without making the part undersize. Otherwise known as geometric compensation and material allowance, stocking on material is common place when parts are designed to be manufactured by sand and investment casting followed by conventional material subtraction processes such as milling and turning. This experiment was designed to quantify out how much material compensation is required to remove the outer skin of an SLM part, revealing only dense unblemished metal.

# Chapter 5: Experimental Results

## 5.1 Overview

This chapter describes the results from the experimentation to gather the data for development of design rules. The geometries that were investigated to inform the design rule development were selected by deconstructing compound geometries to expose the fundamental geometries that are used in the construction of all design features, ranging from simple cuboids to complex lattice structures. The specific design rules were not identified at this stage, however, these are the fundamental geometries that will inform the development of the design rules.

The cyclic "Plan-Do-Study-Act" (PDSA) (Deming, 1994) methodology was used to create the results shown in this chapter. This PDSA approach to the experiments encouraged each result to be reviewed after each experiment was completed to identify if the dimensional data required from each test part was achieved. The order of the experiments was strategically planned so that they became more complex and as they progressed, and so that the data gathered could inform following experiments. Each experiment was repeated with revised geometrical changes until the required dimensional data was obtained and could be used to inform the test part design for subsequent experiments.

The results are divided into "part A" and "part B". Part A describes the results and significant findings of fundamental geometry experiments. These fundamental experiments were devised as a breakdown of the building blocks that construct more complex geometries. Part B describes the results of compound experiments that were constructed from the results in part A.

The results shown in this chapter were exposed to peer review. This was done by presenting at conferences to get expert peer review feedback. The expert review feedback stated that the results were valid (See Thomas & Bibb, (2008a) Thomas & Bibb (2008b), and Dotcheva *etal* (2009) in appendix 6)

## *5.2 Results part A: Fundamental geometries:*

### *5.2.1 Experiment 1: Simple orientation*

Several experiments were completed to identify the minimum build orientation of a flat surface. Cuboids were built in orientations of 90˚, 85˚, 80˚, 75˚, 70˚, 65˚, 60˚, 55˚, 50˚ and 45˚ were built in alignment with the x-axis and y-axis as shown in Figure 5.1.

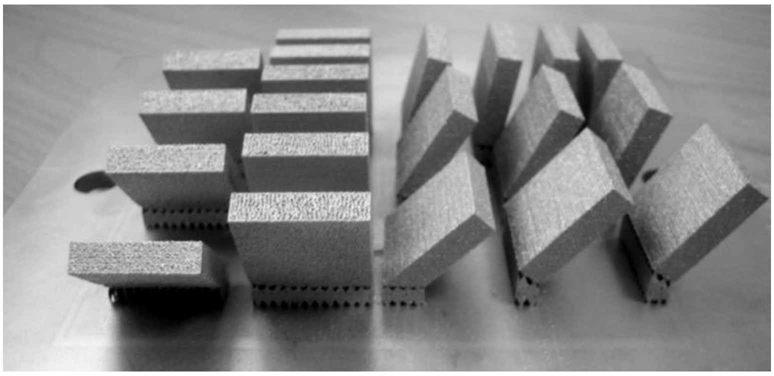


Figure 5.1: Photograph of the orientations; left is along x-axis, and right is along y-axis

In both the X and Y direction 45˚ proved to be the lowest orientation with a curl of 1 (see curl scoring criteria in Table 4.2). The curl was not significant enough to obstruct the build efficiency.

The experiment was repeated with lower orientations and no parts below 45° built successfully along the y-axis. However, 40°, 43° and 44° built across the x-axis parallel to the powder recoating system. This was not repeatable in further attempts, but it showed that the x-axis was more stable than the y-axis, with the direction of the wiper system being the only difference. All further test parts were orientated so that curl distortion would occur on the weaker y-axis to prevent limitations being restricted to just the x-axis.

Vandenbroucke & Kruth (2007) have previously stated that the staircase effect decreases proportionally with the cosine of the sloping angle. As the angle decreases, the staircase effect increases, meaning that the size of each step increases. This was evident in this experiment. As the minimum orientation is 45°, the maximum overhanging step (layer) size was the same size as the layer thickness, at 75µm (See Figure 5.2). It was apparent that this is the maximum layer overhang, because greater than 75µm caused residual curl distortion during the SLM build. Experiment 4 (5.2.4) shows the residual curl occurring as a result of excessive over-hanging geometries.

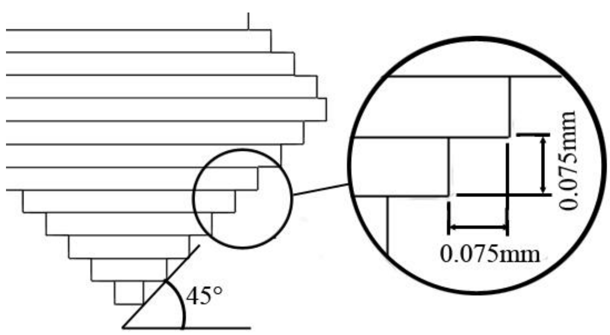



Figure 5.2: Illustration of the 74µm maximum layer overhang at 45°

### *5.2.2 Experiment 2: Surface roughness*

The average of the roughness profile (Ra) of all previously completed parts was measured (45, 50, 55, 60, 65, 70, 75, 80, 85, and 90°). Three surfaces from each part were measured in increments of 5°on all parts, see Figure 5.3.

- Surface "A" was measured from 90° to 45° up-facing.
- Surface "B" allowed surfaces from 90° to 45° down-facing.
- The top surface (C) was perpendicular to the side walls (A and B), this allowed all up-facing orientations from 0° (parallel to substrate) to 45° to be measured.

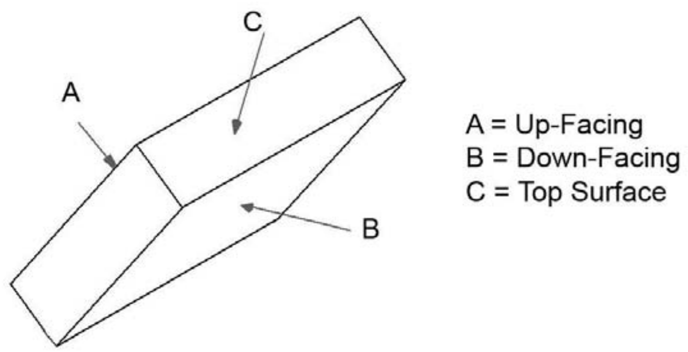



Figure 5.3: Illustration of the three surfaces measured in this experiment

All results were gathered using a Taylor Hobson Sutronic 3p surface gauge (see surface roughness measurement protocol). The aim of this experiment is to identify correlation of orientation on surface roughness. Initially the test parts were to be measured only once, however, the first results consisted of a large amount of variability and an irregular surface roughness pattern caused by a small amount of weld spatter that had adhered to the part the wall during the build. To identify if the variability was a result of the measurement method used or whether it is process inherent, a pen line was drawn across the clearest path along the part surface avoiding the surface voids. Only parts from the y-axis were measured, as the results were similar across x and y-axis in the first test. The final results are shown in Figure 5.4.

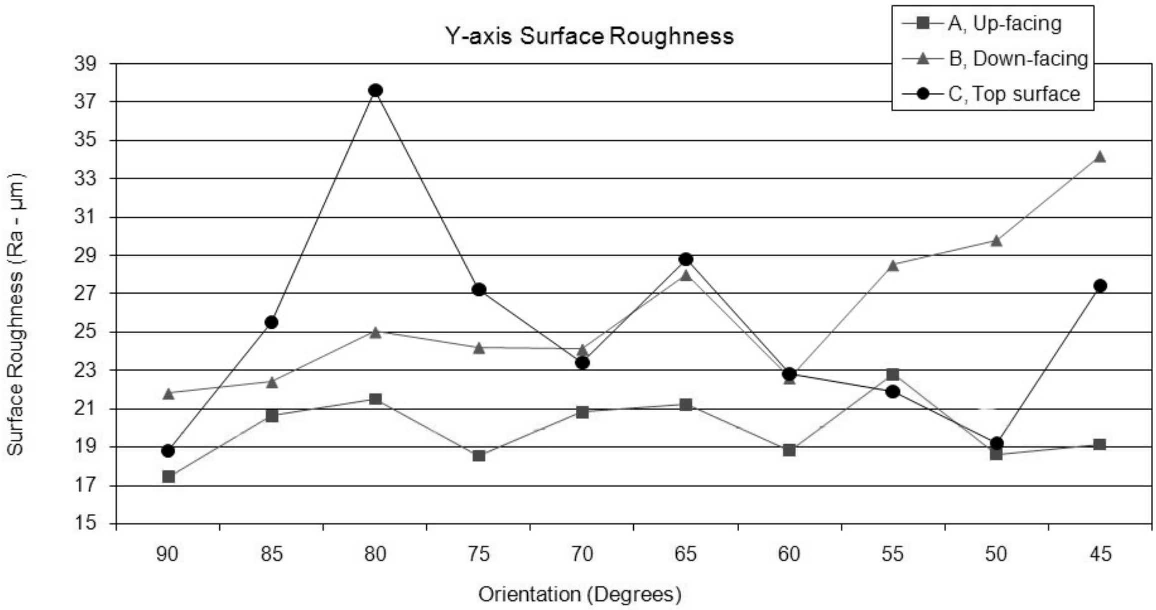



Figure 5.4: Graph illustrating the results from the second roughness measuring test.

The results showed there was variability in the data. However, the results do match the visual appearance of the test parts. When trend lines were added to the graphs, the slope of the lines suggested that the staircase effect was present, which correlated with work by Vandenbroucke & Kruth, (2007), this is illustrated in Figure 5.5.

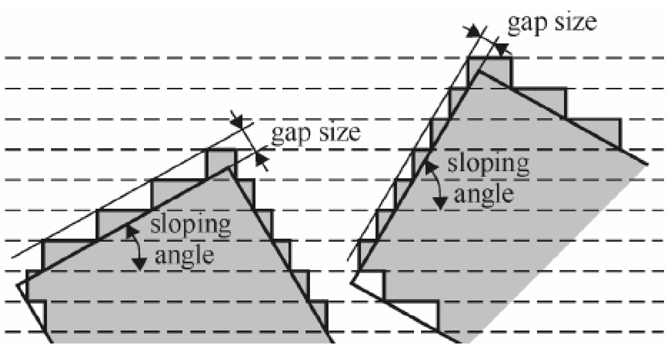



Figure 5.5: Illustrating of the staircase effect changing at different orientations, the higher the orientation the more step occur, resulting in a lower surface roughness image from (Vandenbroucke & Kruth, 2007)

### *5.2.3 Experiment 3: Minimum slot and wall thickness*

The aim of this experiment was to determine the smallest slot, and the thinnest wall thickness that can be built by SLM. To measure the minimum wall section, a boundary of a 10 mm tall cube was built, this ensured that only one pass of the laser would melt each layer to ensure minimum melting which results in a minimum thickness (see Figure 5.6). The boundary was built directly onto a substrate plate, with no support, and was measured using a vernier calliper. The wall thickness measured 0.4mm with a tolerance of ±0.02mm because of the accuracy of the vernier.

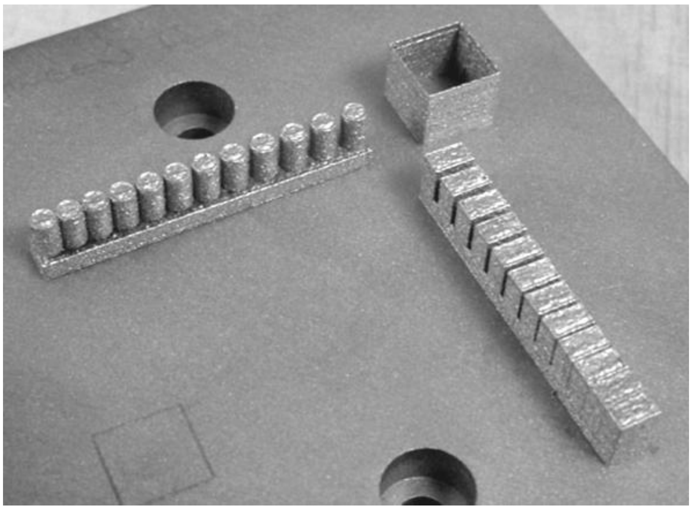


Figure 5.6: Image of the hollow cube used for measuring the minimum wall thickness, and the two parts for identifying a minimum slot size.

To identify the minimum slot thickness, two test parts were created and measured using the shadowgraph (see Figure 5.6 and Figure 5.7). One part consisted of 5mm diameter cylinders with gaps from 1 to 0.05mm thick, and the other was constructed of small cubes with slots of the same sizes. The two different tests show what the smallest slot is, and to see if the depth of the slot makes a different. The minimum slot size was found to be 0.3mm, for both parts. The 0.3mm slot appears to be partially blocked because the surface roughness of the parts protrudes and overlaps in the two-dimensional shadow image. A feeler gauge was used to ensure the slot was fully open.

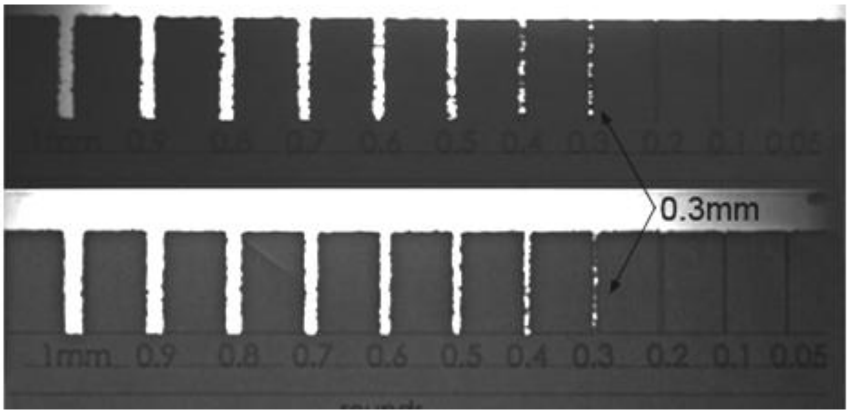



Figure 5.7: Image showing the minimum wall thickness measured on the shadowgraph. The top image is the cubed slots and the bottom image is the round slots. The results are clear in this image.

The slot was built vertically at 90°. However, a change in the orientation will affect the size of this slot, and the lower the orientation is the larger the minimum slot will become. At orientations lower than 45° the slot will not self support and will therefore need a support structure. However the support may not be able to be removed if the slot is less than 4 or 5mm.

### *5.2.4 Experiment 4: Parallel ledge*

This experiment was undertaken to identify how large a ledge could be built with no supports, and parallel to the substrate plate. Ten test parts were designed and built, with overhangs from 0.5mm 5mm, in increments of 0.5mm. The final part images and curl distortion values are shown in Figure 5.8.

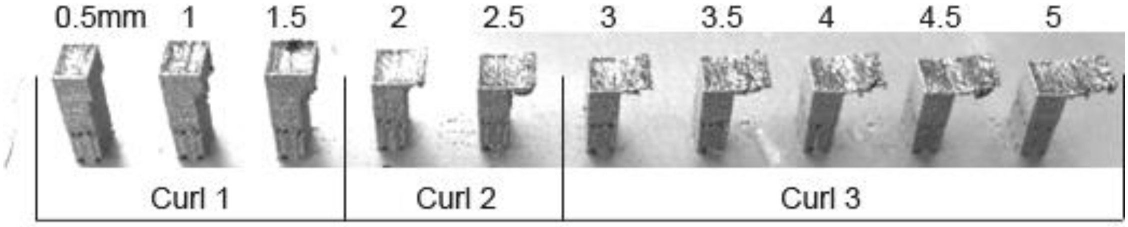



Figure 5.8: The completed SLM parts on the substrate plate.

Only overhangs 0.5mm, 1mm and 1.5mm completed the build. All other parts had distortion values (curl) that were too large to finish, causing interference with the wiper system recoating procedure. It was identified by using a shadowgraph, that the only acceptable geometry was the 0.5mm overhang (see Figure 5.9). Overhangs larger than 0.5mm do not represent the original square geometry. Experiment 1 (5.2.1) shows that the minimum overhanging step size of a single layer is 75µm. The 0.5mm result in this experiment is for one single step, and shows examples that an overhang size larger than 75µm will promote curl distortion.

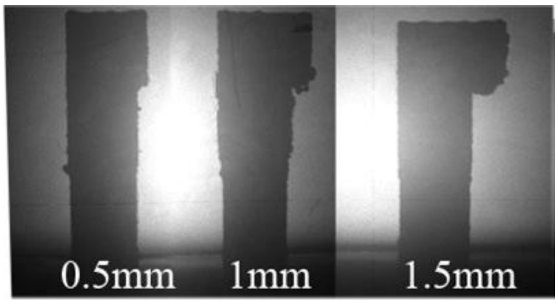



Figure 5.9: The shadow images of the parts that had completed the test build.

During the build it was observed that the part would only curl when the raster scan was scanning perpendicular to the curl direction. The start of the curl is illustrated in Figure 5.10. When the laser scanned the x-axis no curl occurred. When the laser scanned along the y-axis, the unsupported material curled up from the surface powder. This correlates with work by Mercelis & Kruth (2006) who have identified the influence of the scanning direction.

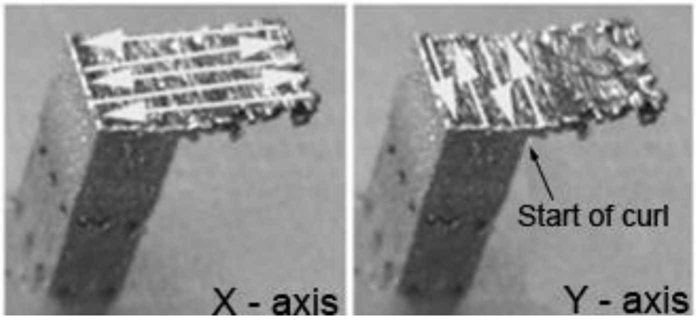



Figure 5.10: The curl occurring during the SLM builds. The left image shows no curl effect as right shows the curl starting point.

### 5.2.5 *Experiment 5: Angular overhangs (chamfers)*

A chamfer is a typical feature found on many part designs. It is commonly used to remove sharp edges of a part, especially on metal parts, making the parts safe and easier to handle. Chamfer angles 45° to 65° were chosen for investigation in increments of 5°. Shadowgraph imagery was then used to measure all parts and microscopy was used to visually inspect the parts. Using an outline from the correct original CAD geometry, the visual alignment of all parts was measured and any deviation was recorded. The results are shown in Table 5.1 and Figure 5.11.

| Angle | Curl | Angle Tolerance | Negative Material | Positive Material |
|---|---|---|---|---|
| 45˚ | 0 | +1.5° | 0.2mm | 0mm |
| 50˚ | 0 | 0° | 0.2mm | 0mm |
| 55˚ | 0 | +1.5° | 0.2mm | 0mm |
| 60˚ | 0 | 0° | 0mm | 0mm |
| 65˚ | 0 | 0° | 0.15mm | 0mm |

Table 5.1: Showing the results of the chamfer measurements.

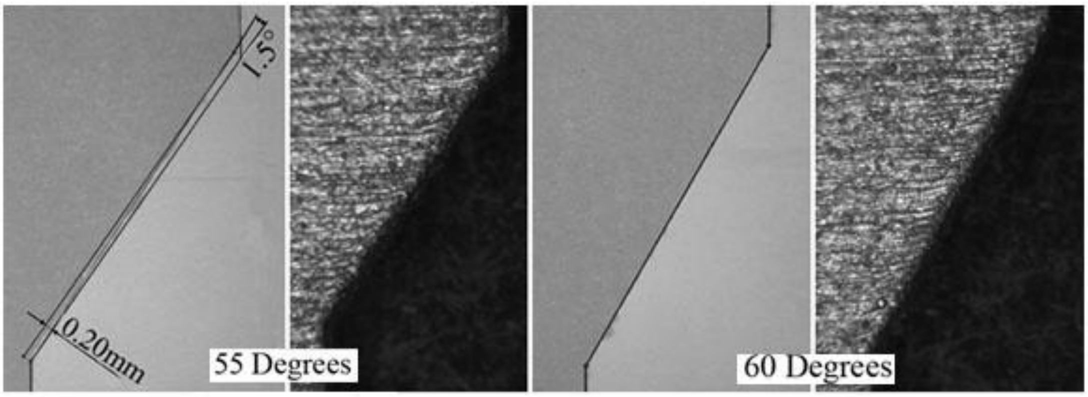



Figure 5.11: Images of the shadowgraph measurements and microscope images. The visual alignment at 55°is 1.5°, and at 60° is there is no deviation.

The test geometries were not repeatable to within a tolerance smaller than 1.5° or 0.2mm. Microscope images show that all layers curl away from the original CAD geometry on the chamfer, which is why all inaccuracies were negative (undersize). This suggested that that further experimentation will result in part deformations being undersize rather than oversize.

