UNIVERSITEIT·STELLENBOSCH·UNIVERSITY

jou kennisvennoot • your knowledge partner

Capability Profile of an Additively Manufacturing Machine based on the Selective Laser Melting Process

Final Year Project

Jessica Kirsten Mantel 15145263

Study Leader: Prof. Dimitri Dimitrov

10/27/2011

Department of Industrial Engineering

Declaration

I, Jessica Kirsten Mantel, hereby declare that the work contained in this final year project is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

………………………………………………….. ………………………

Date

ECSA Exit Level Outcomes References

Exit level outcome		Description
1. Problem solving		The objective of this project was to construct a capability profile of an Additive Manufacturing machine and to derive application areas from this capability profile. The problem was defined and the information gathered in the form of an Additive Manufacturing overview (sections 1 and 2) which highlighted various advantages, disadvantages, existing industrial applications and process descriptions. The construction of the capability profile required analysis and evaluation skills (section 4). A method for determining and comparing the applicability of the machines to specific industrial areas was modeled using weighted scores derived from the capability profile (section 4.5).
2. Application of engineering & scientific knowledge		The Additive Manufacturing industry knowledge gained during the project was used during the analysis and construction of the capability profile and during the modeling of the method for determining the industrial applicability of the machines. Other engineering and scientific knowledge that was required included some material science knowledge and research skills.
5. Engineering methods, skills & tools, incl. IT		A SWOT analysis approach was used to identify the overview required for the construction of the capability profile. Microsoft Excel was also put to use during the formulation of the method for determining the industrial applicability of the machines.
6. Professional & Technical communication		As demonstrated in this project report.
9. Independent learning ability		Reflections and conclusions were drawn in section 5 that show independent learning

Exit level outcome		Description
		abilities.
10. Engineering professionalism		As demonstrated in this project report.

Abstract

Additive Manufacturing is a relatively young technology that involves the layer-by-layer addition of material in solid, liquid or powder form to create parts. It is ideally suited for producing complex parts with small production batches. The industrial applications of these techniques as well as the advantages and disadvantages of Additive Manufacturing are explored and an overview of the different Additive Manufacturing techniques is detailed. Selective Laser Melting is one Additive Manufacturing technique that is discussed further and the characteristics of the M2 Laser CUSING machine and the EOSINT M 270 machine are detailed. A capability profile of various Additive Manufacturing machines is ultimately formed and this capability profile is used to identify the applicability of the different machine types to the Tooling, Medical and Aerospace/Motor Industries.

Opsomming

Toevoegende Vervaardiging is 'n nuwe tegnologie wat behels dat laag-vir-laag toevoeging van materiaal in die vaste-, vloeistof of poeier vorm om produkte te maak. Dit is ideaal geskik vir die vervaardiging van komplekse dele met 'n klein produksie lotte. Die industriële toepassings van hierdie tegnieke asook die voordele en nadele van toevoegende vervaardiging is ondersoek en 'n oorsig van die verskillende toevoeging vervaardiging tegnieke is bespreek. SLM is een Toevoegende Vervaardiging tegniek wat verder bespreek is asook die kenmerke van die M2 Laser CUSING masjien en die EOSINT M 270 masjien. 'n Vermoë profiel van verskeie Toevoeging Vervaardiging masjiene is uiteindelik gevorm en hierdie moontlikheid profiel word gebruik om die toepaslikheid van die verskillende tipes masjien met betrekking tot die Tooling, Mediese en Vlug / Motoriese Sektore.

Table of Contents

List of Illustrations

List of Tables

1. Introduction

1.1 Problem Statement

Additive Manufacturing, which is a relatively new approach to manufacturing, involves the use of a computer aided design and layer-by-layer manufacturing method to construct parts. The Stellenbosch Industrial Engineering Department has purchased a M2 Laser CUSING Machine, which is an Additive Manufacturing machine, for current and future research purposes. This machine uses the Selective Laser Melting (SLM) process and is able to process reactive powder materials like aluminium and titanium alloys as well as nonreactive materials. The process capabilities of the machine needed to be analysed in order to determine its applicability in various industrial areas.

1.2 Project Objectives

The purpose of this project is to establish how the analysis of the process capabilities of the L2 Laser CUSING machine at Stellenbosch University would fit into the body of research that has already been done in this field. Additive Manufacturing is discussed, with a particular interest in the SLM Process.

A comparative capability profile is then compiled of four Additive Manufacturing processes:

- SLM, which is the step-by-step construction of parts using a laser to selectively and completely melt each layer of a single-component powder
- Laser CUSING, which uses the same process as SLM but is owned by a different company
- Direct Metal Laser Sintering (DMLS), which sinters powders composed of various different components and forms the part at the lowest melting temperature of the various components
- Electron Beam Melting (EBM), which melts powders with several different components using an electron beam instead of a laser.

The machine process capabilities that needed to be determined were dimensional and geometric accuracy, surface roughness, mechanical properties of the various processed materials and minimum wall thickness, to name a few. These achievable mechanical properties then had to be compared to those mechanical properties achieved using conventional manufacturing methods. Finally, economically viable application areas of the Laser CUSING machine in various industries have been explored using the results of the process capability study as a guideline.

2. Additive Manufacturing Technology – An Overview

2.1 Background

Additive Manufacturing is the construction of finished products and prototypes using additive rather than subtractive methods. Additive Manufacturing systems join liquid, solid or powder materials layer by layer to create finished 3D objects, whilst subtractive manufacturing methods involve the removal of material until a desired shape is achieved and the assembling of the machined parts to complete the final product. The actual manufacturing process of a part is still a lot slower than the process involved in producing the same part by subtractive manufacturing techniques. The direct manufacturing of parts using Computer Aided Design (CAD) makes it an invaluable manufacturing technique because unimaginable design possibilities are introduced that have not been available to product designers before. The layer-by-layer building techniques also eliminate the need for special tooling and enable the production of highly complex designs (Hao *et al.* 2010). The 'rapidness' of rapid manufacturing refers to its quick design and product development phases since it is a CAD-based automated manufacturing process that requires no tooling. The integration of production planning and testing procedures into the product development phase also aids fast product design and development duration. Taking into account the short product development time, the vast design capabilities and the relatively slow manufacturing process, Additive Manufacturing lends itself towards the manufacturing of a small batch of complex, customised products (Eyers *et al.* 2010, Hopkinson *et al.* 2006).

The global manufacturing industry has become highly competitive since third world countries started manufacturing mass-produced goods. The inexpensive labour and ease of access to raw materials in these countries, resulting in lowered costs, have made it impossible for smaller countries, where labour and raw materials are more costly, to compete in this arena. For this reason, manufacturing is now becoming more focused on faster product development cycles of high quality, unique, reasonably priced products (Petrovic *et al.* 2011).

Additive Manufacturing techniques have the ability to manufacture unique products that meet customer requirements (Zhang *et al*. 2005). In the past, Additive Manufacturing systems were used primarily for making prototypes but in recent years their application to the manufacturing industry has been explored and further developed (Aronson. 2009). Additive Manufacturing methods have emerged as an alternative to conventional subtractive manufacturing methods in industrial, consumer, medical, military and other such markets because products of greater complexity can be designed, manufactured and quickly released into the market in true accordance with the needs of the customer (Li *et al* 2010).

Additive Manufacturing can be split up into three categories, namely:

- Liquid-based processes
- Solid-based processes
- Powder-based processes

The oldest Additive Manufacturing process is Stereolithography, which is a liquid-based process that uses an ultraviolet laser to cure a particular resin layer-by-layer, thereby creating a solid 3D object (Hopkinson *et al.* 2006). The patent for the Stereolithography process was granted in 1986 and the first commercial Stereolithography machine was on the market in 1987. Since then the development of Additive Manufacturing has continued with the introduction of various patented Additive Manufacturing processes and machines by individual companies. Additive Manufacturing of metals first made an entry into the industry in 1971 when a patent was issued for a manufacturing method similar to a 3D Laser Cladding process and then again in 1977 when a patent was issued for a system similar to the Selective Laser Sintering (SLS) system. These early ideas for the Additive Manufacturing of metals were not commercialised at the time because of a lack of computers with enough power to aid the design and product development of parts and the expense of lasers (Santos *et al.* 2006). The most recent metallic powder-based systems are capable of processing metals such as stainless steel, tooling steels, titanium alloys, aluminium cobalt-chrome and others.

2.2 Advantages of Additive Manufacturing

Consumers are interested in buying unique products, but they will not tolerate lengthy product development times or elevated prices. These customer requirements can be addressed by implementing mass customisation in certain sectors of the manufacturing industry. Mass customisation is the production of goods to satisfy the needs of the individual consumer whilst incurring the same costs as mass production techniques. The concept was developed more than 20 years ago, but the method has still not succeeded in replacing standardised mass production techniques in most manufacturing sectors because it is not as cost effective as mass production. This is where Additive Manufacturing enters the scene. The absence of tooling and the direct use of CAD in Additive Manufacturing allows for a decrease in set up times, design phase and product development duration therefore decreasing time to market. It also presents a cheaper option for manufacturing small parts with low production runs since high volumes are not required to offset the cost of tooling. This is ideal for the mass customisation concept (Eyers *et al.* 2010).

The product development phase may take weeks rather than months because of the removal of tooling during Additive Manufacturing. When a new product is being developed it is designed using CAD, the CAD data is divided into layers for manufacturing and the automated Additive

Manufacturing machine then builds the part according to the CAD design. The single step is simply the layer-by-layer creation of the product directly from the CAD design; it does not require the assembly of a large number of components. However, when a new product is being developed using a subtractive manufacturing system, the part is designed, the required manufacturing process is planned and broken down into sequential steps and then the physical aspects of the process are addressed, including the purchase of the specific tools required. Each of these steps is time consuming and delays in the purchase of tooling could lengthen the process further. Since Additive Manufacturing involves only one step between product design and product completion, market lead times can sometimes be considerably shorter depending on the size and quantity of the products. The ability to get new or redesigned products to the market quickly using Additive Manufacturing means that profits can be made in a shorter time period and there are no risks involved in purchasing tooling for the manufacturing of new products either (Eyers *et al.* 2010, Bourell *et al.* 2009).

The use of Additive Manufacturing eliminates the ‘design for manufacture’ requirement which is a major limitation on a product designer. This is again related to the removal of tooling requirements. Designing for manufacture is irrelevant because of the ability of Additive Manufacturing machines to build parts layer-by-layer, making construction of the parts’ interior just as accessible as its exterior during the manufacturing process (Eyers *et al.* 2010).

The ability to get the customer involved in the actual product design process is also a major advantage of Additive Manufacturing. The customer can be more involved in this product development phase because it is easier to conceptualise the customer’s ideas using CAD. There is no need to translate designs and customer requirements into phases in the manufacturing process plan since manufacturing occurs exactly according to the CAD data. This may save time and money by avoiding expensive re-designs or alterations, as well as ensuring customer satisfaction right from the beginning of the design process (Zhang *et al.* 2005).