### *5.2.6 Experiment 6: Fillet radii (convex radii)*

A fillet radius is a common geometry used for both aesthetic and functional reasons. It is considered that a radius is part of the construction of any design using curved surfaces, and multiples of a simple radius is used in more complex shapes and forms. This experiment investigated the constraints and possibilities of building self-supporting convex radii.

The lowest point of a traditional convex radius is vulnerable to curl, as it is down-facing and exceeds the overhanging size limit identified in previous experimentation. The first experiment proved this, as only 1mm and 2mm radii out of five larger parts built successfully. The accuracy of the radii was poor and the radius did not resemble the original CAD data (see Figure 5.12).

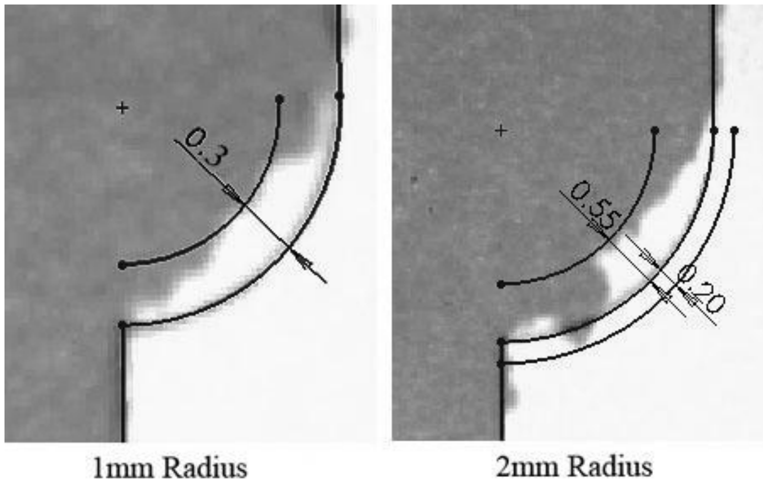



Figure 5.12: Shadowgraph images compared against the actual CAD data

Further experimentation was undertaken which incorporated a tangent change at the lowest point of the radius so that the part would become self-supporting (see 30° examples in Figure 5.13). The tangent at the top of the radius remained tangential so that the transition of the radius to a different feature would have a blended edge. It was confirmed that the tangent was the dimension that determined the success of the build, and more curl distortion occurred as the radius size increased. Further experiments were then undertaken investigating different sized overhangs of 5, 10 and 15mm as shown in Figure 5.13. The tangent angles tested were 22° to 44°.

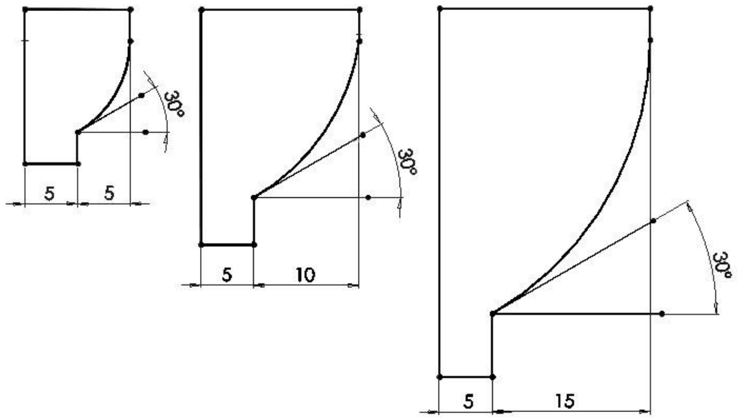



Figure 5.13: Illustrates the three different size parts built. The overhang sizes are 5mm, 10mm and 15mm, the tangents changed for each test piece.

Once the final test was completed, all parts were measured using a shadowgraph, and plotted in a table along with the amount of curl distortion and the dimensional values. This table shows the tangent angle where each size part built successfully, and most accurate, allowing for a general tolerance to be achieved. Parts with a curl of 3 did not finish and were not measured (See Table 5.2: The accuracy and the curl level of the convex test parts, the blank boxes were not measured as they did not build

| | 5mm | 5mm | 10mm | 10mm | 15mm | 15mm |
|---|---|---|---|---|---|---|
| Tangent | - | + | - | + | - | + |
| 22 | -0.35 | 0.25 | | | | |
| 24 | -0.25 | 0.2 | | | | |
| 26 | -0.15 | 0.25 | | | | |
| 28 | -0.1 | 0.15 | | | | |
| 30 | -0.15 | 0.3 | | | | |
| 32 | -0.1 | 0.15 | 0 | 0.3 | | |
| 34 | 0 | 0.4 | -0.15 | 0 | -0.5 | 0 |
| 36 | 0 | 0.4 | 0 | 0.2 | -0.35 | 0 |
| 38 | 0 | 0.15 | 0 | 0 | -0.35 | 0 |
| 40 | 0 | 0.1 | 0 | 0.2 | -0.2 | 0 |
| 42 | 0 | 0.25 | -0.1 | 0.05 | -0.1 | 0 |
| 44 | 0 | 0.2 | -0.05 | 0.1 | -0.15 | 0 |

| CURL 0 | CURL1 | CURL 2 | CURL 3 |
|---|---|---|---|

Table 5.2: The accuracy and the curl level of the convex test parts, the blank boxes were not measured as they did not build

- The results showed that the larger the overhang, the larger the starting tangent of the radius needs to be. This was the same for the earlier radii experiments.
- It appeared that the part accuracy and the amount of curl distortion were related. Parts with curl level of 2 were significantly less accurate than parts with no curl at all. This is illustrated in Figure 5.14

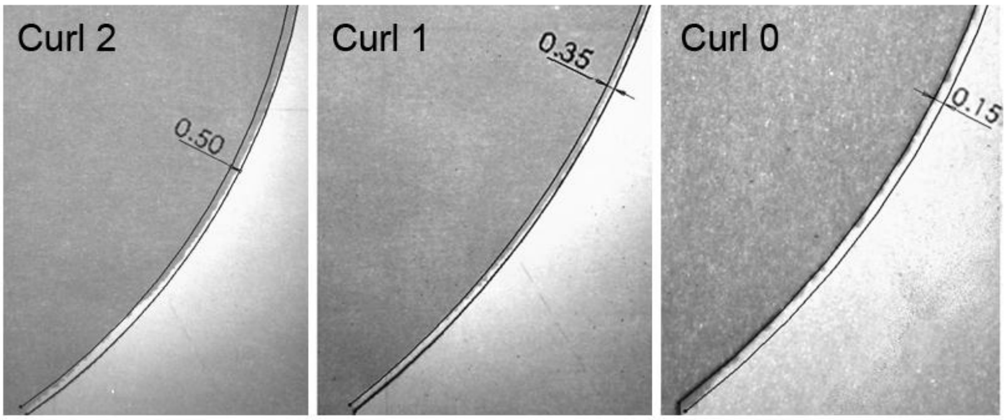



Figure 5.14: Shadow images of the three different curl values. This image illustrates that the less curl the more accurate that the part is

- Although the accuracy was not consistent for all parts with a curl of 2, 1 or 0, from Table 5.2 and the shadowgraph images (Figure 5.14) it was clear that there is an accuracy difference between each curl value.
- The accuracy is undersize more frequently than oversize because the distortions curled the geometry of the SLM away from the correct geometry.
- The surface roughness at the lowest point of the radii is the roughest, and improves at the surface tangent angle increases.
- If there is a small amount of curl, the curl value is 1, and the overall tolerance of the convex radius will be ±0.4mm, the tolerances vary from ±0.1 to ±0.4 for each part built within a curl of 1 for the 5, 10 and 15mm overhangs.

- To achieve a tighter tolerance there must be no residual curl occurring throughout the build, tolerances of ±0.25mm can be achieved, although this tolerance varies from ±0.0mm to ±0.25mm.

At the first layer of a convex radius, the tangent angle is at its lowest and increases to become more self supporting as the layers progress on the z-axis. As found in experiment 1, the layer overhang is maximum at 75µ which is at 45°. The start tangents in this experiment were smaller than the expected 45°, this can only happen because the consecutive layers become self supporting, and the curl distortion does not get a change to accumulate. However, as the radius size increases, the start tangent needs to increase because there are more layers between the tangent and the self supporting 45° tangent to accumulate an excessive curl distortion, see Figure 5.15. Increasing the start tangent also increases the overall height of the radii, which may become a design limitation.

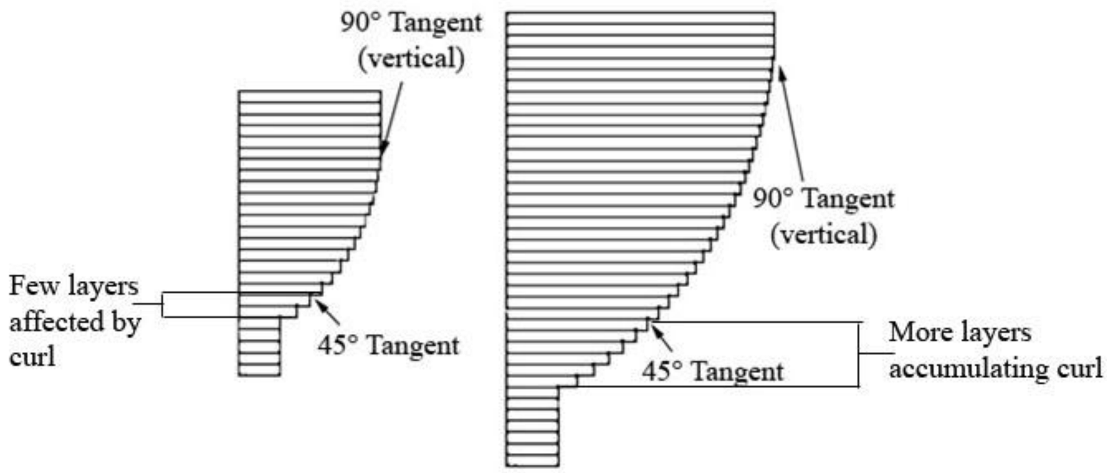



Figure 5.15: Illustration showing the number of layer increase as the convex radius size increases, the number of layers below 45° also increases.

### 5.2.7 Experiment 7: Fillet radii (concave radii)

A concave radius is the opposite curve to a convex radius and a simple design feature that can be incorporated into designs to eliminate sharp corners and can be found in the construction of curved surfaces. The results from the previous experiment on convex radii were considered in analysis of the test parts. This experiment investigated the limitations of manufacturing concave fillet radii using SLM.

Previous findings identified that a tangential convex radius could not be built successfully. The first experiment identified that tangential concave radii could not build successfully as the top of the radius is not self-supporting, because the tangent decreases to 0° as the part grows in the z-axis, resulting in excessive layer individual overhangs. Radius sizes 1, 2 and 3mm did build but the geometry did not resemble a radii, and the 3mm had a unsafe curl value of 2 (see Figure 5.16).

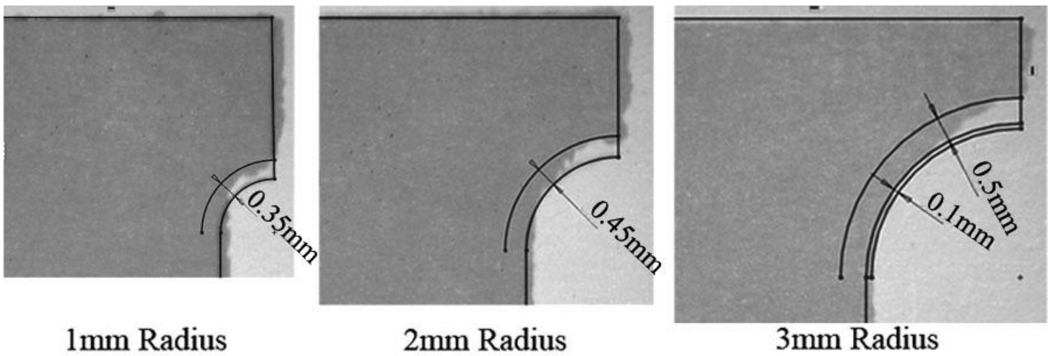



Figure 5.16: Images showing the shadowgraph images of the tangential radius, the images are measured against the original CAD data.

To ensure that concave radii could be built with self supporting dimensions, the top tangent of the curve was increased (see 30° tangent example in Figure 5.17). Three experiments were undertaken to identify the minimum tangents required to build a concave radius without the use of support structures.  It was identified that as the tangent angle increases, the curl distortion decreases and the accuracy of the curve was improved.  When measured, all parts were oversize rather than undersize as with the convex radii.  The following experiments were completed at 5mm, 10mm and 15mm overhangs.

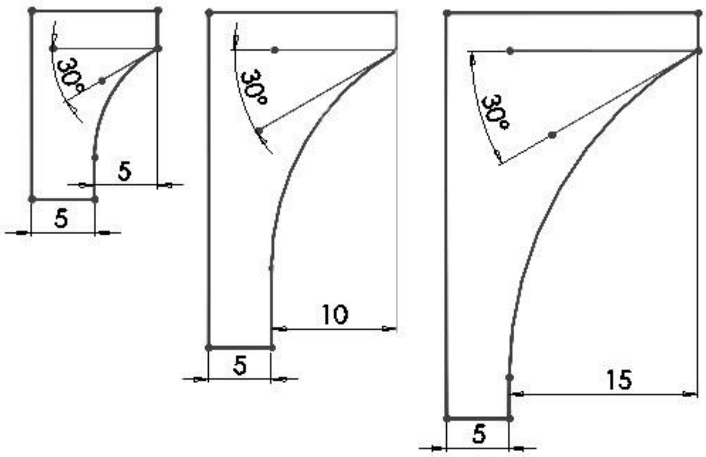



Figure 5.17: Illustration showing the overhanging ledge sizes and the position where the tangent is changed.

Once the final test was completed, all parts were measured using a shadowgraph, and plotted in a table along with the amount of curl distortion and the dimensional values.  This table shows the tangent angle where each size part built successfully, and most accurate, allowing for a general tolerance to be achieved.  Parts with a curl of 3 did not finish and were not measured (see Table 5.3).

| | 5mm | 5mm | 10mm | 10mm | 15mm | 15mm |
|---|---|---|---|---|---|---|
| Tangent | - | + | - | + | - | + |
| 22 | -0.6 | 0.1 | | | | |
| 24 | -0.5 | 0.15 | | | | |
| 26 | -0.6 | 0.15 | | | | |
| 28 | -0.6 | 0.1 | | | | |
| 30 | 0 | 0.2 | -0.5 | 0.1 | | |
| 32 | 0 | 0.2 | -0.6 | 0.1 | | |
| 34 | -0.15 | 0.2 | -0.25 | 0.1 | | |
| 36 | N/A | N/A | -0.2 | 0.2 | | |
| 38 | N/A | N/A | -0.2 | 0.1 | -0.5 | 0 |
| 40 | N/A | N/A | -0.2 | 0.1 | -0.1 | 0.1 |
| 42 | N/A | N/A | -0.2 | 0 | -0.1 | 0.1 |
| 44 | N/A | N/A | 0 | 0.15 | -0.15 | 0.1 |

CURL 0 CURL 1 CURL 2 CURL 3

Table 5.3: Showing the accuracy related and curl level of the concave test parts, the greyed out boxes are not shown as the geometry was unsuccessful and failed.

- The level of curl distortion appeared to become a reliable visual representation that occurs during the build, of how accurate the parts actually are.
- It appeared that the part accuracy and the amount of curl distortion were related. Parts with curl level of 2 were significantly less accurate than parts with no curl at all. This is illustrated in Figure 5.18.

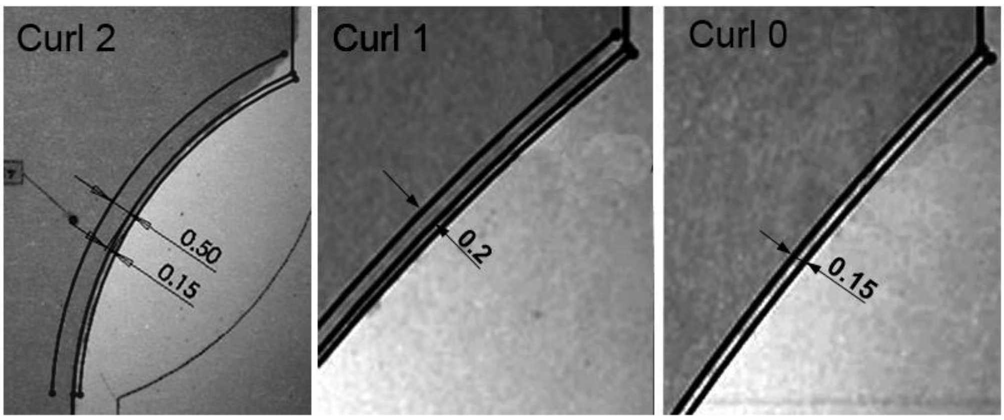



Figure 5.18: Shadow images of the three different curl values. This image illustrates that the less curl the more accurate the part is

- Although the accuracy was not consistent for all parts with a curl of 2, 1 or 0, from Table 5.2 and the shadowgraph images (Figure 5.18), it was clear that there is an accuracy difference between each curl value. When no curl occurred the radius is complete and ends with a sharp corner.
- The shadowgraph measurements show that the larger the overhang, the larger that the tangent needs to be.
- The surface roughness on the concave radii degraded as the tangent of the radii increased when the parts built up in the z-axis.
- The part tolerance when building with the recommended tangents will be -0.2mm and +0.1mm, therefore a safe tolerance will be +/- 0.2mm. Parts that are built with smaller tangents than recommended, will either fail, or will have a curl value of 2.

Many of the results were lower than the minimum surface orientation of 45° (see experiment 1). As the radius experiments progressed it became clear that this phenomenon relates to the number of layers that were lower than 45° that exceeded the minimum layer overhang size. If only a few layers are lower than 45° then the curl will not have enough layers to accumulate and cause a failure. As the parts get larger the number of layers increases resulting in more layers vulnerable to accumulate high levels of curl. See Figure 5.19.

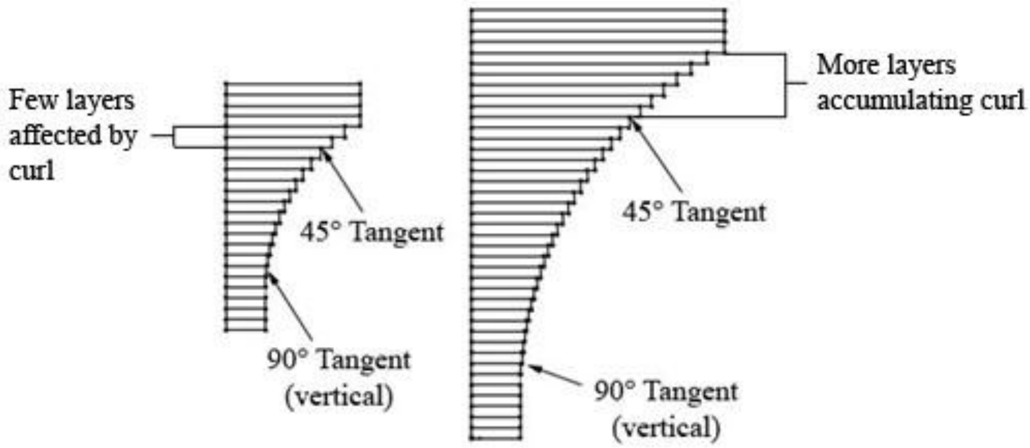



Figure 5.19: Illustration showing the number of layer increase as the concave radius size increase, the number of layers below 45° also increases.

One possible design limitation occurs as a result of increasing the tangent to create a self-supporting radius. The height from the bottom to the top of the radius increases, which also results in the radius value on the curve increasing. See Table 5.4.

| | **Height of Radius** | | |
|---|---|---|---|
| **Tangent °** | **5mm Overhang** | **10mm Overhang** | **15mm Overhang** |
| 22° | 7.41 | 14.83 | 22.24 |
| 24° | 7.7 | 15.4 | 23.1 |
| 26° | 8 | 16 | 24.01 |
| 28° | 8.32 | 16.64 | 24.96 |
| 30° | 8.66 | 17.32 | 25.98 |
| 32° | 9.02 | 18.04 | 27.06 |
| 34° | 9.4 | 18.81 | 28.21 |
| 36° | 9.81 | 19.63 | 29.44 |
| 38° | 10.25 | 20.8 | 30.75 |
| 40° | 10.72 | 21.45 | 32.17 |
| 42° | 11.23 | 22.46 | 33.39 |
| 44° | 11.78 | 23.56 | 35.34 |

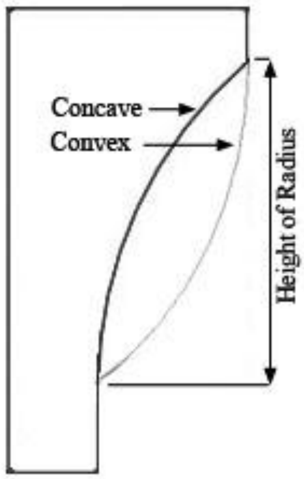



Table 5.4: Showing the increase in height when the tangent increases, also the radius values as the tangent increases.