Although further machining and polishing may be required once the part has been manufactured, the manufacturing of the part to near net shape involves only one step and work in progress is effectively carried on the Additive Manufacturing machine. This reduction in work in progress has a cost benefit because the company’s capital is not tied up and it can be used in a more profit oriented manner. It is also beneficial to the company because no losses can occur due to breakages or misplacement of work in progress during storage. Further cost reductions are made because costly storage space is not required (Hopkinson *et al. 2006*).

The one-step manufacturing cycle also eliminates the need for a traditional manufacturing process layout in a traditionally sized factory. This implies that manufacturing can take place in a more convenient location which makes logistics and distribution of products easier and less expensive (Hopkinson *et al. 2006*).

Additive Manufacturing also has a reduced carbon footprint since it generates very little waste and it enables the design of optimized products (Hopkinson *et al.* 2006). This small generation of waste can be attributed to the recycling of certain materials, depending on the Additive Manufacturing technique used, and a much lower defect rate than subtractive manufacturing processes since production batches are smaller and human error is minimal. The customised design of products reduces the product's impact on the environment because, ergonomically speaking, less energy is required to use a product that has been tailor-made for a task at hand. In addition, products that are especially designed for a particular scenario are likely to last longer than a product designed for a more general function, again resulting in less waste in the long term.

2.3 Disadvantages of Additive Manufacturing

The main disadvantage of Additive Manufacturing processes is the low production speed compared to conventional (subtractive) manufacturing processes. In terms of the capability to quickly produce large batches of identical products, the Additive Manufacturing process does not measure up to current manufacturing process standards.

A second limitation is Additive Manufacturing machine design. Some machines are designed such that part accuracy is sacrificed for better production speed. This is a difficult problem to address because the low production speed is recognised as the biggest disadvantage of Additive Manufacturing, but part accuracy is still important. This trade-off should be avoided if possible. Part accuracy is an important factor that should not be disregarded because consistency and accuracy of parts are vital in the Aerospace, Automotive, Medical or Electronic Industries (Bourell *et al.* 2009).

Another major limitation on the development of the Additive Manufacturing industry is possibly the global market's resistance to change. The development of Additive Manufacturing in some areas of industry has been very gradual because the processes are expensive and time consuming relative to conventional methods of manufacturing. The limitations on part batch sizes are also a hindrance, as well as the high start up costs and risks involved in investing in Additive Manufacturing machinery (Wohlers 2010, Bourell *et al.* 2009).

The materials required for Additive Manufacturing are more costly per kilogram than those used for conventional manufacturing processes. Some materials are also difficult to purchase since the material requirements for Additive Manufacturing processes are quite specific. Additive

Manufacturing machines are expensive too because the technology is still relatively new, and maintenance costs of additive machines are high since the technical maintenance tasks involved often require highly skilled operators (Hopkinson *et al* 2006, Bourell *et al.* 2009).

The quality of additive manufactured parts is a challenge that needs to be addressed. Dimensional accuracy, material properties and surface finish measures are sometimes inferior to those achieved using conventional manufacturing methods. There may be multiple reasons for these inferior results and researchers are therefore developing comprehensive data about processing parameters and materials for Additive Manufacturing. Finished additive-manufactured parts are evaluated depending on a variety of factors such as material mechanical properties and surface quality.

The recent economic downturn had a negative impact on the Additive Manufacturing industry. The rate of product development in Additive Manufacturing has not yet returned to its pre-2008 level but it is on the rise again. The impact of the economic crisis on Additive Manufacturing could be related to the fact that it is still an emerging concept in the manufacturing industry that is viewed as a risky option for manufacturing when considering cost effectiveness (Wohlers 2010).

Additive Manufacturing machine vendors do not allow users to make necessary alterations to the set processing conditions. They have a closed architecture policy which benefits them because it ensures that their patented machinery and processes are being used as intended and their brand name is upheld, however this sometimes limits the manufacturing process (Bourell *et al.* 2009).

2.4 Descriptions of Additive Manufacturing Processes

All Additive Manufacturing processes use 3D CAD-based models. A 3D CAD model of the desired part is created and a Standard Triangulation Language (STL) file is then generated from that model. The file is loaded directly into the Additive Manufacturing machine and the part is then produced (Eyers *et al.* 2010). Compared to conventional manufacturing, Additive Manufacturing processes have very few technological constraints. One of the biggest constraints is the availability of the additive manufacturing material required by a specific additive manufacturing machine (Wohlers. 2010).

A Liquid-Based Process worth mentioning is Stereolithography. During the Stereolithography process, an acrylate-based, photo-curable resin is deposited into a vat and an ultraviolet laser causes a curing reaction in the resin. The laser is driven by the CAD design via the STL file to select sections of the resin that need to be cured and solidified according to the CAD part design. This process also involves a layer-by-layer construction of the part (Hopkinson *et al.* 2006).

Fused Deposition Modelling (FDM) and Laminated Objet Manufacturing (LOM) are two different Solid-Based Processes. Fused Deposition Modelling creates a part by extruding material (usually a thermoplastic polymer) through a nozzle that moves in the X and Y direction to construct each 2D layer. LOM involves the cutting and stacking of 2D sheets of various materials. The sheets are cut and bonded together and the waste is then removed (Hopkinson *et al.* 2006).

Powder-based processes involve the joining or binding of materials in powder form to create solid parts. There are numerous forms of powder-based Additive Manufacturing processes, but only a few are discussed (Hopkinson *et al.* 2006).

During the Selective Laser Sintering (SLS) process, the surface of a bed of powdered material composed of various different components is selectively scanned by a laser and sintered or 'joined' according to a CAD model, forming a solid layer. A new layer of powder is then added to the top of the powder bed so that a second layer can be sintered and bonded to the previous layer. A polymer binder is used to bind the material properly. In this way, the 3D part is created layer by layer. The un-sintered powder in each layer of the powder bed acts as supporting material (Hopkinson *et al.* 2006, Santos *et al.* 2006).

SLM is similar to SLS, except that its laser fully melts the powder layers which are composed of only a single component. This process is ideal for high density products with complex lattice structures. This discussion is continued in Section 3.1 (Hopkinson *et al.* 2006, Santos *et al.* 2006).

Direct Metal Laser Sintering (DMLS) is similar to Selective Laser Sintering because it sinters non-homogeneous metal powder. However, it differs from Selective Laser Sintering because the powder particles are sintered together when the lowest melting temperature of the various metal powder components is reached. This metal component of the powder essentially acts as a binder. In contrast, during Selective Laser Sintering, a polymer binder is added to bind the metal particles together (Hopkinson *et al.* 2006).

During the Three-Dimensional Printing process, layers of deposited powder are solidified using a liquid binder. The machine spreads layer of powder from a powder feed box to the cover surface of a build piston. The printer then prints a binder solution onto the loose powder from four print heads. The powder is subsequently glued together wherever the binder is printed and the residual powder remains loose and acts as a support for the next layers. The build piston is lowered when each cross section is complete. This process is repeated layer by layer until the part has been completed and finally the build piston is raised and the loose powder is removed (Hopkinson *et al.* 2006).

Electron Beam Melting (EBM) has a similar approach to SLM, except it uses an electron beam instead of a laser (Hopkinson *et al.* 2006).

Selective Mask Sintering involves printing a mask of infrared radiation reflecting material onto a glass sheet placed over a powder bed. Infrared radiation is then applied to the glass sheet and allowed to selectively pass through the mask and sinter the powder below (Hopkinson *et al.* 2006).

Another powder-based process that is currently on the market is Direct Metal Deposition. This process also uses a laser beam to create 3D Parts layer-by-layer. A laser beam is focused onto a previously deposited metal layer to form a melt pool and metal powders are then deposited into the melt pool by a separate nozzle. The system has a closed-loop control to maintain layer thickness and can manufacture relatively large parts (Dinda *et al.* 2009).

The Additive Manufacturing process that is of particular interest for this project is SLM of metals.

2.5 Industrial Applications

Consumer products, tooling and electronics have been the leading industrial sector in Additive Manufacturing for the past five years. Second on the list is the motor industry, followed by the medical/dental sector. Functional models still constitute the highest usage of additively manufactured parts in these industrial sectors (Wohlers 2010).

One of the earliest applications of Additive Manufacturing processes was the production of tools with special cooling channels for plastic injection moulding machines (Li *et al* 2010, Petrovic *et al.* 2011). Today, Additive Manufacturing is used to produce medical implants, orthopaedic products, dental products, hearing aids, forming tools, aerospace and automotive parts, electronics, video game avatars, art, jewellery, commercial lighting, three dimensional textiles and more. Research is currently being done involving the use of Additive Manufacturing in living tissue generation so the variety of industrial applications will continue to develop and expand in years to come (Hopkinson *et al. 2006*).

Additive Manufacturing machines can manufacture injection moulds with free-form cooling channels which produce high quality injected parts (Petrovic *et al.* 2011). Figure 1 shows an engine sump which was sand foundry equipment produced by a 3D printer. The complexity of the mould for this engine sump was easily accommodated by the 3D printing process since the part was manufactured layer-by-layer. Since the mould for the engine sump was relatively large, with dimensions of 500 x 330 x 270 mm, it was manufactured by building the five different sections of the part separately and later fusing them together. The dimensional and geometrical accuracy of this part was of particular importance and quality inspections were included in the 3D printing process of the engine sump mould to ensure that these requirements were met (Dimitrov *et al.* 2008).

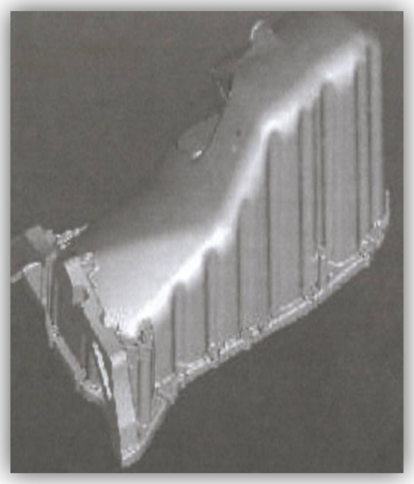


Figure 1: Engine Sump

Source: (Dimitrov *et al.* 2008)

Figure 2 shows an injection mould which contains laser sintered inserts. These complex inserts were manufactured in 290 hours total build time on a Direct Metal Laser Sintering machine (Langer *et al*. 2006).