Both concave and convex radii will be affected with the radius height increasing in exactly the same manner. This may become a design constraint as traditionally a radius is the same size across the overhang as it is on the height.

## 5.3 Results Part B: Compound shapes:

### 5.3.1 Experiment 8: Holes and channels

Pilot studies completed earlier in this research identified that round holes cannot be built upright without failure or distortion. Holes smaller or equal to 7mm build safely but will have an average of 0.5mm of sag at the top of the hole, which is uncontrollable even with supports, and prevents the overall hole from being perfectly circular. Larger holes above 7mm show evidence of excessive curl distortion which impairs the build safety and results in larger inaccuracies. Holes are traditionally round due to drilling and reaming, however, since holes that are manufactured in RM are built layer-by layer, there is an opportunity for holes to be made any shape.

When the hole experiments where planned, it seemed necessary to set the dimensions of the holes according to cross sectional areas of $5mm^2$, $10mm^2$, $20mm^2$ and $30mm^2$. This was so that the holes could also be used as channels that could manage calculated amounts of fluid flow. Designing the holes based on area became a challenge because as one dimension was set to meet the area values, it had an impact on the other feature dimensions. This then required modifying the dimensions that were previously applied to the holes, which then resulted in other dimensions on the same feature needing to be changed to match the modifying dimensions.

The achieved results had dimensions that were driven by setting the required area on each hole. The dimensions all fell between the 0 to 5mm, 10mm and 15mm overhangs that were tested. The initial thought was that these results would fill in the gaps between 5mm, 5 to 10mm and also 10 to 15mm. On completion of the experiment it was found that the final results could not be used to design new holes, this was because designing the holes to set areas removed an element of control from the experiments. The following shows the results of all hole experiments, and significant findings that need to be considered in further developments of the holes. The shadow images and original geometries are shown in Figure 5.20.

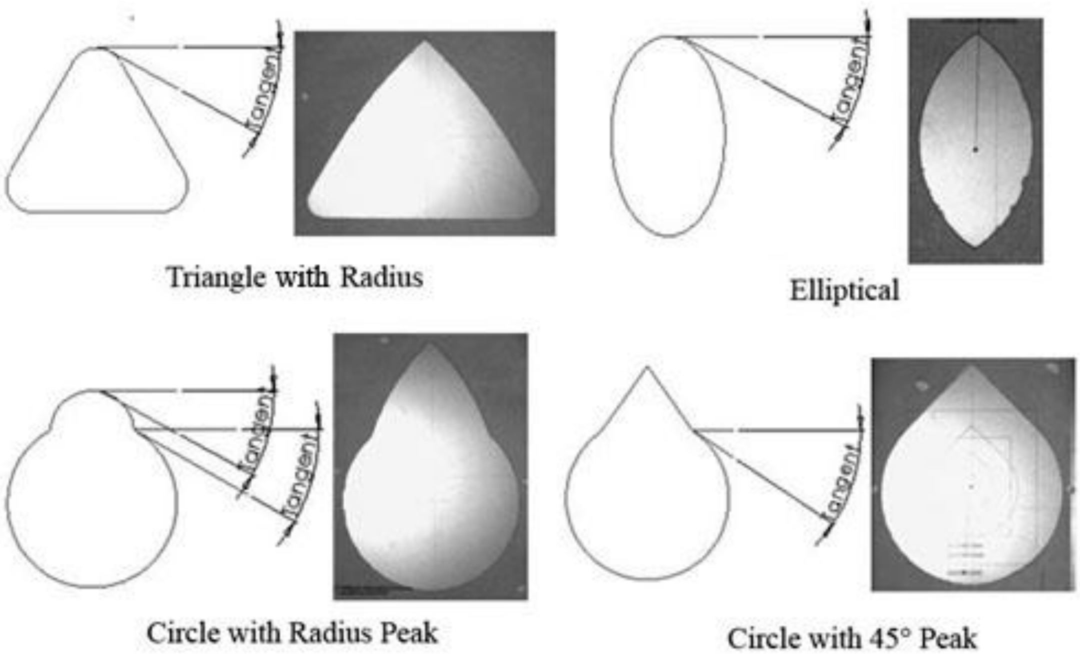



Figure 5.20: Shadow images and original hole designs.

- The geometries of the triangle with radius, ellipse, and circle with radius peak were designed so that no sharp corners would cause stress concentration zones when applied to actual useable parts. When self-supporting dimensions were applied to the geometries, the radius became a sharp point. The circle with peak was created exactly the same as expected from the original design (see Figure 5.20).

- All parts built with a curl distortion value of 1, and the accuracies were all within 0.2mm which was also predicted from previous experimentation.
- When two features of a part are built on top of one another, the lower feature must have no distortion where it connects to the top feature. If distortion is present then it creates a poor foundation for the top part, which will result in distortion within the first few layers of the top feature. If the top feature is built at the lower self-supporting limit the distortion may accumulate further from the lower feature and cause a build failure. Alternatively, if the top part is not built at the lower self-supporting limit the distortion will be corrected within the first few layers. This was identified when building, the circle with radius, and the circle with a 45° peak at the lower self-supporting.

The equilateral and isosceles triangle holes proved to be less complex to build than all other holes. This was because only self-supporting flat surfaces were required; the results are as shown in Figure 5.21 and Table 5.5.

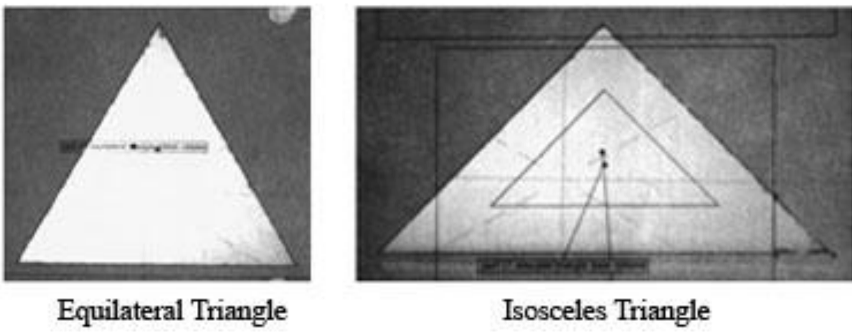



Figure 5.21: Showing shadow Image of the equilateral and isosceles triangles

| | | | | | Accuracy (mm) |
|---|---|---|---|---|---|
| Hole Type | Hole size | Angle | Curl | - | + |
| Equilateral | 5mm$^2$ | 60° | 0 | 0 | 0.08 |
| Equilateral | 10mm$^2$ | 60° | 0 | 0 | 0.08 |
| Equilateral | 20mm$^2$ | 60° | 0 | 0 | 0.1 |
| Equilateral | 30mm$^2$ | 60° | 0 | 0 | 0 |
| Isosceles | 5mm2 | 45° | 1 | 0 | 0.13 |
| Isosceles | 10mm2 | 45° | 1 | 0 | 0.04 |
| Isosceles | 20mm2 | 45° | 1 | 0 | 0.1 |
| Isosceles | 30mm2 | 45° | 1 | 0 | 0.1 |

Table 5.5: Results and geometrical details of the equilateral and isosceles triangle test parts

- The size of each triangular hole does not affect the accuracy as the walls are self supporting.
- The result was predictable when considering the little difference between a curl of 0 and 1 in previous experiments.

#### *5.3.1.1 Critical analysis:*

Investigating the limitations of self-supporting hole designs using hole area had proven to be unsuccessful, therefore, it was relevant to repeat the investigation with a different approach. Rather than creating many hole designs, the geometries were designed to be as close to a round hole as possible to maximize the surface area of the actual hole round, and to retain the maximum functionality where a traditional round hole is used. To do this further investigations of the hole labelled “circle with radius peak” was required as it had the most circle surface area, and the peak height could be minimised if tangent limitations were applied.

Previously, the tangents at the base of the radius peak were unconstrained on every test piece, which affected the height of the peak, and therefore, its ability to build as a self-supporting geometry. This is illustrated in Figure 5.22.

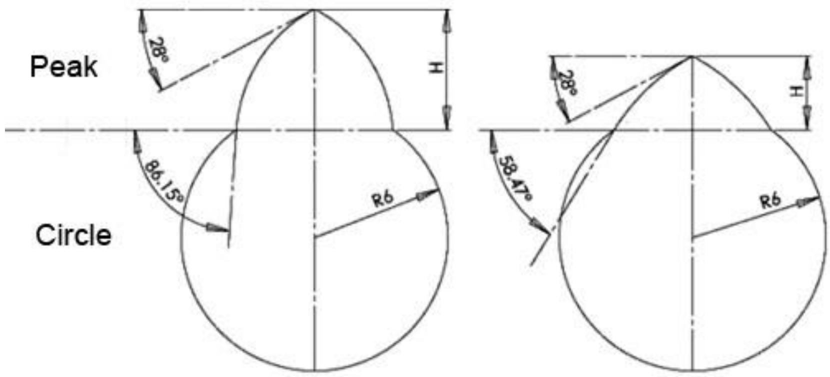



Figure 5.22: Shows the possible changes in peak height when under constrained

The first experiment was to identify the maximum height that the circle could be made without supports. 1mm to 15mm radius test parts were created and as they began to curl the layer number was recorded and the part was stopped from building further. After the first test build, the experiments proved to be challenging as the point of the build where the curl that was safe, to the point of the curve where the curl became unsafe, was spread over many layers. As only judgement was used when deciding to stop the parts, it was possible that some parts were stopped too early and some were stopped too late which caused the variability shown in Figure 5.23. The results are shown in Figure 5.23 and Figure 5.24.

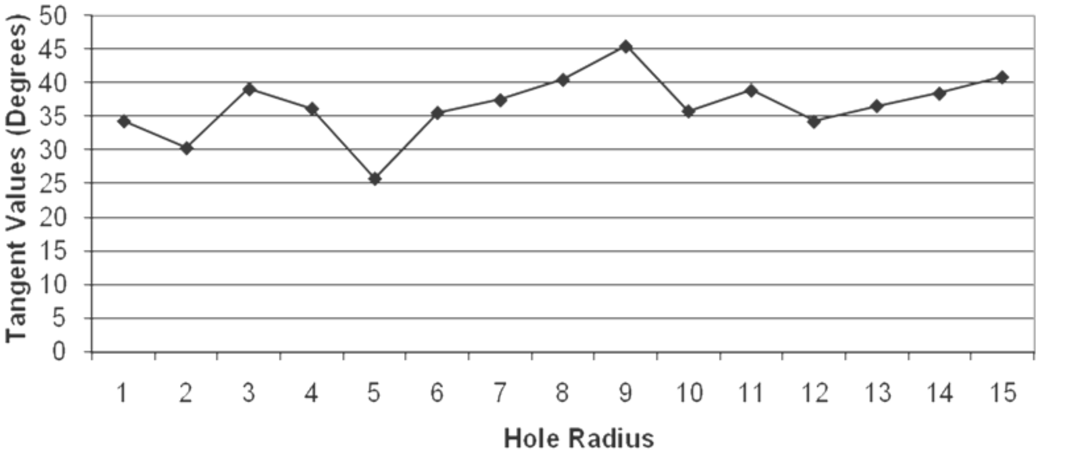



Figure 5.23: Graph of the results taken from attempt 1

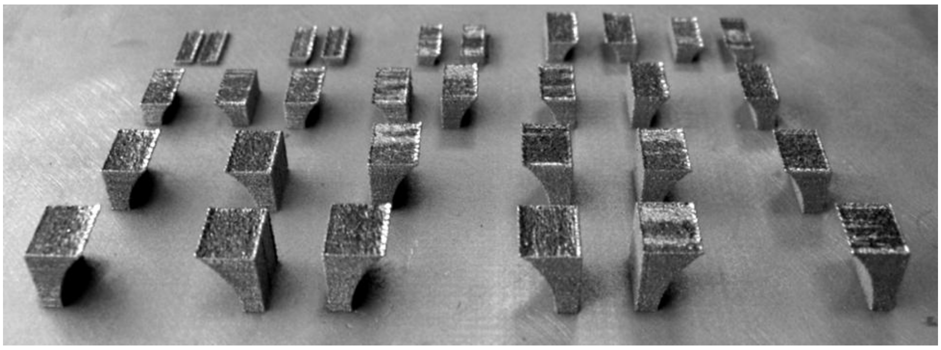


Figure 5.24: Actual SLM test pieces on substrate plate

To ensure that the maximum height of the hole was correct, the middle point of the layer that the first sign of curl occurs and where the curl clearly became unsafe (curl 2) was investigated. This ensured that the maximum height that all holes could be built to was consistent. The results and centre points are shown in Figure 5.25.

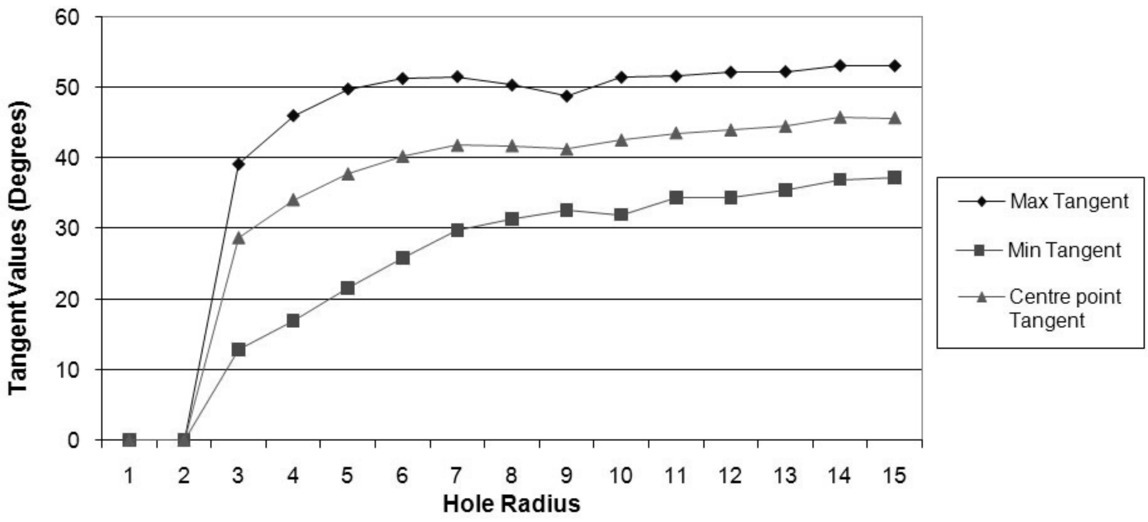



Figure 5.25: Graph showing the centre point of the max and min tangents

The parts from the centre point on the graphs were rebuilt successfully with no curl. The 1mm and 2mm radius built as a complete circle with no curl as shown in Figure 5.26. The holes were measured using the shadowgraph, the accuracy of both these holes shows that there was a sag of 0.3 to 0.4mm, this suggested that a peak was required to enhance the accuracy.

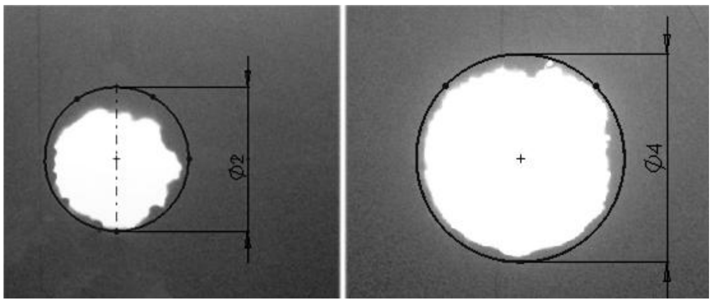



Figure 5.26: 1mm and 2mm radius holes built using SLM

#### *5.3.1.2 Developing a self-supporting peak:*

The maximum height, and tangents of the circle part of the hole were identified, the following explains how the peak was designed. Previous experimentation on radii identified a minimum tangent at the highest point of various concave radii (see Figure 5.27). The results of the three radii were driven by the size of the overhang, which is effectively the size of the ledge that required a radius. A mirror of one radii was used to create the hole peak.

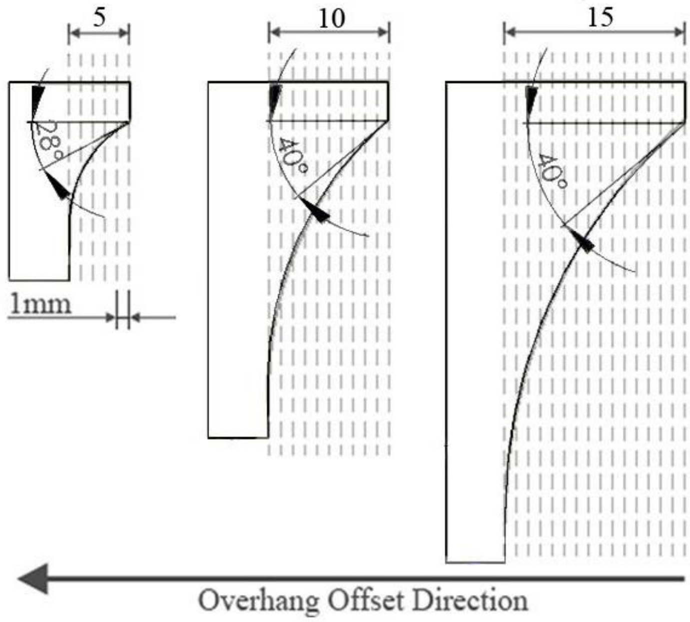



Figure 5.27: The previously concluded curves and lines where the curves were sectioned

As the tangents and layer number that the circle built up to is known, it was possible to calculate the size of the gap at the top of the circles, and therefore the size of the overhang for the peak radius was known. The curves were split up into 1mm sections that represented different overhang sizes as shown in Figure 5.27. The line and curve intersections are the dimensions required for the radius peak. To keep the hole size to a minimum, the overhangs were selected starting from the highest point (lowest tangent) of the curve. If the overhangs were selected from the lowest point of the curve the tangent angle would start as 90° tangential, which means that the curve will fully blend into the vertical surface and the height of the peak will be the largest possible.

It was decided that the 10mm overhang curve was not required. This was because it had no benefit over the larger 15mm overhang curve, as the top tangent was 40° on both. The height of the curve will be lower if the largest curve is used, and up until a certain height the smallest curve will give a lower height. Based on the intersected curves in Figure 5.27, the following theoretical design rules were established that would create self-supporting peaks that have the lowest height so that the hole remains as close to the original round geometry as possible. The theories were tested and all holes are shown following this theory.

- If a curve has an overhanging geometry of less than 3.65mm, the 28° curve gives a lowest height compared to the 40°curve. Therefore the smaller curve should be used in this below overhangs of 3.65mm. Figure 5.28 shows the 28° curve at 3.65mm, and Figure 5.29 illustrates the height difference on the 28° and 40° curves with a smaller overhang.

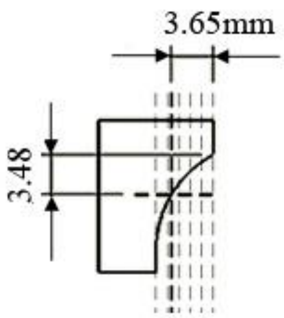



Figure 5.28: Shows that 3.65mm overhang will give a 3.48mm height for both small and larger curves.

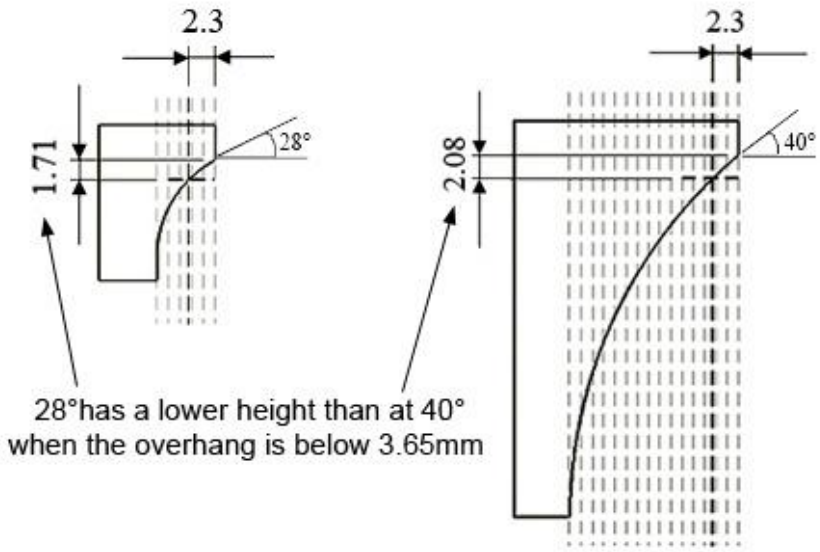



Figure 5.29: An illustration of the 28° curve having a lower height than at 40° when the same overhang values are used under 3.65mm

- Between an overhanging distance of 3.65mm and 5.18mm, the larger 40° curve will have a lower height. Therefore this curve should be used if the overhang of the radius falls in between 3.65mm and 5.18mm. Also the 28° curve is not large enough. See Figure 5.30.