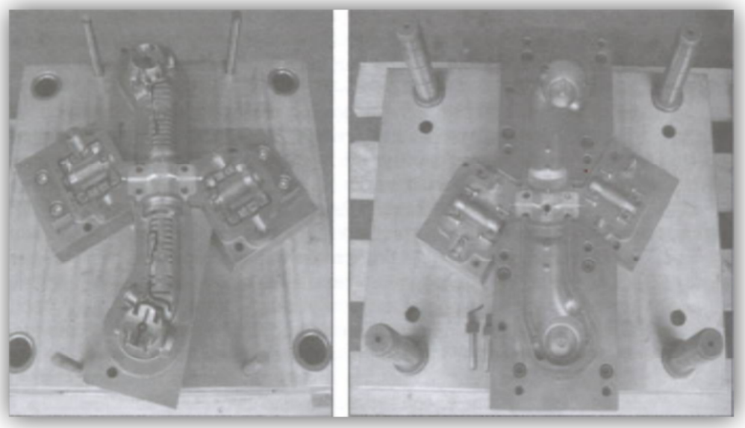
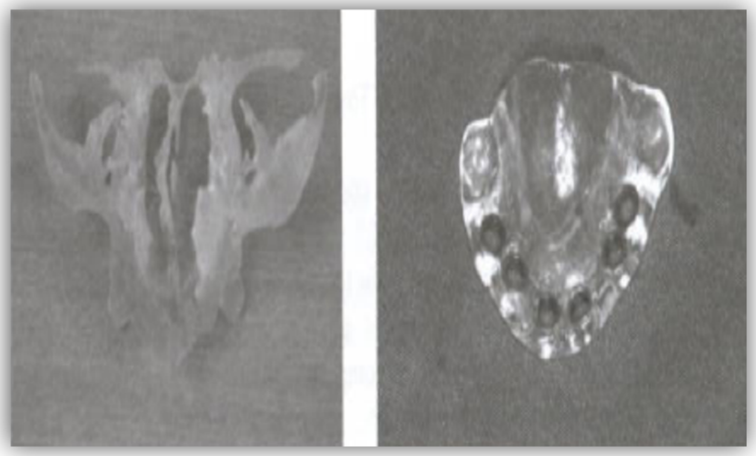


Figure 2: An injection mould containing eight laser sintered tool inserts

Source: (Langer *et al*, 2006)

There are many examples of medical and dental applications of Additive Manufacturing. Implants, prosthetic limbs, hearing aids and dental crowns are all small parts that have low production runs that need to be customised to fit the patient comfortably. These requirements make the products well suited for Additive Manufacturing (Bibb *et al.* 2011).

Figure 3 shows a photograph of two models that were manufactured using Additive Manufacturing techniques for utilization during dental surgery. Figure 3a is a picture of a model of a dental patient's maxilla; the bones that are fused together to form the upper jaw. This model could be studied by the dental surgeon in preparation for a dental implant operation, saving the patient from any unnecessary trauma during the operation. Figure 3b shows a picture of a dental drill guide that was manufactured to be used during surgery to ensure that holes were drilled in the correct positions for a successful dental implant (Dimitrov *et al.* 2008).



a) Model of a patient's maxilla b) Drill guide model

Figure 3: Dental Applications

Source: (Dimitrov *et al.* 2008)

Medical models that are created using Additive Manufacturing techniques can be studied and utilized in the medical industry to improve surgery results and times. More specifically, the use of models in preparation for facial reconstructive surgery has proven beneficial. Figure 4 shows a medical model of a patient's bone tumour. In this case, the tumour was exerting pressure on the patient's mandible, causing facial damage. Studies were done to investigate the benefits of using this model for surgery preparation and bone graft modelling during operations and it was found that surgery times could be reduced (de Beer *et al*, 2008).

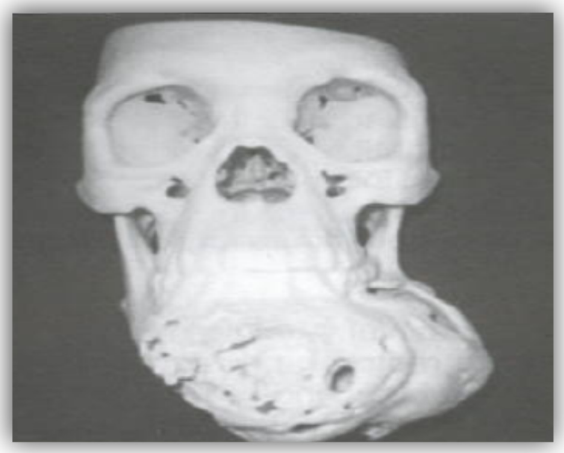


Figure 4: Medical model of a patient's bone tumour

Source: (de Beer et al, 2008)

These are just a few examples of the industrial applications of general Additive Manufacturing. Section 3.3 discusses some examples of industrial applications of SLM.

3. The Selective Laser Melting Process

3.1 Detailed Description of the Process

As mentioned before, the SLM and SLS processes are very similar, except that SLM is used to create parts of uniform material by fully melting the powder particles. This enables the full melting of powders to create high density solid parts that do not often require downstream finishing processes. SLM is known as a successful Additive Manufacturing process for manufacturing metal parts in particular.

Figure 5 is an illustration depicting the SLM Process. The internal structure of the machine consists of a powder bed, a piston, a powder feed, an x-y scanning device and a laser, as can be seen in Figure 5 (a) and (b). The SLM of Aluminium or Titanium requires an inert atmosphere; usually either nitrogen or argon gas is present. The part is automatically created directly from CAD data that has been subdivided into layered sections. Each layer of material has a height of approximately 50 um. The first thin layer of powder is deposited directly onto a substrate plate by the powder container. The surface of the layer of powder is smoothed out by the blade inside the powder container. This layer of the part is selectively melted by the laser beam using the x-y scanning device and the piston is then lowered by one layer thickness. The particles that have been melted solidify to form the first layer of the part and any particles untouched by the laser beam remain loose. A new layer of powder is added to the powder bed and this layer is solidified in the same way and is simultaneously bonded to the previous layer. This process is repeated until each layer of the CAD design has been formed with alternating scan directions after each layer to prevent imperfections from developing (Hopkinson *et al.* 2006, Santos *et al.* 2006).

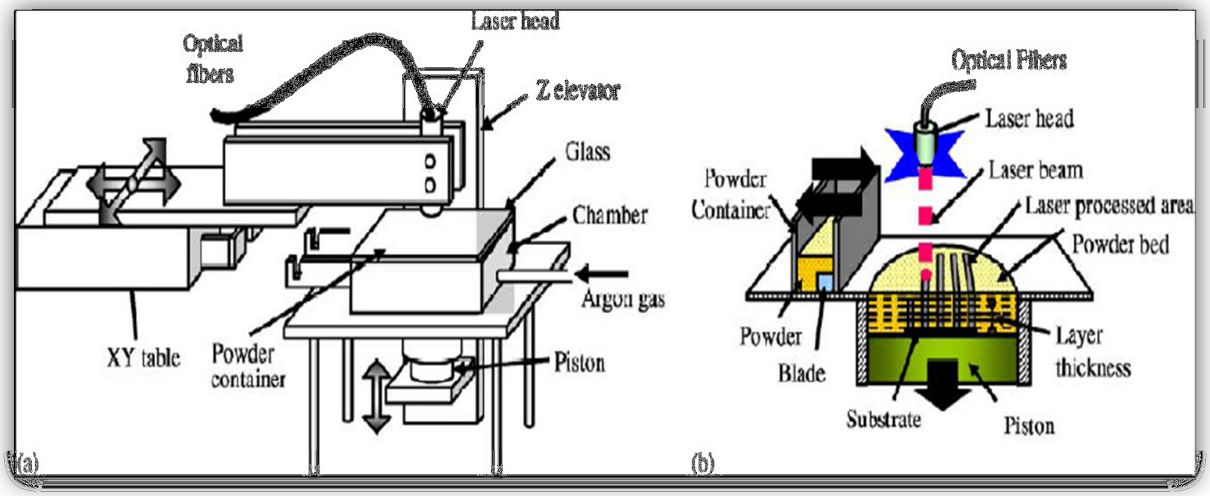


Figure 5: Selective Laser Melting Process

Source: (Santos et al. 2006)

The final result of the SLM process is close to 100% dense finished products with intricate geometries. Once the part is complete, any loose powder is removed and may be recycled depending on the material type (Hopkinson *et al.* 2006, Santos *et al.* 2006).

Products that have been manufactured using a SLM technique need to meet various quality-related requirements. High density, mechanical properties matching those of products manufactured using conventional subtractive techniques and high surface quality must be achieved. In addition to these quality requirements, the manufacturing process must be economic, meaning that the production process must be as fast as possible. The SLM process is sensitive to various parameter variations such as powder layer thickness, laser power, the diameter of the laser beam, laser scanning velocity and laser scanning intervals. There is also a correlation between the particle size, shape and distribution and the final part density that should be taken into consideration. The use of coarse powder particles result in a rough surface, which is not ideal, since further finishing processes then have to be done to produce a satisfactory final product. Also, finer particles result in higher density final parts with lower power requirements and better mechanical properties are also achieved when fine powder particles are used. This is because fine particles are easier to melt than coarse particles. However, there is a tendency of increased ductility in parts with a certain amount of larger particles in the powder mix. A good particle size distribution in the powdered particles is required for high density parts with a good surface finish, good mechanical properties and some ductility (Spierings *et al.* 2011).

3.2 Machinery and Materials

There are a few different companies that produce SLM machinery, and their respective machines are all slightly different in physical structure and manufacturing procedure, but the main concept of the technique is the same. The M2 Laser CUSING machine will be discussed in detail.

Electro Optical Systems released the EOSINT M 270, a Direct Metal Laser Sintering machine, which is capable of processing many materials such as steel, cobalt chromium, titanium alloys, bronze-based alloys, nickel-based alloys and more. Finally, Concept Laser owns the patent for Laser CUSING, another SLM technology. Concept Laser has released three different machines; the M1, M2 and M3. The M1 and M3 machines can process stainless steel and tool steel, whilst the M2 machine can process non-ferrous, reactive powder materials like titanium and aluminium as well as stainless steel and tool steel and more.

In this project, the M2 Laser CUSING machine capabilities will be compared to the capabilities of the EOSINT M 270 machine. The M2 Laser CUSING machine is shown in Figure 6 and the EOSINT M 270 machine is shown in Figure 7.

The M2 Laser CUSING machine has dimensions of 2440 x 1630 x 1992 mm, has a build area of 250 x 250 x 280mm and a production speed of 0.56-5.6 mm^3/s, depending on the type of material being processed (www.concept-laser.de). The M2 machine has some added safety requirements since it processes powdered materials that could react with any oxygen present in the atmosphere. These safety features include sensors that monitor the oxygen and inert gas atmosphere levels throughout the machine and storage and handling systems that ensure that the up to two materials are stored in an inert atmosphere and transferred from the build chamber to the storage chamber quickly. The M2 laser is a 200W fibre laser which results in final parts with high quality mechanical properties and highly complex designs (www.concept-laser.de).

The EOSINT M 270 machine has a build area of 250 x 250 x 215mm, a production speed of 2-20 mm^3/s, depending on the material being used. This machine has a 200W, fibre laser (www.3trpd.co.uk). Table 1 shows a summary of the comparative capabilities of these two machines.

Figure 6: M2 Laser CUSING Machine

Source: (www.concept-laser.de)

Figure 7: EOSINT M 270 (DMLS) machine

Source: (www.3trpd.co.uk)

Table 1: Table comparing the EOSINT M270 and M2 Laser CUSING machines

	EOSINT M270	**M2 Laser CUSING**
Laser Type:	Yb-fibre laser, 200 W	Fibre laser 200W (cw)
Layer Thickness (material-dependent):	20 - 60 µm	20 - 50 µm
Effective Building Volume (including building platform):	250mm x 250mm x 215mm	250 x 250 x 280 mm
Building Speed (material dependent):	2 - 20 mm³/s	2 – 20 cm3/h (approx 0.56 - 5.6 mm³/s)
Scan Speed:	up to 7.0 m/s	up to 7.0 m/s
Variable Focus Diameter:	100 - 500 µm	70 – 200 µm

3.3 Typical Industrial Applications of the Selective Laser Melting Process

SLM is mostly used in the tooling industry. The capability of SLM machines to create parts with intricate interior geometries makes them ideal for manufacturing tooling with complex interior cooling channel systems.