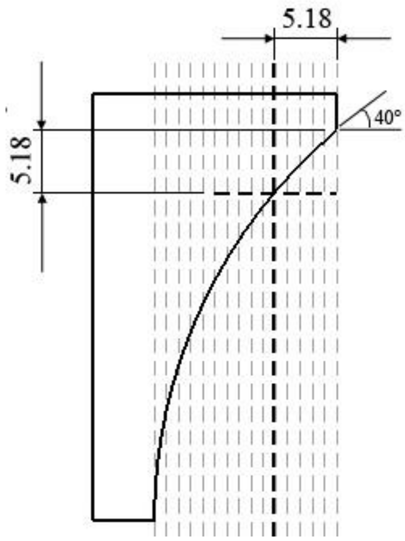



Figure 5.30: Showing the height is the same as the offset at 5.18mm on the 40° curve.

- After 5.18mm, the peak becomes higher than if a 45° angle was used. Therefore a 45° angle peak should be used instead of a radius for all sizes larger than 5.18mm. See Figure 5.31.

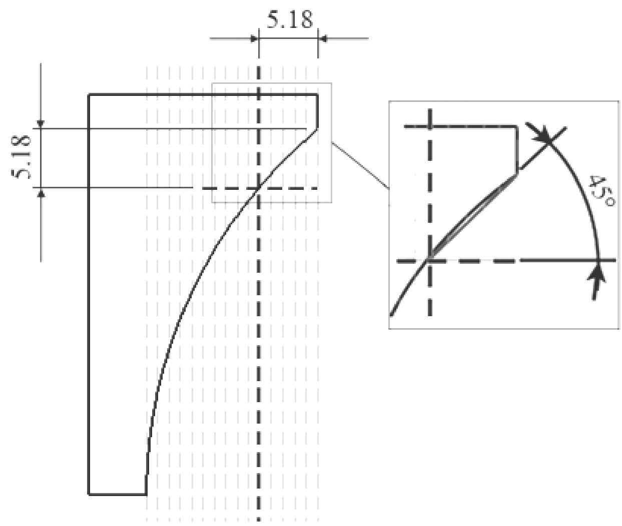



Figure 5.31: Illustration of the 45° position at a maximum 5.18mm

#### *5.3.1.3 Experiment - Applying the self-supporting peak theory to actual holes:*

Using the rules shown above, self-supporting peak designs were created for holes of radius 1mm to 15mm. The peak designs and the hole circles were constructed together and then built using SLM. Table 5.6 describes the peak geometry details that was used for each hole size, and Figure 5.32 shows illustrates an example of each peaks design used. The overhang of peak describes one half of the peak, which is the single curl mirrored to construct the peak.

| Radius | Overhang of Peak (Half the Gap) | Peak Used |
|---|---|---|
| 1 | 0.55mm | 28 Curve |
| 2 | 1.45mm | 28 Curve |
| 3 | 1.45mm | 28 Curve |
| 4 | 2.25mm | 28 Curve |
| 5 | 3.05mm | 28 Curve |
| 6 | 3.9mm | 40 Curve |
| 7 | 4.65mm | 40 curve |
| 8 | 5.35mm | 45 Degree Angle |
| 9 | 5.95mm | 45 Degree Angle |
| 10 | 6.75mm | 45 Degree Angle |
| 11 | 7.6mm | 45 Degree Angle |
| 12 | 8.35mm | 45 Degree Angle |
| 13 | 9.1mm | 45 Degree Angle |
| 14 | 10.05mm | 45 Degree Angle |
| 15 | 10.75mm | 45 Degree Angle |

Table 5.6: Overhang sizes for peaks and the associated geometry feature

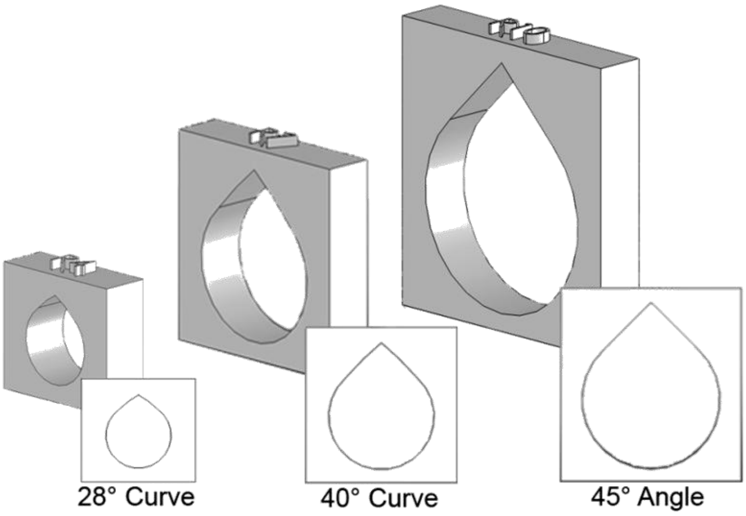



Figure 5.32: Three example holes (R4, R7 and R10) with their associated peaks geometries.

The 1mm and 2mm radius holes built without requiring a self supporting peak. As described earlier, sag occurs on round holes even as small as 1mm and 2mm radius. Therefore, a peak will be added in this experiment to eliminate the sag causing inaccuracies. All holes built complete and successfully (see Figure 5.33), at no point during the build did any curl on the test pieces exceed a value of 1.

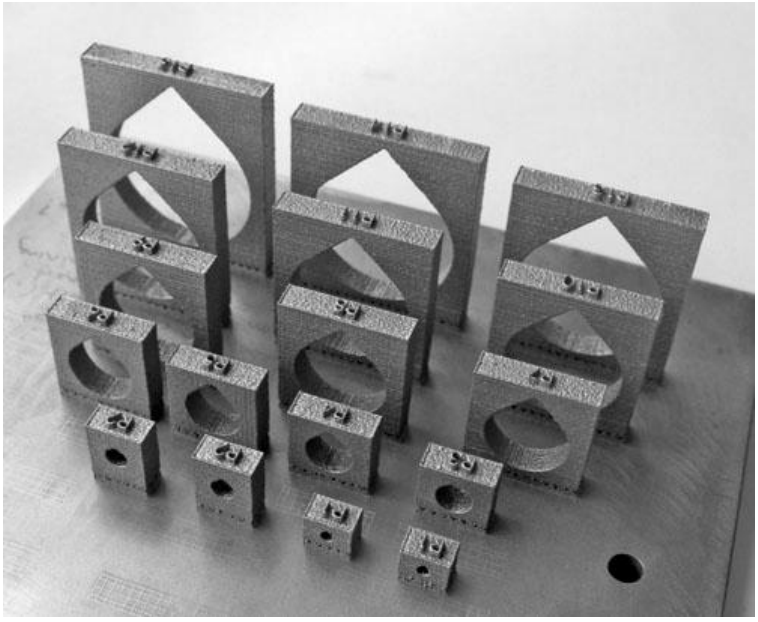


Figure 5.33: Picture of completed holes, R3 to R15

All parts were measured using the shadowgraph method. It appeared that the larger the hole size, the more accurate the hole became. Radius 3mm and 4mm built with a tolerance of ± 0.2mm. All holes larger than this up to a radius of 15mm measured to a tolerance ± 0.1mm, these results corresponded to previous experimental results. See Figure 5.34 showing an example of two shadowgraph images.

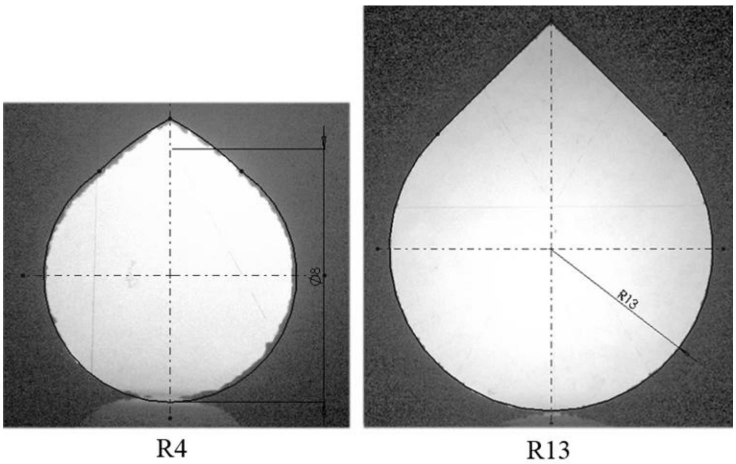
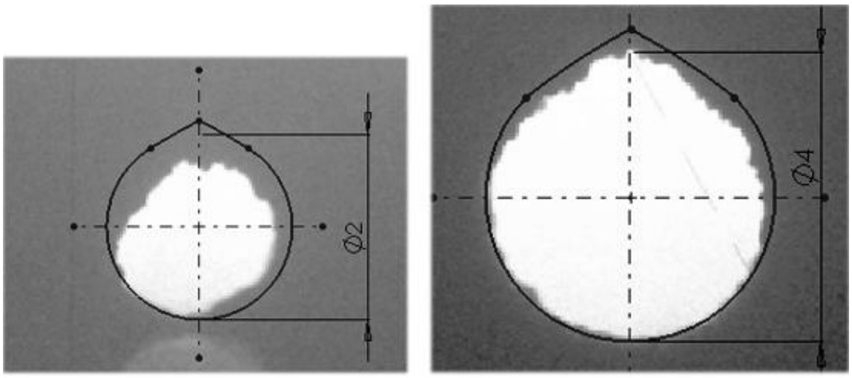



Figure 5.34: Shadow of 4mm (± 0.2) and 13mm (± 0.1) radii

Hole sizes of radius 1mm and 2mm previously built without a peak but it gave a poor geometry because of sag collapsing in the hole. In this experiment, a peak was added to try to eliminate this sag causing the inaccuracies. The results showed a very small improvement (See Figure 5.35). The peak was barely recognisable; there was still excess material inside the circle of the hole, although the sag was less apparent. These holes measured to a tolerance of ± 0.3mm.




R1 R2

Figure 5.35: Shadow images of 1mm and 2mm radii

### *5.3.2 Experiment 9: Tapping and reaming a self-supporting hole*

This experiment consisted of Tapping and Reaming the alternative hole designs developed in experiment 6. Threads and holes with high accuracy are a common occurrence in the design of a functional metal component. If the design rules are to suggest a new type of hole design to be used, it is important that a guideline for tapping and reaming the holes is also illustrated.

One large (M12) and one small (M6) hole was selected. Both holes corresponded to the dimensions used in the holes experiment, however the circle section of the holes to be tapped were designed at the tapping drill sizes (M6 = 5mm diameter and M12 = 10.2mm diameter) and the holes to be reamed were made 0.3mm smaller to allow the reamer to cut. All parts were held in a machine vice and were tapped by hand, and reamed by a pillar drill.

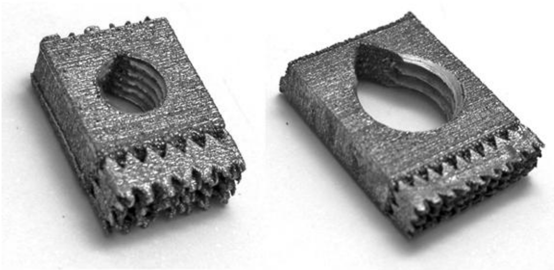


Figure 5.36: Image showing the M6 (left) and M12 (right) holes after being tapped.

- Both test parts were tapped and a M6 and M12 bolt screwed through.
- The thread was not even, as both taping drills pulled towards the self supporting peak. At the side of the holes the thread was at the correct depth. At the base of the hole the thread depth was too small.
- The uneven tapping effect is worse on the M12 bolt because the peak is larger than at M6. This was clear when the hole was being tapped as the M12 intermittently cut, and the M6 did not. See Figure 5.36 for image of the tapped holes.

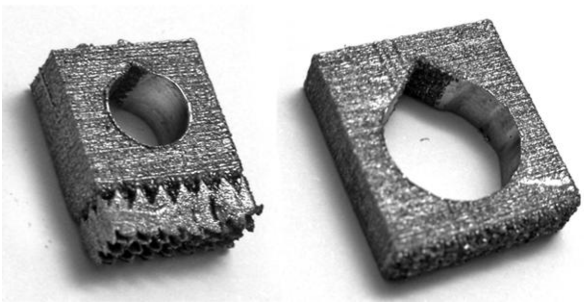


Figure 5.37: Image showing the M6 (left) and M12 (right) holes after reaming.

- Both holes reamed, however the larger hole chattered as the reamer was cutting. The reamer intermittently cut because one cutting edge of the reamer was located in the peak as the others were cutting. This resulted in the hole not being round.  See Figure 5.37.

- Both holes did not ream centrally as the reamer pulled towards the self-supporting peak.  This was evident as witness marks of the SLM surface roughness were visible at the lower point of the hole.

### *5.3.3 Experiment 10: Shrinkage*

This experiment was completed to investigate the shrinkage that became apparent on many test parts throughout the experiments.  This was first observed on pilot studies investigating hole design issues (Figure 5.38), and was persistent throughout the experiments.  This experiment was completed in two parts. Part 1; simple test pieces were designed to promote the shrinkage, and Part 2; A retrospective analysis of all previous test parts was completed, to identify when and why the shrinkage occurs.  The following describes the results of this experiment.

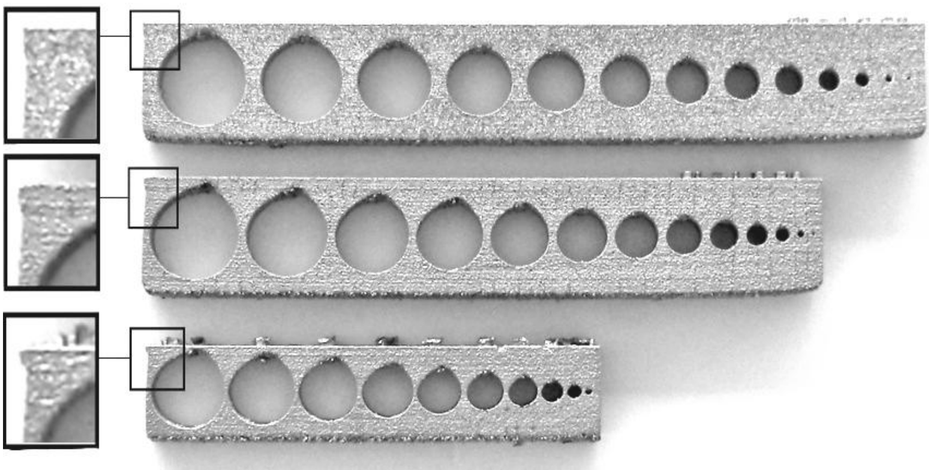


Figure 5.38: Image showing the shrinkage / distortion on the pilot test pieces

#### *5.3.3.1 Part 1: Test parts analysis*

The test parts consisted of a 10mm round hole that was positioned in offsets of 1mm from the centre of 5mm thick cuboids. The offsets created wall thicknesses of 1-10mm. The round hole was built without support to promote the distortion. It was clear that distortion had occurred on the outside walls when they were measured using a shadowgraph. However, the shadow images do not show the distortion as clearly as when inspected by eye. The images are shown in Figure 5.39.

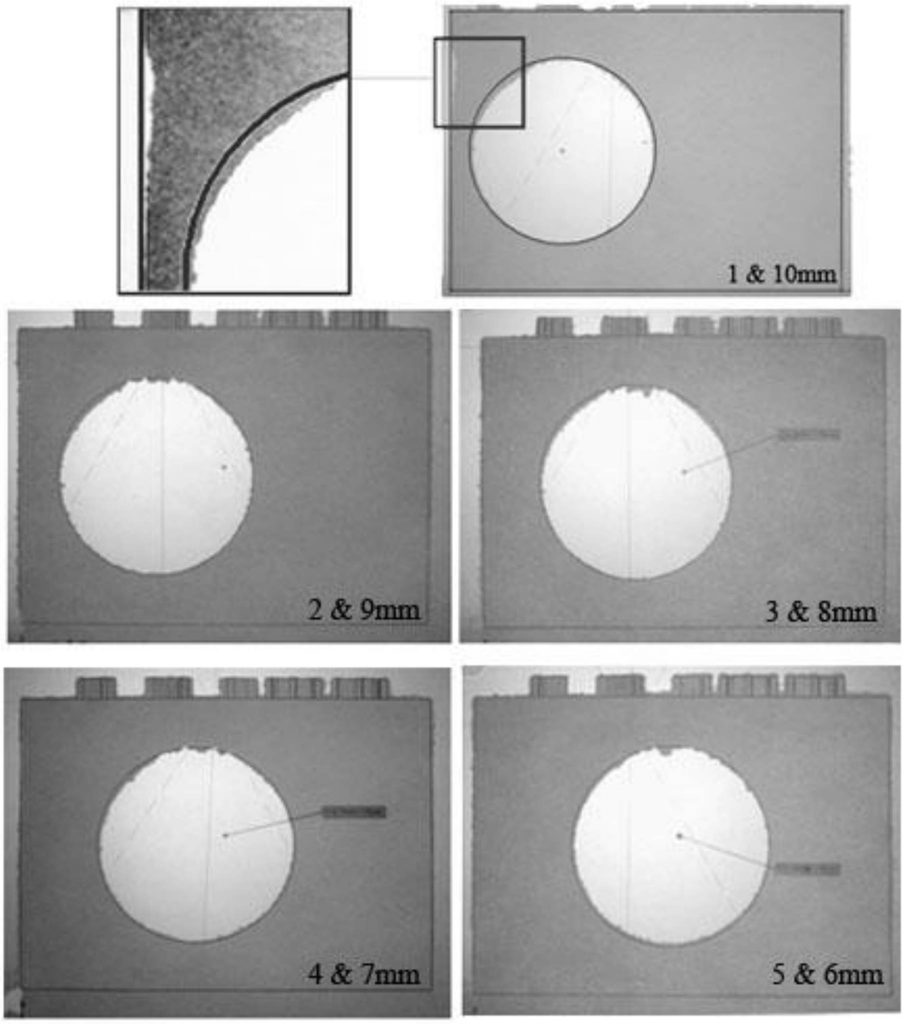



Figure 5.39: Shadowgraph images showing the distortion on wall thicknesses of 1mm to 10mm

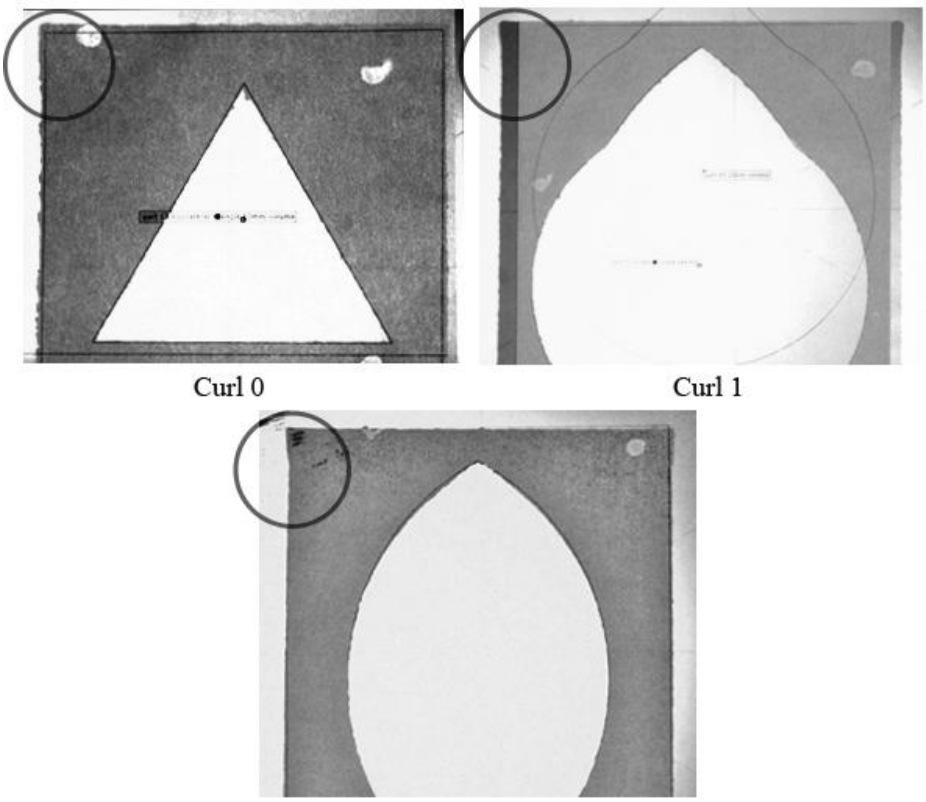
- All test parts had a planned curl of 2 at the top of the holes.
- The shrinkage was evident on the side of the parts with a wall thickness of 1mm to 7mm and no shrinkage was evident on parts of 8mm wall thickness and above.
- The smaller that the wall thickness, the worse that the shrinkage appeared to be. 1mm had the worst shrinkage where 7mm was only a small amount.
- The shrinkage occurred at the same height as the deformations at the top of the holes.

#### *5.3.3.2 Part 2: Analysis of previous test parts*

The occurrence of curl on previous test parts was quantified using a scoring system in previous experimentation. The results were re-visited to identify correlation between the curl distortion and shrinkage.

Four parts from each category of curl, 0, 1 and 2 were selected and analysed using the shadow images of the previously taken during experiment 8. The only information that was required at this stage was whether or not the distortion had occurred, and how much distortion there was.

- The results showed that the shrinkage increased the larger the curl value was during the build, as highlighted in Figure 5.40.
- It was clear that when the distortion does occur, it consistently around the same layer as the very top of the holes.



Curl 0 Curl 1

Curl 2

Figure 5.40: Shadow images of parts with curl 0, 1 and 2, the distortion is evident and increases with the curl values

The study aimed to highlight the distortion that has occurred and create enough information for it to be avoided; therefore, no definitive conclusion has been achieved. However, it is possible to suggest that geometries using self supporting features contribute to minimizing the shrinkage, and the severity of the shrinkage caused by other features, decreases when the wall thickness increased.

### *5.3.4 Experiment 11: Stock on material / sacrificial geometry*

Many applications of metallic parts require high accuracy, and a polished surface finish. This experiment identified how much material would need to be removed from the top, side, and bottom surfaces of an SLM part for it to be machined to dense metal. Three cuboids (30x30x15mm, 20x20x15mm and 10x10x15mm) were built. Before the parts were removed from the substrate plate, the top surface was milled using a vertical milling machine. This allowed the parts to be held square in a vice to machine the side and bottom surfaces. The parts were then removed and the side and bottom surfaces were machined whilst recording how much material was being removed, as shown in Figure 5.41. The quantities of material removed are shown in Table 5.7.

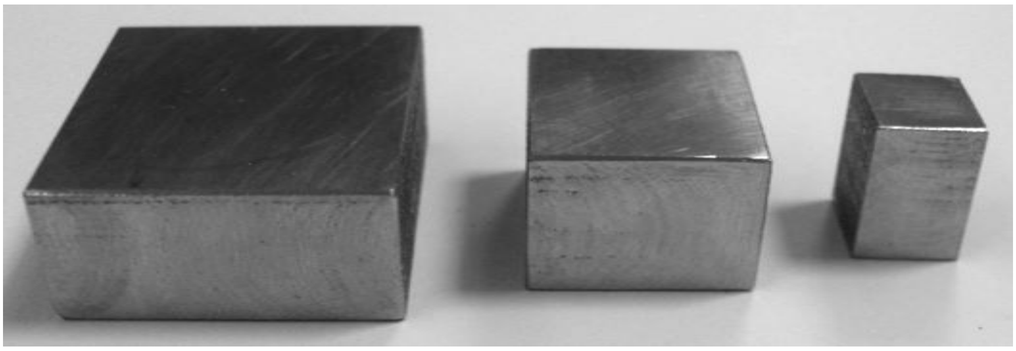


Figure 5.41: Photo of the three cuboids after they were machined on all surfaces

| Block Size | 30 x 30 x 15mm | 20 x 20 x 15mm | 10x10x15mm |
|---|---|---|---|
| Height before material removal | 15.7mm +/-0.2 | 15.8 +/- 0.2 | 15.8 +/- 0.2 |
| Material Removed until flat (Bottom) | 1.1mm | 1mm | 0.8mm |
| Material Removed until dense | 1.6mm | 1mm | 0.8mm |
| Material Removed until flat (Top) | 0.3mm | 0.2mm | 0.2mm |
| Material Removed until dense (Top) | 0.7mm | 0.6mm | 0.6mm |
| Material Removed until dense (Side) | 0.12mm | 0.12mm | 0.12mm |
| Final Height | 13.1 +/- 0.1 | 13.75 +/- 0.05 | 13.99 +/- 0.01 |

Table 5.7: Results from stock-on-material experiment, showing how much material was removed from each part.

- All blocks built 0.7 to 0.8mm oversize on the down-facing surface, which was caused by the laser penetrating more than one layer of powder on the first layer. The down-facing surface was avoided throughout this research study as it is the main cause of inaccuracy.

- The larger the surface area of the down-facing surface, the more material needed to be removed. This is because caused by shrinkage of the thin first few layers of the build. As parts grow taller the material becomes thicker which prevents the layers shrinking. However, this creates residual stresses.
- Each top surface was not flat before they were machined; the top surface had a higher boundary than the hatched material.
- The side surfaces completed flat, and measured to within a tolerance of 0.05mm before they were machined.

## *5.4 Summary*

The first part (A) of the results chapter was an investigation of fundamental geometries that were key to the construction of compound shapes. The results of the experimentation identified the geometrical constraints, and accuracies of the fundamental geometries, which proved to improve when the geometrical constraints were known and applied.

The results of the orientation and surface roughness experiments identified that the staircase effect was present with SLM parts. There appeared to be variability in the roughness average values of the parts measured, which resulted in surface roughness trends to be identified rather than accurate values. The minimum surface orientation was identified, which resulted in the minimum overhang size of each layer being the same as the layer thickness at 0.075mm, which was considered in the design of all overhanging test pieces. The thinnest possible wall thickness achievable was identified in one simple experiment, along with the minimum slots size that can be produced.

The final fundamental geometry tested was concave and convex radii. The results showed that designing radii for manufacturing by SLM is more complex than conventional processes as tangential radii could not be built without support structures. Tangent changes were applied to the radii and the constraints were identified in order to design self supporting radii.

The compound experiments in part B were created considering all results from part A. Shrinkage was witnessed throughout all experimentation; therefore a retrospective experiment measuring all test parts was completed. The results identified that the wall thickness and neighbouring distortion elsewhere on the same layer caused the shrinkage marks, and using self supporting geometries were a preventative solution.

The results from designing various hole profiles using previous radii results, when combined with achieving area values proved to be unsuccessful because the dimensions could not be fully controlled since the holes needed to be specific area. The results could not be used to create design rules, therefore, the experiment was repeated with a different approach based on keeping a round hole as close to round as possible by using a self-supporting peak. Holes were successfully designed and had repeatable accuracies and provided data that can be used as a design reference for creating self-supporting holes of 1mm to 15mm.

The ability to post-process SLM parts was considered and the results showed exactly how much material that would need to be added to a design if the surface were to be machined, and that tapping and reaming self-supporting holes is inaccurate as the cutters intermittently cut.

The following chapter describes how the design rules were initiated from the experimental data created in this chapter, and how the design rules were evaluated to identify future developments and challenges.

# Chapter 6: Design rules initiation / development

## *6.1 Introduction*

Previous quantitative experimentation was used to identify all limitations and constraints of SLM components. Individual design features were investigated, and results have been created to be used in the development of design rules for SLM. This chapter describes how the design rules were initially created from the raw experimental data gathered in the main experimentation, and describes the semi-structured interviews used for the evaluating and developing the rules. Finally, this chapter shows the analysis of the designer responses to the rules, and how future requirements for developing successive design rules for SLM were identified.

## *6.2 Research synthesis: Creating design rules from the experimental data*

Developing the design rules required interpretation of the raw data gathered from the quantitative experiments, to ensure that the rules could be understood by a product designer without the need for further interpretation. Presenting the experimental results to a designer would not provide clear rules and illustrative guidelines to designing for SLM, because they would be unformatted, too complex and too difficult to interpret.

The methodology used to identify the geometrical limitations of SLM, created a logical step between raw data and the design rule initiation by providing results that needed very little interpretation to become illustrative. The Plan, Do, Study, Act (Deming, 1994) approach to research, encouraged each experimental result to be studied after each test part was built, which ensured that the experimental objective of creating geometrical data for use in design rules was met. Each experiment was based on fundamental geometries that are part of the construction of compound geometries. Since there are a vast number of compound shapes that could be presented in the design rules, only fundamental geometries were conveyed that could inform the construction of the more complex forms. Therefore, associating the experimental data to each design rule became a simple task of re-writing the results and refining the presentation. On completion of the experiment, if the results could not be used to inform the design of the subsequent experiment, the experimental parameters were reconsidered, and the experiment cycle was repeated and reviewed until the results could be used to inform further experiments. The methodology flow diagram is shown in Figure 3.1 in the methodology chapter.

The systematic methodology approach also encouraged the results of one experiment to inform following experiments in series. This ensured that the results were evaluated as the experimentation progressed. If an experiment was complete, the results would successfully inform the design of following experiment test parts, and therefore indicate that the results are able to inform the design rules. If this was not possible and test parts could not be designed, it meant that the data was inconclusive and was not comprehensive enough to inform the design rules. Further experimental iterations were required until the results could be used to inform the following experiment.

When the design rules were first created, existing design rules on traditional processes were reviewed (see literature review chapter 2). These processes included injection moulding (Rees, 1996), aluminium extrusion (Sapa Ltd, 1997), metal injection moulding (MIM) (Groover, 2002), rotational moulding (Beall, 1998) and also the DFMA principles by Boothroyd and Dewhurst (2002). From reviewing these rules, a number of significant points for both the introduction and main content of the rules were identified. These points were considered in the development of the design rules within this research, and are described as follows: (for the completed design rules refer to Appendix 4)

- **Design rule introduction:**

The design rules introduction must describe the how the technology works and any underlying issues that will affect the way that the rules are perceived. The introduction must also provide enough background information to set the scene for the design rules to facilitate the understanding of each design rule. The introduction must also include enough information for the designer or engineer to ensure that the process they have chosen is the correct process.

It is important to describe any technical terminology at the start of the design rules. The rules are aimed at all levels designers with various levels of experience, therefore, some designers may not be familiar with some terminology especially if they are not familiar with additive manufacturing.

- **Presenting the design rules:**

Within the content of the design rules, it was necessary to illustrate the occurrence of any process inherent distortions and explain why they occur. The design rule associated with the distortion should illustrate how good design practice will eliminate or avoid the distortion. This can be done by showing an illustration of a good design together with a poor design. An example of this is shown in Figure 2.15 and 2.16 within the literature review.

Both two-dimensional and three-dimensional images can be used to illustrate each design rule.  The two-dimensional images should be used to show detailed dimensional data, where a three-dimensional image shows a greater resemblance of the design feature in context.

When several variations of a single geometry needs to be described, it is not necessary to show an illustration of them all, because a single, fully labelled two-dimensional image can be used alongside a table that refers to each dimensional variation of the features shown in the two-dimensional image.

Large blocks of text should not be used amongst the design rules as they can be discouraging to read, and could also result in a design rule being discouraging to read. Instead, precise and smaller bullet points, or short concise paragraphs should be used to ensure that the rules are clear and simple to read.

Best practice (Sapa Ltd (1997); Groover (2002)) indicated that design rules needed to be first put into context.  Accordingly, an overview of Additive Manufacturing (AM) is needed in order to inform the reader how different AM is compared to traditional subtractive and moulding processes.  An overview of SLM is also needed to introduce SLM to designers who have no previous experience of the technology.  The introduction to SLM included an image of the laser during processing; an explanation to how powder layers are recoated and how layers merge to produce parts; and, background information about geometry deformations that occur as a result of exceeding process limitations.

A trade off was illustrated which explained how optimum orientation, support and part quality effects a designer’s choice when selecting orientation. The research that informed the supports and orientation and geometric deformation background information was taken from the experience gained of both topics throughout all experimentation. However, one experiment was completed to establish a greater understanding of geometry deformation, so that key design considerations could be presented.

Figure 6.1 shows a chart of all design rules and the experiments that informed them. Some experiments were informed by just one experiment, for example, the minimum size between features and minimum wall thickness experiments were informed by only one experiment. However, other design rules such as material allowance/ geometric compensation were informed by two experiments. Two informing experiments were unintentional, although the results indirectly informed the planning of the second experiment that was the main contributor to the rules. Detailed reports of the experiments are shown in the results section of this thesis.

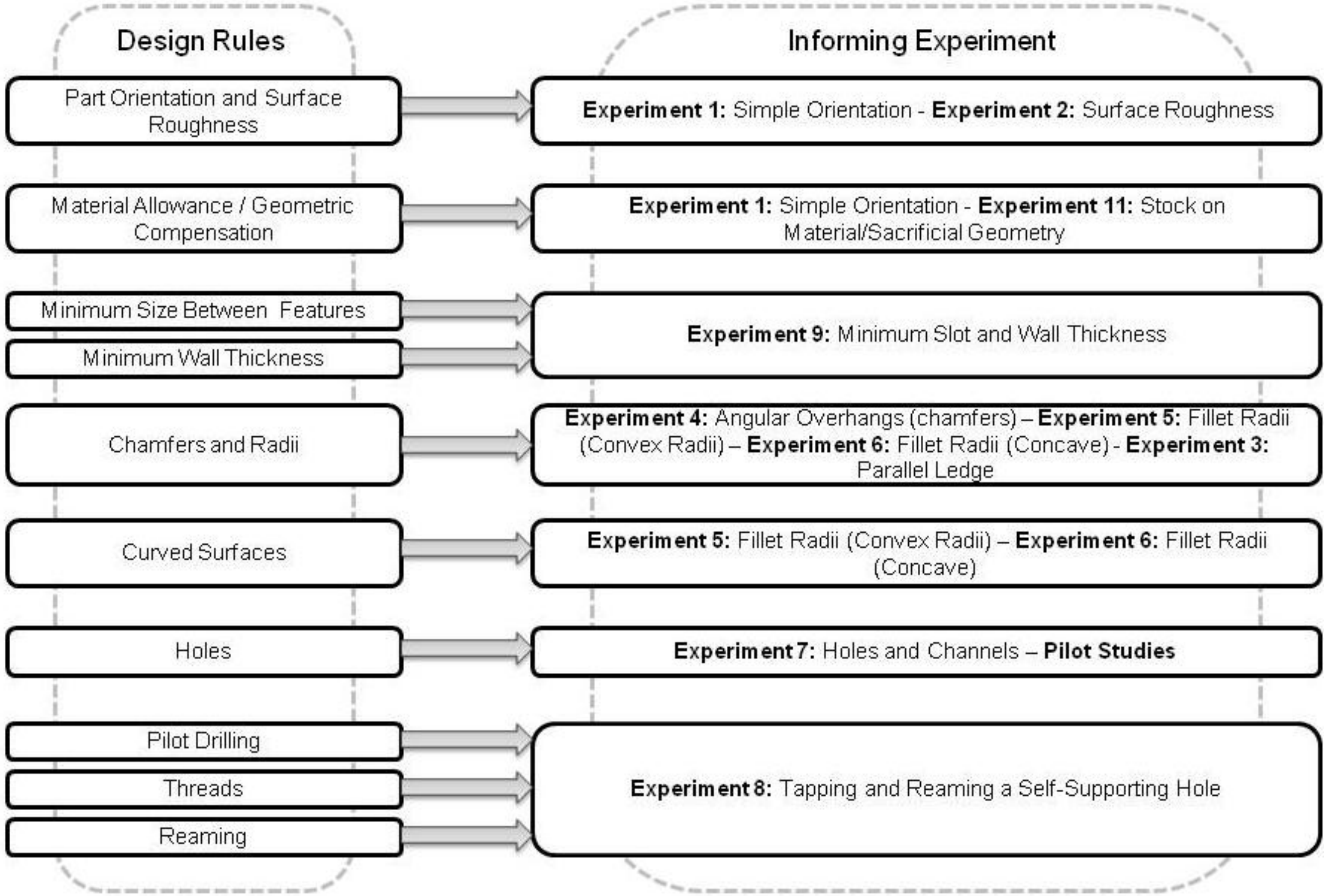



Figure 6.1: Illustration showing what experiments was used to develop each design rule

As explained previously, many experimental results did not need an extensive interpretation to make them illustrative when presented in the design rules. However, the following design rules required reconfiguration so that they would convey the data effectively.

### *6.2.1 Part orientation and surface roughness*

The first design rule that was reconfigured illustrates the link between surface roughness and the orientation of a surface. This design rule is numbered as 5.1 in the design rules and is shown in appendix 4. The rule describes the optimum surface orientation and angles where support structures must be used.

This design rules incorporated two different experiments that influenced one another, into one rule. The results were combined as they would be confusing and overcomplicated if they were presented separately. The first experiment identified all possible build orientations of a flat surface, and the second experiment identified the surface roughness at the different orientations. Different ideas were considered to establish an illustration combining both sets of results. Figure 6.2 shows the concluded illustration used in the design rules. The different shades of grey represent the surface roughness at different orientations.

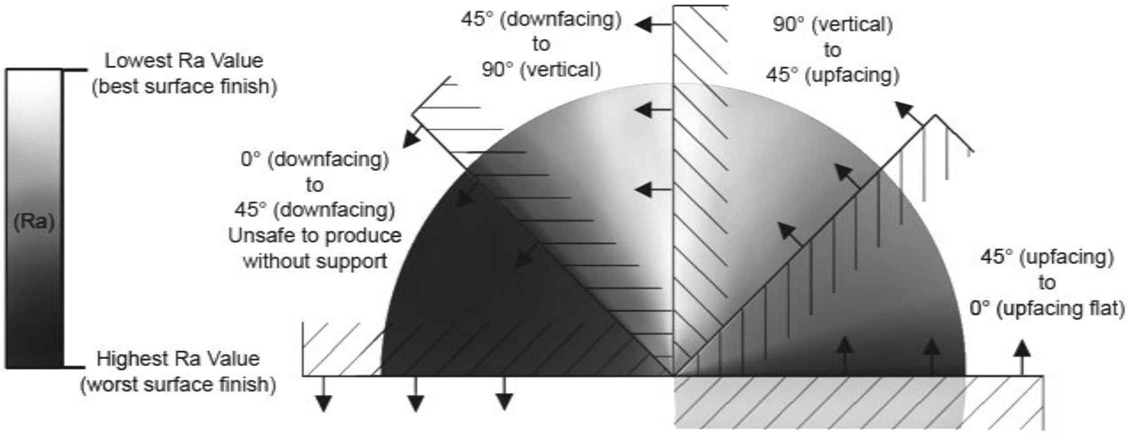



Figure 6.2: Illustration showing the relationship between orientation and surface roughness

### *6.2.2 Chamfers and Radii: Concave fillet radii and convex fillet radii*

This design rule is part of a number of design rules that illustrate overhanging design features. This rule provides a dimensional breakdown of how to create self-supporting convex radii. This is numbered as 5.5.3 in the design rules shown in appendix 4

The concave and convex radii experiments were concluded with three curves that represent the limitations of building radii, as shown in Figure 6.3. The Concave curves were analysed in greater depth during the holes experiment as part of the construction of self supporting hole designs. The curves were drawn in 2D using CAD software and intersected at 1mm intervals to establish dimensional values for different overhang sizes of radii (see Figure 6.3). The analysis identified that any section of the curves can be used as a radius. From this, rules were established and were successfully tested on self-supporting holes.

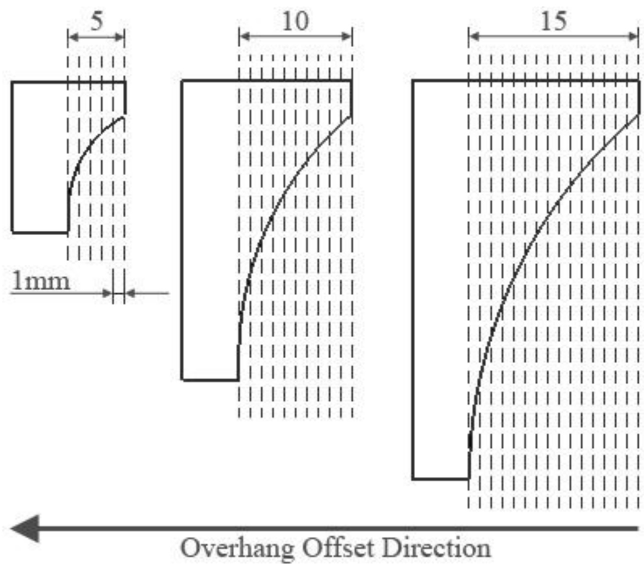



Figure 6.3: An illustration of the three concave curves with intersection lines in increments of 1mm. This was created during the self-supporting holes experiment.