Automotive, aeronautical and aerospace applications of SLM are lightweight, complex, metal components for aerodynamic improvements. In these applications surface roughness, shape and temperature considerations are the most important factors involved to ensure that the part is aerodynamic and can withstand extreme temperatures.

Medical instruments and some medical implants and dental products are also manufactured using the SLM method. These products are small, complex and they have to be customised for specific patients, so the use of the SLM process is ideal. Titanium in particular is a good material to use to make implants because it is noncorrosive in the human body, and titanium can now be processed using the M2 Laser CUSING, MCP-HEK Realizer or EOSINT M 270 machines (www.concept-laser.de).

3.4 Conclusion

The Additive Manufacturing industry as a whole requires some rapid development itself in order to become an industry that is capable of competing with conventional Subtractive Manufacturing techniques. Production times and costs both need to be reduced in order for the technique to become a viable alternative to conventional manufacturing processes of parts with short production runs for a wider variety of applications. However, Additive Manufacturing has the potential to develop and expand in the future, and there are many new and exciting applications in the medical industry as well as many other industries that are currently being explored. The design potential that is introduced by Additive Manufacturing is something that the manufacturing industry has not been exposed to before, and it will lead to advancements in product design in the near future.

SLM is useful for the manufacturing of highly complex parts from powdered materials. The M2 Laser CUSING machine in particular seems to have an important niche in the Additive Manufacturing industry, particularly because of its ability to process metals like aluminium and titanium. Titanium in particular is useful in medical applications because it is non-corrosive in the human body. The capability profile of this Laser CUSING process is required for the optimised use of the machine in various application areas such as the tooling, automotive, aerospace and medical industries.

4. Process Capabilities of Selective Laser Melting Based Machines – A Literature Study

4.1 Introduction

A literature study was carried out to compare the capabilities of Selective Laser Melting (SLM), Direct Metal Laser Sintering (DMLS), Laser CUSING and Electron Beam Melting (EBM) machines. The aim of this literature study was to determine the limitations of each of these additive manufacturing machine types. Although SLM and Laser CUSING processes are technically the same, it must be stated that the capabilities of the two machines were compared, not the capabilities of the processes involved. The capabilities under consideration were dimensional and geometric accuracy, surface roughness, minimum wall thickness, minimum hole and cylinder diameters, various mechanical properties and manufacturing time and cost. Determining the advantages and disadvantages of these different types of additive manufacturing machines was useful in order to identify their potential industrial applications.

Three case studies comparing the capabilities of the different additive manufacturing processes were analysed during this literature study. The first case was based on an article which compared the benchmarks manufactured by five additive manufacturing machines including an MCP-HEK (SLM), a Concept Laser (Laser CUSING) and an EOS machine (DMLS) which are relevant to this literature study (Kruth *et al.* 2005). The second case was based on an article which also compared the products of five machines, with the Concept Laser M3 Linear (Laser CUSING), MCP-HEK Realizer (SLM), EOSM250X (DMLS) and ARCAM (EBM) machines being applicable to this literature study (Abdel Ghany *et al.* 2006). Unfortunately the EBM machine was unable to manufacture the benchmark in case 2 and the reason for this had to be investigated. Finally, case 3 was based on a comparative capability study of a benchmark manufactured by four different machines including a Concept Laser M3 Linear (Laser CUSING) machine and a MCP Realizer (SLM) machine (Castillo. 2005).

Similar testing procedures were carried out during each case study. Benchmarks that were specifically designed for the capability studies were manufactured by each machine and the dimensional and geometric accuracy, mechanical properties and other parameters of these samples were measured and discussed in order to determine the different machine limitations. The raw materials used to manufacture each sample varied, as did the powder characteristics and the process parameters. The best combination of raw materials, powder characteristics and other process parameters should have been selected to ensure that each machine's capabilities were properly represented by their samples.

The choice of raw materials has an impact on the resulting hardness and strength outcomes of the sample, whilst the density of the sample is dependent on various process parameters such as layer thickness, particle size and building speed (Abdel Ghany *et al*). A large laser beam diameter can also place limitations on the ability of the machine to produce thin walls and holes and cylinders with small diameters and to achieve good geometric accuracies. This can be compensated for by using offset and scaling values (Kruth *et al*). Warpage, which is the distortional change in a processed part once it has been completed, is caused by inhomogeneous shrinkage and it depends on the material properties, benchmark geometry and process conditions.

In some cases the optimum parameters were selected by manufacturing a few iterations of the benchmark with slightly altered parameters and identifying the best alternative. In other cases the parameters recommended by the manufacturers were implemented. Case 1 involved a few iterations of the benchmark tests to reach the optimum processing parameters, whereas in case 2 only the set of processing parameters recommended by the machine manufacturers was used. In case study 3 an optimum set of processing parameters was used, although it is unclear how these optimum parameters were identified.

4.2 Methods of Research

In this literature study, the process capabilities in three case studies were compared and assessed. The methods that were used to conduct each case study were discussed, and so were the results and conclusions relative to each case. Since benchmarks with different dimensions and testing capabilities have been used, the results of the three different cases were not directly compared. However the limitations of the different additive manufacturing machines discovered during each respective case study were compared and evaluated.