Although concave and convex radii were investigated in the main experimentation, only concave radii were analysed in greater depth described, because they were required in the construction of self-supporting holes. Therefore further analysis of the convex radii results was required for creating both concave and convex design rules (see Figure 6.4). The results of this additional analysis contributed to the design rules by illustrating a breakdown of the critical dimensions of both convex and concave radii. (To see the full design rule, refer to Appendix 4)

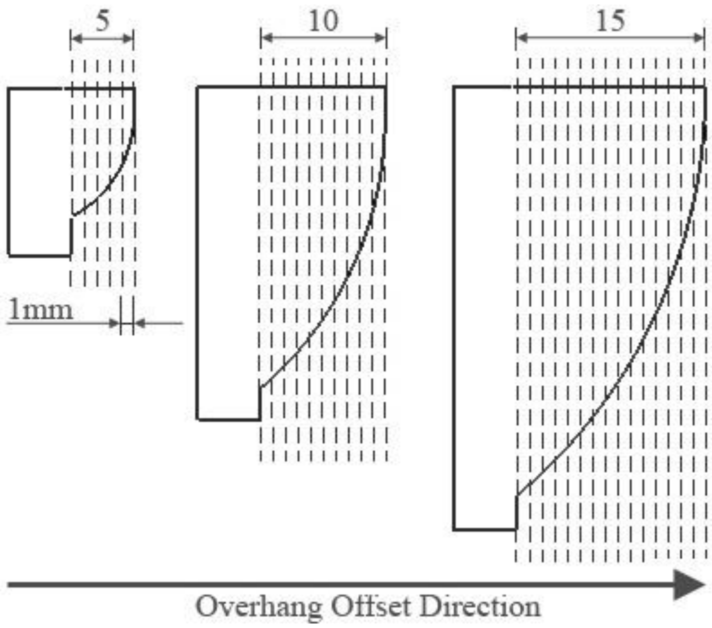



Figure 6.4: An illustration of the three convex curves with intersection lines in increments of 1mm. This was established after as part of the design rule synthesis.

### 6.2.3 *Curved surfaces*

Design Rule 5.6 – This design rule describes how to construct a surface from more than one radius. The rule illustrates how to identify and apply the appropriate dimensional limitations to create curved surfaces. This design rule is numbered as 5.6 in the design rules shown in appendix 4.

The geometrical features chosen for investigation throughout the quantitative experimentation were chosen because they are the most common features and are the building blocks to more complex geometries. Experiments were focused on investigating the limitations of building flat surfaces, no experiments directly investigated curved surfaces.

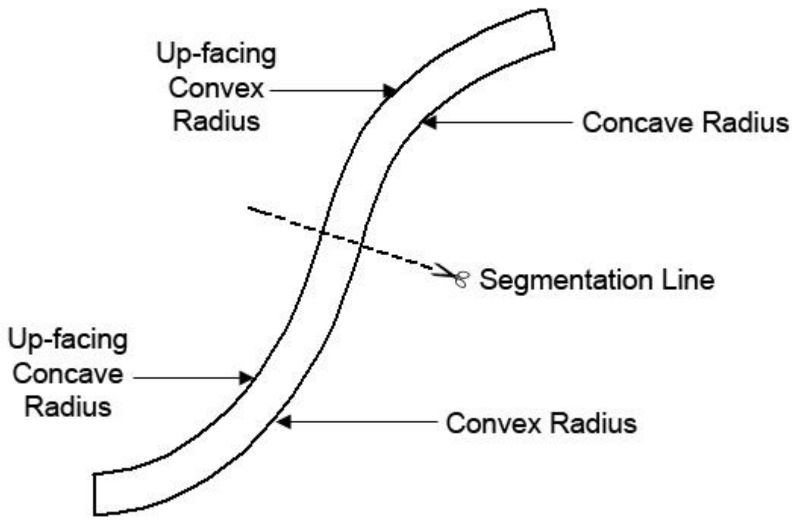



Figure 6.5: Illustration of curved surfaces broken into individual less complex radii.

A radius is a design feature that is commonly used to replace sharp corners. The results of the radii experiments informed the need for curved surfaces design rules. The radii experiments were used for illustrating how to breakdown a complex curve into individual less complex radii and to emphasize the location of critical surface tangents (see Figure 6.5). The dimensions given in the radii design rules were then referenced within the curved surfaces design rule. This allowed the construction of self-supporting curved surfaces.

After all design rules were created, they were analysed by the end user to discover their effectiveness and requirements for future work. The following section describes the analysis process.

## 6.3 Analysis

Six design professionals agreed to review a hard copy of the design rules, and participate in semi-structured interviews to evaluate the design rules. The six participants were selected because they had different roles within the design industry, including both academic and industry based initiatives. The need for a designer was a key point, since designers are key users of design rules. An RM expert was also required, because the rules are based on a RM technology. A design academic is someone who has understanding of transferring academic design research into industry, and therefore was also chosen for the research. A design for manufacturing expert was used to be able to asses the suitability of the design rules to inform manufacturing practice. The criteria for selecting the potential participants to evaluate the design rules were based on four professional roles, which are described as follows:

- Designers: Industrial based designers who are active in product development and design for manufacture. The majority of the respondents needed to be design practitioners as they would be the most likely to use and benefit from the design rules.
- RM Expert: A RM expert must know the RM field and any inherent technical issues. They should also be fully aware of the possible advantages and disadvantages of RM technologies.
- Design Academic: The academic must be involved in product development technologies but not necessarily RP or RM. The academic will give a broadened perspective of how the technology is portrayed in the design rules.

- Design for Manufacturing (DFM) Expert: A DFM expert will be familiar with the use of design rules and will therefore be qualified to provide constructive feedback from an industry point of view.

Through personal communication and recommendations made, all selected participants met the criteria to provide critical feedback. Selecting professionals across different fields of design offered a range of perspectives based upon a range of specialties. The following describes the professional roles of the six respondents selected (see Table 6.1).

| | Professional Profile |
|---|---|
| Respondent 1 | Product Design graduate and has been a researcher for over five years. Area of interest and expertise include the application of product design and development technology implementation and management processes in small manufacturing companies. He has particular knowledge of the design and development processes. |
| Respondent 2 | A production engineer with a degree in mechanical engineering. Previously a senior development engineer creating software and hardware for NC machining, and has more recently set up and now manages a rapid manufacturing department within a large company. |
| Respondent 3 | Respondent 3 has several years of industrial experience as a product development manager prior to becoming a senior design lecturer. His specialist areas include concept development and design for manufacture, which include process and material selection, and requires an in-depth understanding of design constraints and considerations of manufacturing processes. |
| Respondent 4 | Development and Project Manager for a large medical device manufacturer. His primary role is in the development of new products, through liaising with surgeons and developing design ideas into manufactured products. He also develops marketing strategies and controls all regulatory requirements for new product development (NPD) |
| Respondent 5 | Industrial designer with expertise in front-end design and product styling. Respondent 5 is part of a design team that has won 10 international design awards. He has worked on over 70 commercial projects with clients that include inventors, Small to Medium Enterprises (SMEs) and multinational companies. |
| Respondent 6 | Respondent 6 is a Senior Industrial Designer; he is responsible for every element of the product’s design to manufacture, ensuring they comply compiled with international safety requirements, whilst he also managed the Rapid Prototyping side of the business. |

Table 6.1: Describing the professional profiles from each respondent

The design rules were emailed to the recipients four weeks before the semi-structured interviews were arranged. A series of questions were designed to analyse the design rules and to evaluate the clarity of the rules, ensuring that the content of each rule was clear, illustrative and comprehensive to what each respondent would typically expect within design rules. Questions were planned to asses how the introduction to the SLM technology set the scene to the design rules, and if this introduction was detailed enough for the respondents who were unfamiliar with SLM.

Although questions were set to identify whether the rules were clear and illustrative, it was known before any interviews that many rules were more complex than existing rules for traditional subtractive processes. For example, the holes required peaks that had several dimensional constraints. Questions were designed to identify whether the complexity of the rules would discourage the use of the rules and the SLM process, or whether they would be encouraged to explore SLM and exploit the process within their industry.

The questions were piloted with respondent 1. The response was used to refine and finalise the questions, and was then used as part of the constructive analysis. The questions are shown as follows:

**Question 1:** Overall, were the design rules a good insight to the SLM process?

**Question 2:** Were the rules clear and illustrative?

**Question 3:** Is the introduction to the technology useful?

**Question 4:** Were the rules complete? Are there any design features missing?

**Question 5:** Would you feel confident to use the design rules in design practice?

**Question 6:** Since reading the rules, did your feelings change about using the SLM process in the near future?

**Question 7:** What is your opinion of the SLM process since reading the design rules?

**Question 8:** The benefits of SLM, such as hollow and freeform geometries are not described within the rules; would this prevent you from considering unique design features that cannot be made using other processes?

**Question 9:** Many geometrical features such as radii and holes are now more complex than other processes such as milling and casting. Are the descriptions of each rule clear or are they to complex for what are traditionally simple geometries?

**Question 10:** What do you think about the length of the rules?

**Question 11:** Are any rules unnecessary?

Each interview took no longer than one hour and was completed at the convenience of the respondents at their place of work during January 2009. All responses were recorded in the format of notes made by the author during the interviews, and the respondents were given access to a pencil and paper so that they were able to express themselves using sketching when it was difficult to use words only. All respondents were asked to write in the design rules documents critical feedback on individual rules. The design rule documents were then collected together with comments at the time of the interview.

## *6.4 Analysis of results*

The following show the results and analysis of the semi-structured interviews. Each respondent responded with two degrees of response. The first degree was a direct response to interview questions which were not directed at specific rules. The second degree was detailed comments that were specific to individual design rules. These included comments on illustrations, requests for illustrations, requests for further explanations and example components. Each response was summarised and the responses were categorised as positive or negative together with the respondent number (see Table 6.2). All respondents are labelled as R1 to R6 (respondent 1 to respondent 6)

| | Interview Response Analysis | Positive | Negative |
|---|---|---|---|
| 1 | All six respondents stated that the design rules were a good insight to the SLM process. However, suggestions for improvements were given including:<br>• Examples of the rules being applied to products.<br>(For further detailed comments see appendix 5) | R1, R2, R3, R4, R5, R6 | |
| 2 | 4 out of 6 respondents found the design rules to be clear and illustrative, 2 stated that the rules were unclear. Detailed improvements were suggested in the design rule document (For further detailed comments see appendix 5) | R1, R2, R4, R5, R6 | R3, R6 |
| 3 | 5 out of 6 respondents found the introduction to the technology useful. 1 of 6 found the introduction was not descriptive enough. All Respondents described improvements: (Detailed comments are shown in appendix 5)<br>• More process information<br>• A breakdown of terminology<br>• Add Information about common orientation to the substrate plate<br>• A comprehensive description of all possible part deformation together with images.<br>• Images of commercial examples<br>• Comparison of SLM to conventional processes.<br>• Show a process schematic image<br>• Emphasise Implications of the limitations | R1, R2, R3, R4, R5 | R6 |
| 4 | 5 out of 6 respondents thought the rules were comprehensive to all common geometries. 1 out of 6 stated that information on assembling SLM parts is missing. (For further detailed comments see appendix 5) | R1, R2, R4, R5, R6 | R3 |
| 5 | 5 out of 6 respondents stated that they feel confident to use the design rules in practice. 1 respondent stated that showing applications of the design rules would boost confidence to apply the rules in design practice. (For further detailed comments see appendix 5) | R1, R2, R4, R5, R6 | R3 |
| 9 | 5 of 6 respondents stated that the design rules were more complex than conventional processes. However, the responses show that they are not discouraged from using the design rules as a result of complexity. However 1 Respondent stated that the rules were too complex and would be discouraged to use SLM to manufacture. (For further detailed comments see appendix 5) | R1, R2, R3, R4,R5 | R6 |

| | | | |
|---|---|---|---|
| 10 | 5 of 6 respondents thought that the design rules were not too long, including a statement saying that the rules were short and concise. However, 1 of these 5 respondents found the rules had too many words. 1 Respondent stated that the rules were too long, although the rules were comprehensive and had no unnecessary rules. (see appendix 5) | R1, R2, R3, R5, R6 | R4 |
| 11 | All respondents stated no design rules were unnecessary. (For further detailed comments see appendix 5) | R1, R2, R3, R4, R5, R6 | |

Table 6.2: This table summarised the responses of the semi-structure interviews. Each response is categorised as positive or negative together with the Respondent number.

The responses of questions 6, 7 and 8 could not be categorised into positive or negative responses, the questions are as follows:

**Question 6:** Since reading the rules, did your feelings change about using the SLM process in the near future?

- 5 out of 6 respondents stated that they would consider using SLM as a manufacturing technique since reading the design rules.
- The responses stated that the benefits of SLM are clearer since reading the rules.
- Respondent 1 said that SLM would be used if it was short listed as the best manufacturing process for a specific design.
- Respondent 6 stated he could not understand why it would be used for any application other than organic, freeform geometries.

**Question 7:** What is your outlook of the SLM process since reading the design rules? E.g. limiting, useful etc…

- 5 out of 6 respondents have the same opinion that the SLM process is too constrained.

- Respondent 6 stated that too much needs to be considered when designing an SLM component, and cannot imagine any engineering application.
- Respondent 1 stated that the design rules were a good insight to SLM, however, his opinion of manufacturing functional parts using SLM, was that lots of post processing would be required.
- Respondent 5 did not think that the process was too constrained; he stated that it requires a new learning curve as the process is relatively new. He would apply the rules by designing a part as normal and apply use the rules to make amendments on the final design. He sees the design rules as a lesson in SLM design.

**Question 8:** The benefits of SLM, such as hollow and freeform geometries are not described within the rules; would this prevent you from considering unique design features that cannot be made using other processes?

- Two respondents (R2 and R4) would still consider geometries that are unique to SLM / Layer Manufacturing (LM) capabilities.
- Respondent 2 stated that many examples of these geometries are used as a unique selling point by machine vendors.
- Respondent 4 stated that the advantageous design possibilities of layer manufacturing would still be considered if the process limitations are known.
- Respondent 1, 3, 5 and 6 are not familiar with these geometries and would need to see examples of them in the design rules.

### *6.4.1 Analysis of negative responses:*

There was a wide range of positive and negative responses as highlighted in table 6.2. The positive responses help to validate the design rules but they do not inform their future development. All negative responses were reviewed in greater detail. The negative responses are the points that would need consideration in future design rule development.

#### *6.4.1.1 Two respondents thought that the design rules were not clear or illustrative: Question 2*

Respondents 3 and 6 stated that the design rules needed to be clearer and more illustrative. Respondents 3 and 6 both specialise in developing designs from a concept design to a manufactured product. A major part of the respondent's job includes preparing designs whilst considering accuracy, tolerances, assembly, and design feature limitations of manufacturing processes. The design rules for SLM must be clear so that all the requirements of making manufactured parts can be applied to SLM designs without significant interpretation prohibiting the design time.

To improve the clarity of each design rule, the respondents suggested giving examples of commercial products designed and made with SLM. This was a common issue raised by all respondents. To select SLM as a manufacturing process, the rules would need to be clear and fully illustrative to all design professionals. The designers that felt the rules were unclear work closest to the manufactured product.

The general opinion about the design rules was that they were only clear when read in their entirety. The respondents identified this because terminology and explanations of distortion occurrence were not all grouped together, but staggered throughout the document. This suggests that all terminology explanations should be addressed at an early stage in the design rules, together with illustrations where possible, as well as the descriptions staggered throughout the body of the rules, so that the rules can be flicked through and understood equally as well as when read cover to cover.

#### *6.4.1.2 One respondent did not find the introduction useful: Question 3*

Respondent 6 did not find the introduction to SLM useful because no commercial examples were shown. Respondent 6 stated that he is familiar with designing for CNC milling (Computer Numerical Control) when metal parts are needed. He can predict the outcome when parts are returned complete after sending them for manufacture, but would not know what to expect with SLM parts. Therefore, respondent 6 stated that he would prefer to use CNC milling over SLM. Examples of parts shown in future design rule developments will allow designers to foresee SLM part outcomes, and will help decide on whether or not the processes is suitable for their manufacturing needs. If the designer still chooses alternative processes to SLM, it should be because SLM was not an appropriate process for the particular product designed, and the chosen process was shortlisted as better suited.

#### *6.4.1.3 One respondent did not think that the design rules were comprehensive to all common geometries: Question 4*

Respondent 3 stated that the design rules were not comprehensive to all common geometries as there were no rules on part assembly. Respondent 3 teaches design for manufacture and assembly principles (DFMA) that were first introduced by Boothroyd and

Dewhurst during the 1970's (Boothroyd, Dewhurst, & Knight, 2002), and has a great understanding of design guidelines and their importance.

The aim of the design rules for SLM is to instruct designers how to avoid process inherent geometrical deformation. This was done by suggesting alternative designs, by only addressing designs for standard features like radii, angles and chamfers. These geometric features are the building blocks to the construction of more complex geometries. And with careful consideration of the accuracies of each design feature, the assembly of two or more SLM parts could be planned.

#### *6.4.1.4 One respondent stated that they would not feel confident using the design rules: Question 5*

Respondent 3 stated that they would not feel confident using the design rules. The reason given was that no examples were present in the design rules to associate the design rules with. Respondent 3 also stated that if examples were present within the design rules document he would feel confident to use them. It was a common response from all respondents, which suggests that further design rule developments should include examples of all parts for individual rules.

#### *6.4.1.5 One respondent said that the complexity of the rules would discourage him from using them: Question 9*

Respondent 6 is an industrial designer who works towards strict time constraints within commercial design projects. The complexity of the rules would discourage him from using them and therefore using SLM. This was because the rules would take to much time too follow, and would be a new learning curve when applying the rules in new product development (NPD). The rules would encourage him to choose a manufacturing process that he is familiar with rather than SLM when tight timelines are involved.

#### *6.4.1.6 One interview stated that the design rules were too long: Question 10*

Respondent 4 stated that the length of the design rules were too long. However, this comment was contradicted because he also stated that the length of the rules was necessary because they were comprehensive to all common geometries, and no rules were unnecessary.

#### *6.4.1.7 Responsibility of using the design rules within the design process.*

When a product is designed it is engineered so that it can be produced via the chosen manufacturing process. To do this design rules are required, for example draft angles are a requirement of injection moulding. Out of all the interviews, two industrial designers who actively apply design for manufacturing rules stated that they would leave the SLM design rules for the SLM technician to apply once they have finalised their design. Respondent 4 stated that he would expect the SLM part bureaus to be the experts and therefore, expect the bureaus to apply the design rules. Respondent 3 stated that he would design parts to how he wanted it to be, and create control drawings so that the SLM technician within the RM bureau would edit the part to suit the manufacturing process. This result suggests that designers can be discouraged when applying new design rules that they are unfamiliar with. All other respondents understood that the design rules were aimed at them to apply during the detailed design stage of the design process.

## 6.5 Summary

This chapter described how the synthesis between raw experimental data and the design rules were established. The methodology ensured that the data gathered in the experimentation phase is used directly in the design rules without major changes. Several design rules did need extensive interpretation to ensure that they were clear and illustrative to the reader. The orientation and surface roughness experiments were inter-reliant on each other, and were combined into one design rule rather than two separate rules. The convex radii results needed further analysis as only the concave radii required analysed in great depth during the creation of self-supporting holes. This ensured that design rules were created for convex radii, rather than just the concave radii. Design rules on how curved surfaces can be designed were as also extracted from the results of the radii experiments to complete the design rules.

The design rules were assessed by six design professionals with different design areas and disciplines. Semi-structured interviews were completed and the results were analysed into positive and negative responses. Many smaller detailed points were made by all designers directly in the design rule document. All negative responses were analysed in greater depth to identify areas and common themes that require consideration in future developments of the design rules. Major points included more examples of each design rule and commercial designs made by SLM should be shown. This was said to increase the confidence of the designer and to improve the design rules, making them easier to follow and refer to when designing within commercial timelines.

Since reading the rules, all designers established a new understanding of what is required of them to design for SLM. All designers agreed that the process is too restricted;

however, they understood the process and would be able to consider SLM in the selection of manufacturing processes and would not be discouraged to use it if SLM was short listed as the most appropriate process for a specific design.  This was not a unanimous comment which resulted in improvements to the design rules being identified.  It was found that the benefits of using SLM over contending metal manufacturing processes were apparent to the respondents, but it was concluded that principle design examples showing possible design features that are unique to layer manufacturing would clearly describe the process benefits.

The aim of this research study was to initiate a first draft of design rules and inform future developments of this work.  Therefore, it was not necessary to action any of the specific feedback highlighted within this chapter; a second evaluation of design rules is outside the scope of this research study.

# Chapter 7: Discussion

## 7.1 Introduction

The aim of this research was to create design rules for SLM. To accomplish the aims of this research, the following objectives were addressed as presented throughout this thesis.

- Evaluate the SLM process, and identify the geometric limitations of SLM.
- Perform analysis and synthesis of the experimental results and create a first draft of design rules appropriate for use in design practice.
- Evaluate the design rules to establish their effectiveness and inform their further development.

The methods used to address the aims and objectives were appropriate and successful in terms of developing the first design rules draft for SLM. The methods for the experimentation created the data required to produce design rules. The methods then led to a smooth transition between the results and the design rules. To identify areas to improve the methodologies a retrospective view was taken. If this research was to be repeated, several protocols and experimental methods would need to be reconsidered to improve the repeatability and accuracy of the experimental results, and therefore, the accuracy of the design rules.

## *7.2 Literature review*

Since the introduction of RP in the early 80's, the trends in manufacturing prototype products have progressed into an increasingly popular research field and industry of RM. SLM is a popular research topic for metallurgists and engineers because of the ability to produce parts from engineering grade metals. This has led to SLM being recognised for being potentially advantageous to high-value industries such as aerospace and medical.

Metals are complex materials that have properties that suit many applications. Metals have numerous chemical and mechanical properties that may change during processing, which may be advantageous, or disadvantageous depending on the application. Almost all previous literature is based on the physics of SLM. However, since industrial interest has increased, there appears to be a recent reduction in the number of published articles. One possible explanation to this is that companies considering the use of SLM within their business, and the companies that are producing SLM machines (EOS, Concept Laser, MTT) are protecting their potentially valuable IP.

Research into materials and process parameters has driven the developments of SLM technologies from just sintering powder particles together (SLS), to fully melting (SLM) an inventory of materials such as aluminium, titanium and tool steel. As metallurgists have increased their knowledge of the physics involved in the SLM process, the inventory of available materials is increasing and the technologies are developing alongside. This has made it possible to create functional parts and has informed the research within this study.

The review of existing literature has identified that there is a clear need for design rules. Not only was the literature from academic backgrounds (Hague. R, 2006), RM practitioners and research from industries who are investigating the use of SLM within their manufacturing process have also recognised the need for design rules (Pullin & Offen, 2008; Wohlers, 2009). It appeared that designers were either avoiding SLM, or were designing for SLM using guidelines for conventional processes such as casting, milling or even injection moulding. Wohlers, (2009) stated that there is very little design experience in RM, and for RM to succeed as viable manufacturing process, designers will need to be eductated, and become less reluctant to design for new RM processes as well as the conventional processes they have become used to.

Advanced and complex SLM designs have identified the potential for SLM to become a valuable process for new business applications. It was found that the lack of design experience needs addressing to prevent it becoming a bottleneck in the development of SLM. If designers know how to design for SLM they will become less reluctant to use it as a manufacturing process which will increase the success of SLM within industry until superior technologies are developed.

## *7.3 Methodology and test methods*

### *7.3.1 Two phase methodology*

To address the aims and objectives of the research, the methodologies were separated into two phases. Phase one was a quantitative evaluation of the SLM process that identified geometrical limitations. The second phase was qualitative and was used to initiate the design rules, and to establish their effectiveness and to inform further development.

Dividing the research into two phases meant that the overall research goal could be addressed in logical steps that could be addressed individually, rather than one larger step that consisted of multiple methodologies and too much data to review and analyse. After the first phase was completed, the design rules were initiated by a synthesis of the experimental results which was successful because the results that were created in phase one could be used directly in the design rules. This was encouraged by the Plan-Do-Study-Act (PDSA) cycle (Deming, 1995) used as the experimental methodology. The experiments were only complete once the results could inform the design of the following experiment in series.

An alternative method to the two phase approach may have consisted of initiating the rules as each associated experiment was completed. This would not allow the design rules to include any unexpected research findings, and rather than encouraging the use of SLM, the rules would be negative by only highlighting the process limitations.

### *7.3.2 Fixing parameters*

All process parameters were fixed throughout the experimentation. This makes the study independent from other SLM research where the build parameters have been the main focus. Fixing the parameters ensured that the study was focused on gathering the required dimensional data to enable the design rules initiation, rather than optimising process parameters to reduce geometrical deformations. At the beginning of this study, time was dedicated to benchmark the SLM parameters used so that the highest quality build of the MCP Realizer SLM was achieved throughout the experimentation. These qualities included surface finish, density, and the parameters that gave the most repeatability to the process.

If the process parameters were not optimised the machine would under-perform which would be unrealistic in comparison to an SLM within a commercial environment. One reason for developing design rules is to bridge research into mainstream manufacture, which will contribute to SLM becoming a true RM process. Therefore, it was necessary that all parameters were optimised to what was acceptable within industry for the MCP Realizer SLM machine available at the start of this study.

One limitation of fixing the parameters is that the rules will only be accurate to the SLM machine and parameters used in this study. However, the principles and features of the design rules will be applicable to all SLM machines with all variations of materials and parameters. If this study was repeated with different parameters such as layer thickness and laser power, the design rules would remain the same, and the dimensional details would be different.

### *7.3.3 Experimental conditions*

The ambient air temperature and humidity of the environment where the SLM machine was situated were not fixed, so that the experimentation would be completed within a realistic workshop environment. To identify if the uncontrolled environment affected the repeatability of the test parts, one test could be built several times at different ambient conditions. When the curl categories were established to quantify the heat induced distortions during SLM processing, the test parts became repeatable when the curl value was 0 or 1, which suggests that controlling the environment would not improve the accuracy of the design rules. Even if the environment was controlled, and the results were more accurate and repeatable, the shadowgraph measurement method used to measure all test pieces would not have been accurate enough for the improvement to be observed.

Further discussion on accuracy requirements and measurement test methods is explained throughout this chapter.

### 7.3.4 T*est methods*

The dimensional accuracy of all test parts was measured using a shadowgraph. A shadowgraph protocol was created that consisted of several steps to measure the accuracy of all geometrical features, regardless of the scale of the surface roughness. The test parts were designed to be measured using the shadowgraph. The parts consisted of the design feature being investigated, and a feature with a known dimension that was used as a reference for scaling. The shadowgraph was a suitable method considering the time constraints of this study, the process repeatability and the surface roughness of the test parts. The shadowgraph protocol led to several significant findings, including a relation between distortions that were visible during the build, and the accuracy of the test parts. This finding was then considered in the analysis of all experimental test parts.

After building the test parts, the shadowgraph protocol consisted of printing a semi-transparent profile, aligning the print with test parts on the shadowgraph display, and importing the image into CAD to compare against original geometry. To measure a part, a total of six stages were required which were all open to accumulating error. According to experienced quality engineers, the tolerance of the measurement technique was expected to be ± 0.05mm. Table 7.1 describes each step and the possible errors that the shadowgraph method may have been exposed to.

| Step | | Possible Error |
|---|---|---|
| 1 | Print scaled semi-transparent CAD profile of test part. | Inaccurate print out. The tolerance of the scaled print out is unknown. |
| 2 | Hold part on shadowgraph | The part needed to be held squarely in a grinding vice, this could have been slightly off square by one or two degrees. |
| 3 | Overlay and align semi-transparent printout | This relied on the shadowgraph user's knowledge to align the image over the part correctly. |
| 4 | Take photo of the shadow | The image needed to be taken standing back from the shadow with the camera zoomed in to reduce any barrel effect in the image. A small barrel effect may still have been present. |
| 5 | Import image in CAD and Scale to size using known dimension. | The accuracy of aligning the geometries was dependant on the user's visual judgement. The known geometry could have been slightly inaccurate, and the scaling of the image may not have been precise. |
| 6 | Offset lines on the original CAD image to compare against the SLM part shadow image | This was completed using visual alignment of two lines, in many cases there was weld spatter on the part which would cause inaccuracy, and the person completing the task could miss-align the CAD against the SLM part image. |

Table 7.1: Each step of the shadowgraph protocol and the possible errors that could accumulate and cause inaccuracy.

The shadowgraph test method was appropriate for this study. However, the test methods would need refinement if the study were to be repeated. To improve the number of steps required to measure each part would need to be reduced so that there is less opportunity for accumulative error. The first step to be removed is printing the scaled geometry profile, which would avoid possible printer inaccuracies, and also inaccuracies of overlaying the image against the shadowgraph display.

Taking the digital photograph of the shadowgraph display is the when the greatest amount of error could occur. If there is a barrelling effect in the photograph, the scale of the image will be distorted, which will lead to inaccurate measurements. To eliminate this, a wider camera lens could be used, or a shadowgraph with an onboard ability to capture digital images. Many of the geometries measured had rough edges, so measuring point to point using the on-board optical system would be inaccurate. Figure 7. shows the reduced shadowgraph protocol with less opportunity for error.

| | |
|---|---|
| Step 1: | Hold part on shadowgraph |
| Step 2: | Take photo of the shadow and import directly to PC at correct scale |
| Step 3: | Offset lines on the original CAD image to compare against the SLM part shadow image |

Table 7.2: The reduced steps of the shadowgraph protocol.

Since a retrospective view of this research could be taken, it appeared that the shadowgraph protocol was not the only method that could be refined if the research was to be repeated, but the number of test parts could be reduced. The large number of test parts in this study was required, although, if the amount of parts were to be reduced a more accurate and time consuming measurement method could be considered.

Using a Coordinate Measuring Machine (CMM) would be a more accurate single-phase method of measuring the SLM test parts. CMM requires much more time to use than using a shadowgraph, but is capable of measuring complex 3-dimensional geometries at higher accuracies. It was deemed unnecessary to use a more accurate measuring technique when the SLM process consists of such rough surfaces and many unrepeatable test parts. If CMM is used, only the self-supporting parts that built with a curl of 1 or 0 would need to be measured, because all other parts have already proven to be unrepeatable and detrimental to the build completing successfully. The poorest surface roughness of parts with a curl of 2 and 3 will cause the CMM probe to touch at different heights of the peaks and troughs within the rough surface, and also on weld spatter which will cause inaccurate and unrepeatable measurement results (see Figure 7.1).

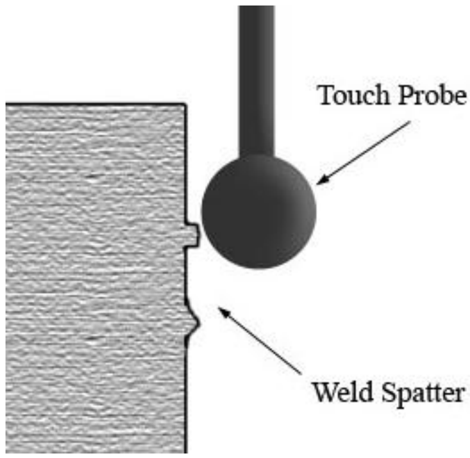



Figure 7.1: Illustration showing weld spatter affecting the touch probe CMM.

### *7.3.5 Accuracy requirements*

The methodologies used within phase one of this research were open to measurement inaccuracies that may have affected the accuracy of the results and subsequently the design rules. Greater accuracies could have been achieved, however, the main aim of this research was to initiate design rules, rather than to create an optimised measurement process for measuring SLM parts. The measurement methods used were accurate enough to gain an understanding of the SLM process, and to identify trends in geometries such as the curl distortion relating to accuracy.

During this research, many process-inherent geometry deformations were identified, and to avoid these problematic geometries, alternative designs were developed. It is possible to measure more accurately than ±0.05mm, although, the increased accuracy was not necessary at such an early stage in the design rules development, and the rules developed with the scope of this research are a first draft.

The design rules could be produced at a higher accuracy if the process repeatability improves, and the surface roughness capabilities of newer generation machines are higher than the MCP SLM Realizer that was used in this research. As this was the first attempt at creating process-specific design rules for SLM, one important result was that the methods used were successful in creating the design rules, and evaluating them to inform further development. The full methodology and measurement protocols are described in chapters 2 and 3.

## *7.4 Experimental Results*

### *7.4.1 45° minimum surface orientation*

The first experiment in this research was aimed at identifying the lowest orientation a flat surface could be built at. The results showed that 45° was the lowest orientation, and when angles between 40° and 45° were built, there was variability in the results as 40°, 43° and 44° built on one occasion only. 45° was chosen as the lowest orientation because it was the only dimension that was repeatable, however, it is possible that the smallest orientation will be less than 45° with more accurate readings of 44.9° or even 44.5°. This amount of detail was not considered during the orientation experiment because the accuracy of down-facing surfaces is affected by poor surface roughness.

The layer thickness used throughout this research was 0.075mm. The minimum orientation was identified as 45°, therefore, the overhang distance of each layer was also 0.075mm, as shown in Figure 7.2. This leads to question whether or not the minimum surface orientation would be reduced if the layer thickness was smaller, and will the 0.075mm layer overhang remain the same for all layer thicknesses?

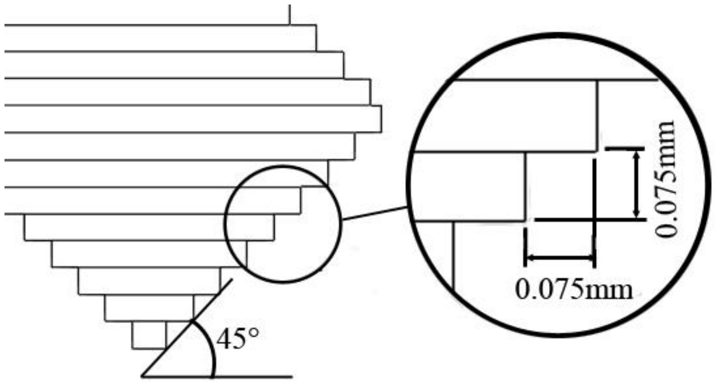



Figure 7.2: Minimum orientation angle with 0.075mm layer thickness and 0.075mm layer overhang.

Work by Vandenbroucke & Kruth (2007) found that the minimum orientation was 20°, and orientations less than 20° required support structures. This result was recorded with a layer thickness of 0.03mm, which was two and a half times less than the 0.075mm layer thickness used in this study. As the layer thickness was 0.03mm and the minimum surface orinetaion was 20°, the overhang of the downfacing layers was calculated at 0.08mm, which is close to the 0.075mm overhang identified in this research. This suggests that a common overhang size for all layer thicknesses is approximately 0.075mm to 0.08mm. Not only was a different layer thickness used, the 20° angle was achieved at three different hatch space distances (100, 120 and 140µm) and three different scaning speeds (90, 140 and 190µm). The machine that was used was a Concept Laser M3 Linear, which was different to the MCP Realizer SLM used in this research.

Research findings by Sutcliffe *et al.* (2005) identified a minimum surface orientation of 38°, and Brooks *et al.* (2007) identified a minimum orientation of 40°. The research was completed using the same SLM as in this study. The layer thickness used is not mentioned, however, Sutcliffe concluded that the parameters for an overhanging feature would need to be controlled independantly from the rest of the part, with a different laser power and a scan strategy that reduces residual stress in the layer. Sutcliffe stated that the scan vectors should be increased to build low orientations, this was also repeated in greater detail by Mercelis & Kruth (2006).

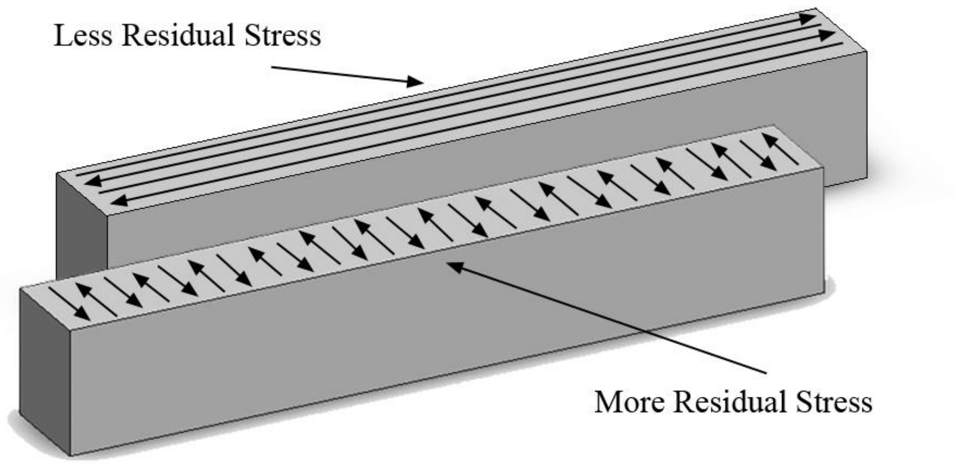



Figure 7.3: Residual stress distortion caused by scanning strategy as explained by Mercelis & Kruth (2006).

Research by Mercelis and Kruth identified that that the scan stratey has a major influence on the residual stress of a part, and therefore, the amount of distortion that occurs during a build. Scanning in short lines across a narrow part creates more residual stress than when scanning longer lines along a perperdicular axis (See Figure 7.3). The more lines that are scanned in one direction the more the curl distortion occurs. Therefore, the fewer scan lines there are in one axis, the less distortion will occurs.

It appears that the minimum surface orientation of a flat surface correlates to the layer thickness. As the layer thickness of an SLM part decreases, the lower the surface orientation can be. By reviewing other research, it was identified that when the layer size is reduced, the size of the layer overhang remains close to 0.075mm, which results in the ability to build at lower orientation without the use of support structures. However, the accuracy of the layer overhang, and the build orientation is subject to carefully controlled parameters. The availability of pre-heated build platforms in SLM machines has also improved the ability to build at lower orientations. This will increase the overall part quality as all geometric features that are constructed of overhanging geometries will become less constrained.

### *7.4.2 Self-supporting radii*

Both convex and concave radii were investigated. The first major finding was that traditional tangential radii were not self-supporting when built in the upright position. This was because the top of a concave radius becomes down-facing, and the bottom of a convex radius starts building down-facing as shown in Figure 7..

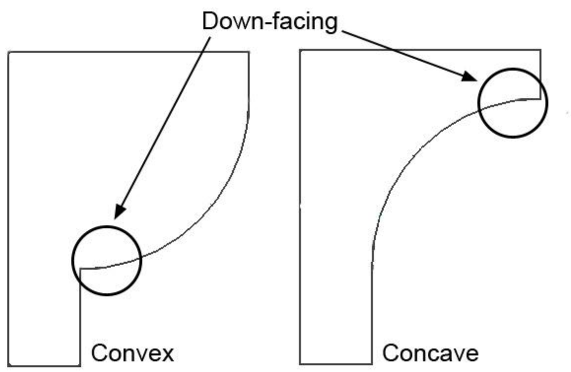



Figure 7.4: Down-facing sections of a convex and concave tangential radius

Previous investigations have identified that when a component is self-supporting, there is a reduction in the part distortion that occurs during the build, and subsequently, an increase in the accuracy of the geometric feature in question. Experiment number 10 was designed to identify convex and concave radii can be designed to be self-supporting. The tangents of the down-facing radii section were changed (see 7.4), and after several experimental iterations the minimum tangent for each test part was identified for making self-supporting radii.

When the tangent on the radii increases, the overhanging size of each layer is reduced creating a steeper curve. This experiment followed the investigation into the minimum surface orientation where the 45° minimum orientation was identified. This result was expected to be common to all geometries, including the tangent of a curve. However, this was not the case as many minimum tangent results were lower than 45°. The larger the radius became, the larger the tangent angle needed to be. For example, the smallest radius required a 28° tangent and the largest radii required a 40° tangent. These unexpected results showed how a simple geometry such as a radii can become so much more complex once it is made using SLM. The minimum surface orientation of 45° still remained the same, although curved surfaces were an exception.

To explain why such low tangents were required, the number of layers for all parts was analysed. The tangent of the curve changes as the layers build up along the z-axis. On convex radii, the tangent of the curve increases, and on concave radii the tangent decreases. Depending on how many layers there are less than 45°, curl will accumulate. The more layers of a radius that are less than 45°, the more chance curl has to accumulate, which is why larger parts require a larger tangent angle. The number of layers may change if different process parameters and materials are used.

The number of layers that can be built under 45° without curl occurring was not measured. However, if the SLM is to become more accurate distortions may need to be measured in greater detail. To increase the accuracy and to reduce the minimum self-supporting angle, it is possible that the layer thickness needs to be reduced, which will be a compromise with added build time.

There was a small amount of variability in the results once they were measured using the shadowgraph method; although, it was still possible to identify that the less curl distortion that occurred during the build the more accurate the parts were. When curl had occurred, the parts were undersize as a result of the curl pulling the SLM part boundary away from the correct geometry.

The results from the radii experiments gave a good insight to building more complex geometries that are constructed from surfaces other than flat. The constantly changing tangent showed how it is possible to build outside the limitations of SLM if it is redeemed within a few layers.

### *7.4.3 Self-supporting holes*

The aim of the hole experiments was to create self-supporting alternatives to a round hole design, and so that intricately detailed components can be constructed of holes and channels without needing access for support removal. The results of the radii experiments were then used to develop a hole design with a peak that was optimised to be as close to a round hole as possible.

One finding from the hole experimentation was if the top layer of a design feature has evidence of curl, it will accumulate onto another design feature that is built on top in the z-axis, only if the top part is built at the lowest possible orientation. This may cause a failure on a feature that would normally be self-supporting. This proved that the elimination of curl and the use of self-supporting geometries are important to create a smooth transition between two or more geometries stacked together.

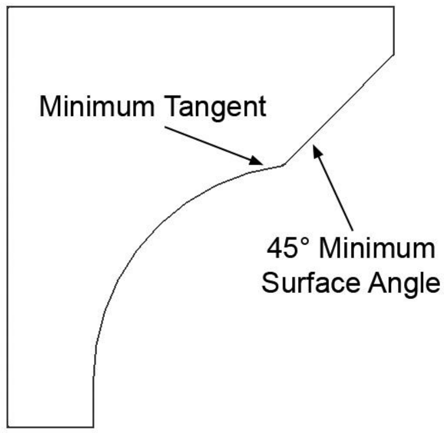



Figure 7.5: Two minimum geometric limitations stacked together

The accuracy of the self-supporting holes developed in this study could be predicted based on previous results. The smallest holes appeared to be the least accurate at ±0.3mm and holes at 5mm radius and above were all within a tolerance of ±0.1mm. The accuracy difference between the smaller and larger holes was an unexpected result. One possible explanation can be explained as a reaction to the heat building up in parts with a small volume. It is possible that the smaller parts could not cool and disperse heat away from the part as quickly as the larger parts. Therefore, the localised heating of the melt-pool had very little dense material to conduct away the heat, resulting in melting excess material against the part boundaries. This occurrence could not be avoided through design changes unless the parts were made larger. This problem would need to be controlled by tailoring the design feature parameters independently to rest of the part, according to the size of the geometry being melted.

### *7.4.4 Variability and repeatability*

The results of the surface roughness experiments were not repeatable, and there was large amount of variability present. When two parts with the same design were measured the results were not the same. This also occurred in other geometry experiments. It is possible that this was caused by inaccurate measurement methods or it may have been inherent to the SLM process. Once curl values were established, it became possible and repeatable to predict the accuracy of a part. However, in some cases when the same or a similar geometry was built, the surface roughness appeared to be inconsistent.

To identify the true repeatability of all geometries, it would be necessary to build more than just one or two parts. Although improving the accuracy of the results would improve the accuracy of the design rules, it may not have improved the results of this study because the rules were a first version that are valued because of the geometries, clarity, and comprehensiveness that would inform designers. As the experiments progressed the test parts became compound and were constructed of geometries from earlier experiments within this research. This resulted in accuracies from the fundamental geometries being applied to the compound designs. The geometries used to create the compound test parts were repeatable to within ±0.1mm as they had no or very little curl distortion.

The surface roughness experiments were completed twice as first attempt consisted of high amounts of variability between each measurement. This variability appeared to be inherent to the SLM process and was caused by the adherence of weld spatter to the part surfaces (See Figure 7.). This experiment was repeated with marker pen lines added to the test parts to indicate the best measurement position for the device (Taylor Hobson Sutronic 3p). The device was calibrated to within aerospace compliance at Gardner Aerospace Wales Ltd, using a surface roughness gauge. After the second measurements the results showed that the variability was still present. The staircase effect was apparent, however, in some places this was only visual rather than what was measured. Therefore, only an indication to the effect of part orientation was presented in the design rules, along with the highest and lowest mean roughness (Ra) values taken from the results.

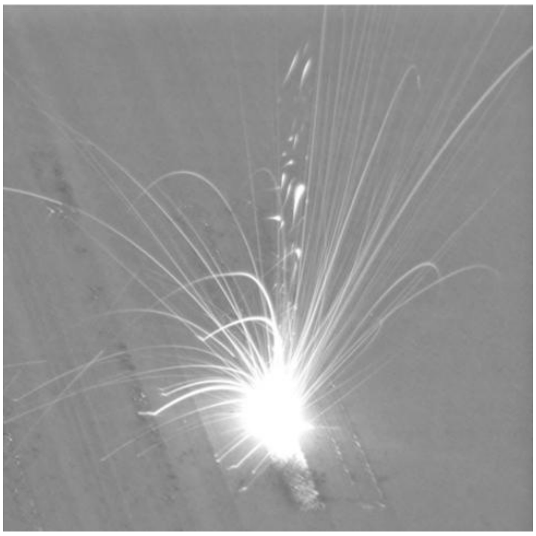


Figure 7.6: Weld spatter occurring during the build of an SLM test part

One possible method of controlling the variability and repeatability was used when creating self-supporting holes in experiment 8. In this experiment the variability in the results was caused by the uncertainty of when curl distortion had exceeded a level that jeopardised the building process. Round holes from a radius of 1mm to 15mm were built and stopped at the point were they were no longer self-supporting and curl distortion had occurred. After the first attempt, it proved difficult to select which layer to stop the build because there was a fine line between safe and unsafe amounts of curl. The experiment was repeated with small changes that controlled the variability by creating a zone where the actual results lies. As the first sign of curl occurred, the layer number was recorded, and the part was left to continue building until it was clearly unsafe as too much curl had occurred. The minimum and maximum curl layer heights were then plotted in a graph and the mid-point between each result was selected as a predicted maximum self-supporting height for holes with a radius of 1mm to 15mm. The parts were then rebuilt and measured to an accuracy that was repeatable from earlier experiments.

If the variability was not controlled, the design rules for holes could not have been created with minimum geometries, as the results would have been too random. However, if variability is present in the SLM process it is important that it is identified so that it can be reflected in the design rules and considered within the accuracy of the overall SLM process.

## 7.5 Design rules development

### 7.5.1 Initiating the design rules

To complete this research the methodology was split into two phases. The first phase was aimed at collecting all of the data required to inform the design rules that were created in phase 2. The first task in phase 2 was to initiate the design rules from the experimental data so that the rules could be used and understood in design practice without the designer needing to interpret the data themselves. To select an appropriate presentation technique throughout the design rules document, and to understand the level of detail required, existing design rules for more traditional and well established manufacturing processes were reviewed. These processes included casting, extrusion and injection moulding. This synthesis of data was not as difficult and time consuming as originally expected because the “Plan-Do-Study-Act” (PDSA) cycle (Deming, 1994) used to complete the experiments ensured that the experimental results were comprehensive, and were completed to a level that could be used to inform the following experiment, therefore, they would inform the design rules without extensive interpretation required.

The PDSA cycle proved to be a successful methodology selection during the experimentation. It was used within individual experiments and for the bigger picture over all experiments. Within each experiment, the PDSA cycle ensured that the required results were achieved by completing and analysing one test part, and then repeating it with controlled changes until the required geometric limitations were identified. Over the entirety of the experiments the PDSA cycle only encouraged progression from one experiment to another if the results of one could inform a dimensional starting datum to the design of the subsequent experiment. Each experiment was based on fundamental geometries that were addressed in the design rules. Therefore, each experiment was associated to a particular design rule. This resulted in all experimental results being directly linked to foreseeable design rules, and presented ready to be used in the rules as they had already been optimised for designing test parts. The methodology is explained in greater detail in methodology, chapter 3.

### *7.5.2 Design rules evaluation*

The design rules were initiated from the quantitative experimental data, as described in chapter 6. The first draft of the design rules document (Appendix 4) was evaluated by six people, each with a different role within the design industry. The results gave a good feedback to the structure and content of the design rules, and also a good indication of further design rule development requirements.

The six individuals chosen to evaluate the design rules were selected because of their capability to provide a constructive feedback from different areas in design. If more than six interviewees were selected, more constructive feedback would be recorded and the accuracy of the results would improve. Six interviewees that were highly experienced within their design speciality was more relevant that a larger amount of interviewees with less experience. The more experienced interviewees would provide more detailed and in-depth feedback that would have a maximum benefit to the accuracy of the design rules at such an early stage in their development.

Large amendments to the design rules would need to be addressed earlier on in their development so that later revisions could be focused on refinements. Further design rule developments may require a different evaluating method such as focus groups. Using a larger number of people in focus groups would allow for accurate results when the design rules are being refined for a wider audience. If the rules need to be tailored specifically for just industrial designers, the focus groups would need to consist of several industrial designers rather than participants from several different design disciplines. If later developments of the rules were to remain generic to all roles within design, a mixed focus group, as used in this study would be required. Focus groups were not used in this study as the feedback required was to be individual to each of the six design professionals, without any dominating respondents who would influence the others.

Further design rule development will require user testing so that the rules are fully evaluated within their intended application. A design challenge could be to presented to designers so that the rules could be testing in actual design practice. The feedback would determine whether or not the design rules are qualified for use in industry. A design challenge was considered as inappropriate in this research study because it may have tested the design ability of each designer, rather than the content of the rules. The results of the design challenge would not indicate whether the rules are difficult to follow, or whether it is just the process that is difficult to design for. An example of a design challenge is shown in thesis work by Burton (2005).

## *7.6 Future design rule optimisation*

When the design rules are developed further, they will need to be proven effective in industry to encourage their use, and to drive the success of the technology outside of research. Currently, SLM knowledge lies with the SLM users and machine suppliers rather than with product designers.

The design rules created in this research are restricted to using the MCP SLM Realizer used in this study. Using newer SLM machines provide greater accuracy than the first generation machine that was used in this research. Different materials and process parameters also produce different results, however, the principles of each design rule will remain the same and only the dimensional details will vary, for example down-facing surfaces will be the least accurate.

The results of the design rule evaluation showed that some designers are reluctant to apply the SLM design rules, and would expect them to be applied by the SLM technician. For the most effective use of the rules they should be applied at the detailed design stage of the design process before any manufacturing begins. Once a product has been designed and the designer then relies on the manufacturer to apply the rules, the functionality and aesthetics of the component will need to be re-evaluated to ensure that they remain the same. This adds two additional stages to the design process as illustrated in Figure 7..

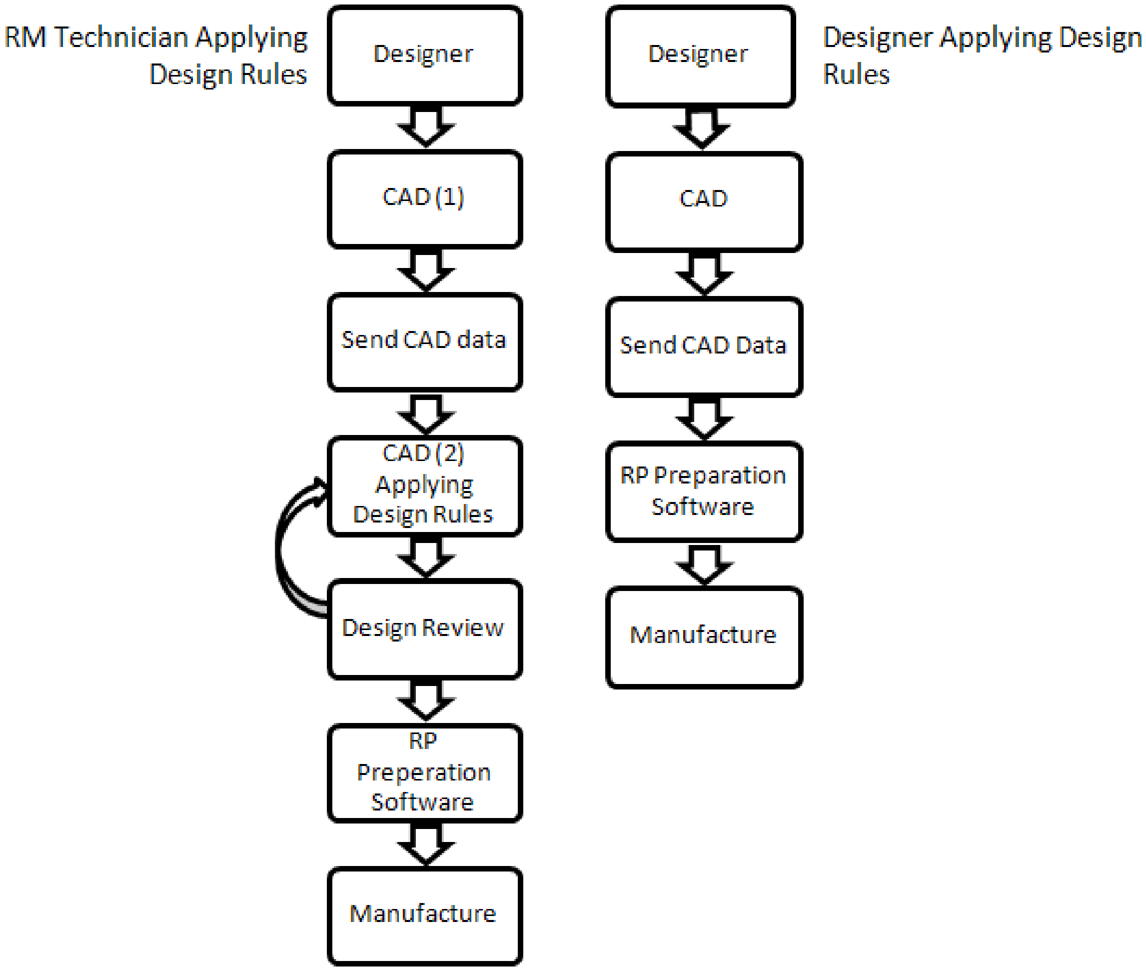



Figure 7.7: Flow Chart showing that the designer applying the rules is the most efficient way of applying the rules

To apply the design rules at the detailed design stage of the design process, designers will need to break away from their usual habits and become less reluctant to learn new design methods. Part of the designer's reluctance may be caused by the time involved in learning new processes, especially when they are unsure of the outcomes of SLM in the first place.

Initially, it is more realistic that the design rules will be used at the RM and STL file preparation stage of the design process. An ideal scenario to apply the design rules most effectively is if they are used as a tool for cross-disciplinary communication, to fill the gap in knowledge between design and manufacture. If SLM is selected as an appropriate manufacturing process, it must be specified by the designer together with the chosen material, during the development of the Product Design Specification (PDS). Firstly, to select SLM as a manufacturing process, the designer must be aware of the principle design rules through a generic design rule document. To complete the detailed design of a part, the designer must then be aware of the detailed geometric limitations. A two way communication must then be formed with the agreed manufacturer who will supply the detailed design rules that represent dimensional limitations of their particular commercial process. Once the designer has applied the detailed design rules the part can be sent for RM. A process diagram is shown in Figure 7.8.

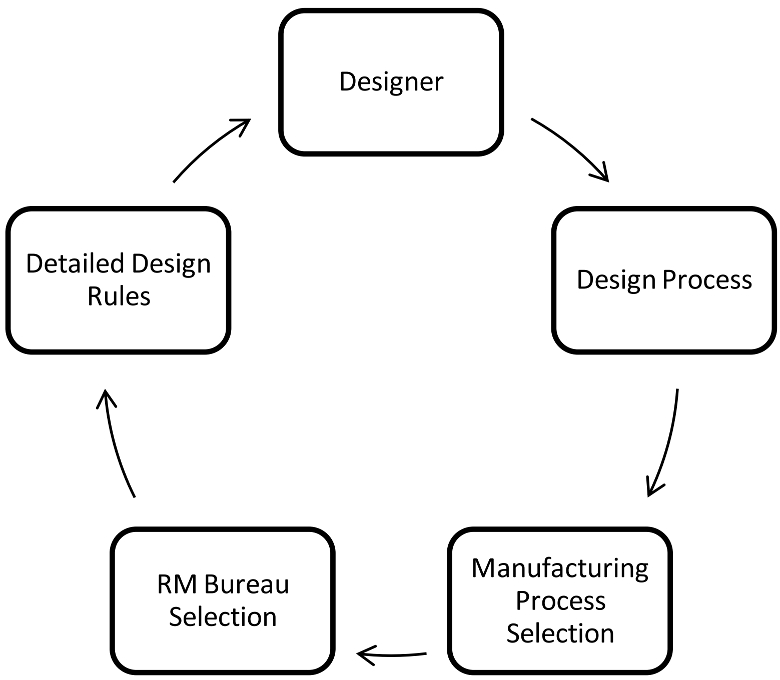



Figure 7.8: Process showing the most effective implementation of the design rules

For SLM to be chosen as a manufacturing process, and for designers to become familiar with SLM, it will need to be driven by commercial decisions. For the RP and RM bureaux to become commercially successful and to gain a larger customer base, they should be able to offer design rules. For the sales of SLM machines to increase, the RM bureaux and industries must have a successful customer base and many successful industrial applications. Therefore, to achieve this it would be in the interest of the SLM machine vendors to publically provide design rules that may advance the use of SLM.  The design rules may also be delivered through CAD software or be available on the internet, with an option to input the parameters that are provided by the RM manufacturer.

# Chapter 8: Conclusions

## 8.1 Introduction

The purpose of this research was to identify the geometrical limitations of SLM, and to develop and evaluate process-specific design rules for SLM. The content of this chapter presents the conclusions of each research objective, and describes the contributions that the research has made to new knowledge. Finally this chapter presents a description of future research to implement process-specific design rules, and to advance SLM into becoming a valued manufacturing solution. To accomplish the aims of this research, the following objectives were completed.

## 8.2 Research objectives

### 8.2.1 Evaluate the SLM process and identify the geometric limitations of SLM

The methodologies used for the experimentation has provided a process model for geometrically analysing SLM, which includes test piece design, and a number of process protocols. The shadowgraph technique allowed the required geometrical process data to be gathered for creating the design rules. The general tolerance and repeatability of SLM parts improved as the parts become more self-supporting. The first significant finding was a minimum layer overhang of 0.075mm occurs at a minimum orientation of 45°, which was also used to identify a correlation between surface roughness and surface orientation. The orientation results were then used to develop other geometries, such as a radii where the tangents needed to be minimised so that they are self-supporting, and an alternative hole design to overcome the difficulties of building round holes. The research showed that designing simple geometries like radii and holes for SLM becomes increasingly complex when compared to conventional processes.

### *8.2.2 Perform analysis and synthesis of the experimental results, and create a first draft of design rules appropriate for use in design practice*

This was the start of the second research phase aimed at creating the SLM design rules. The experimental data was interpreted into a format that was presentable within the design rules. This synthesis of experimental data was not the extensive process it was originally expected to be. The cyclic methodology used to create the geometrical data encouraged each experiment to be complete only when the results could be used to inform the design of the following experiment. This lead to all experimental results being analysed and interpreted to be used directly within the design rules. A set of design rules were created that addressed all geometrical limitations, and presented design solutions for SLM.

### *8.2.3 Evaluate the design rules to establish their effectiveness and inform their further development*

Once the design rules were created they were evaluated. The feedback was positive because the design rules gave designers a new insight to SLM, and increased the designer's confidence in designing for SLM in the near future. The content of the design rules was found to be comprehensive and all of the design rules were relevant, however, the evaluation concluded a number of points that need consideration to advance the design rules in further developments. Commercial examples of the design rules applied used on actual parts are required, and an emphasis of the implications of all process limitations need to be shown. As the designer may not be familiar with SLM a breakdown of terminology and more process background information is also required.

## 8.3 Contribution to knowledge

In completing the research presented in this PhD thesis, the work has created new contributions to knowledge in the field of product design, Rapid Manufacturing and the Selective Laser Melting process. The contributions are described as follows:

- An effective method of categorisation of SLM layer performance based on grading curl.
- The first geometrical analysis of SLM that is comprehensive to all fundamental geometries. Previous to this study, research into SLM has identified some geometrical limitations for a small number of geometries. However, this research is the first to analyse all possible fundamental geometries within one piece of work, with focus on identifying geometrical limitations, and suggesting design solutions.
- The development of a protocol for establishing the geometrical capabilities of SLM that can be repeated and applied to other machines and materials. The overall experimental methodology was configured to facilitate the delivery of a practical set of design rules.
- The development of the first design rules specifically for SLM to be used as a manufacturing process. Through qualitative targeted interviews, information gathered was used to validate the applicability of the design rules in practice.

## 8.4 Recommendations for future work

The research objectives within this research were successfully completed. The following describes several recommendations for future work that could be addressed to expand and advance on the research completed within this study.

- Improve the consistency and repeatability of the surface roughness of SLM parts. This will require efforts to eliminate the weld spatter that occurs during the SLM process, and will reflect on the accuracy of all geometries.
- Investigate if the overhang size of 0.075mm is consistent to all layer thicknesses and process parameters other than those used within this study. If the overhang size is the same for all layer thicknesses then the freedom in design will increase as the layer thickness is reduced.
- Develop the design rules further through a series of focus groups and design exercises. The feedback may be used to refine the design rules, so that they can be used as a benchmark for individualising the rules based on the limitations of other SLM machines with different process parameters, and also different materials.
- Refine the experimental model that was created within this study to produce the design rules. This model included the measurement methods, the experimentation and how the design rules were created. The following points may require further refinement to establish an efficient design rules development model that can be repeated within the constraints of a commercial environment.
    - Reduce, or combine the number of test parts.
    - Implement a more accurate dimensional analysis method.
- Develop a method for delivering the design rules to designers. This may include investigating the possibility of delivering the rules through online software, CAD software and even RP preparation software. The aim of this would be to identify the most effective way to encourage designers to use SLM and exploit design possibilities.

In summary, there appears to be three main strands of research that require further investigation to advance SLM within the RM field. These strands focus on:

technological advancement that improves SLM performance; investigations into how the limitations vary within different experimental parameters; and, case study development to assess the design rules performance for real products in a real working environment.

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