4.2.1 The Purpose of the Benchmark Models

Each benchmark was designed specifically to demonstrate the processing capabilities of the machine being studied. Dimensional and geometric accuracy was measured on the sloping planes, curved surfaces, thin planes, planes positioned at different angles, overhangs, small holes, cooling chambers and cylinders, sharp corners and edges, and fine details added to the benchmarks for this particular purpose.

The sloping planes and curved surfaces demonstrated the stair effect, an unfortunate characteristic of additively manufactured parts, which is the separation of the layers of material once the benchmark has cooled and solidified. This is an undesirable characteristic since it lowers the quality of the part and can cause the formation of serious cracks. The thin planes demonstrated the machine limitations with regards to minimum wall thickness capabilities and they also reveal any distortions present in the benchmark, like curling. Curling can be caused by the contraction of the material upon cooling and the high thermal gradients that are present (Kruth *et al. 2005*). The addition of angled planes to the benchmark design allowed an understanding of the machine's ability to construct angled planes layer by layer. There are often difficulties involved in the construction of angled planes because consecutive layers are not laid directly on top of one another so the binding of the layers can be troublesome and supports might be necessary to hold the planes in position until they have cooled and hardened (Castillo. 2005). Certain machines may also be unable to build overhang planes because of the same problem. Small holes, cooling chambers and cylinders were used to establish the minimum dimensions and the accuracy of these features that are achievable by the machines. The sharpness of corners and edges was also measured or assessed to identify process limitations due to the accumulation of heat at the tips of these angles and to determine any scanning errors. The accuracy of fine details was visually assessed.

The benchmark models needed to be large enough so that adequately sized test samples for the required hardness and tensile tests could be sliced off and tested, but small enough to reduce the manufacturing time, so that conclusions could be drawn quickly.

4.2.2 Evaluation Procedures

Most of the process capabilities being studied in this literature study were quantitative and were therefore easily discussed and evaluated. These measureable capabilities include dimensional accuracies of holes, cylinders and walls, surface roughness, hardness and tensile strength measures and manufacturing times. However the presence of some physical distortions (such as the stair effect and curling) and the accuracy of some features (like overhangs, fine details and sharp edges and corners) were assessed in a more qualitative manner. Corners and edges were classified as "very blunt", "blunt", "sharp" and "very sharp" in case 2. Meanwhile, sharp corners in case 1 were classified as "good" or "too short", overhangs were classified as "good" or "badly built" and distortions like the stair effect and curling were classified as either "good" or "bad". This was taken into account when a conclusion was drawn about machine limitations because the classification of a specific corner as blunt or sharp may vary from one examiner to the next and different criteria were also used in different cases.

4.3 A Description of the Case Studies

During each case study, a specific benchmark was manufactured by all of the additive manufacturing machines and then an evaluation of each machine's process capabilities was performed based on the measurements taken from the respective sample. The features of the benchmarks and the capability testing procedures were discussed for each individual case. The different benchmark specifications for each case were summarized in Table 2.

4.3.1 Case Study 1

Case study 1 involved the analysis of the process capabilities of an MCP-HEK (SLM), a Concept Laser (Laser CUSING) and an EOS (DMLS) machine by using the part shown in Figure 8 as a benchmark.

The benchmark dimensions were 50 x 50 x 9 mm, which is relatively small to enable faster manufacturing times. Mechanical tests were performed on sections cut out of the left half of the benchmark and geometrical and dimensional accuracy was evaluated using the geometrical features on the right half specifically designed to demonstrate these capabilities. These geometrical features are labelled on the Figure 8. The benchmark had a sloping plane and a curved surface that showed any traces of the stair effect. The purpose of the thin plane (which had a thickness of 2mm) was to show any signs of warpage or curling in the benchmark due to thermal stresses. Small holes and cylinders with diameters ranging from 0.5 to 5 mm, thin walls ranging from 0.25 to 1mm thickness and sharp angles ranging from 14° to 45° were all used to measure process accuracy. Overhanging surfaces were present in the benchmark as the ceilings of the circular and rectangular caves along the side of the part. The overhangs were designed like this to prove or disprove the capability of each machine to produce overhangs without the need for support structures.

The surface roughness was measured on a Taylor Hobson Form Talysurf roughness meter with a cut-off length of 2.5mm. Only the Ra values were taken into account for this literature study and the surface roughness measurements have been taken on unfinished surfaces for the SLM and DMLS machines' benchmarks, and on the finished surface of the Laser CUSING machine's benchmark. Measurements were taken in different directions to ensure an accurate evaluation of the part. Density measurements were taken using the Archimedes principle. This principle required the part to first be weighed in air and then in ethanol and the part density was then calculated using these measurements and the density of ethanol. Tensile tests and hardness tests were also performed on these benchmark parts. An Instron 4467 machine was used to do three point bending tests, following the ASTM B312 standard. Yield strength and Young's modulus measurements were taken.

The hardness test used a Vickers indentation with a 100g load on a universal testing machine (Kruth *et al*. 2005).

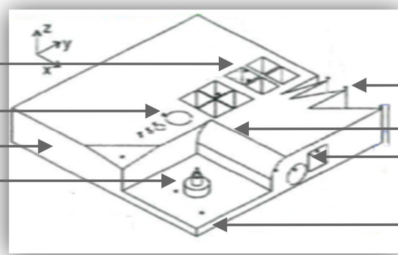


Figure 8: Benchmark for case 1

Source: (Kruth *et al*. 2005)

4.3.1.1 Sample 1

Sample 1 of case 1 was manufactured using an MCP-HEK machine, which is a SLM machine. As discussed in section 1, SLM processes involve the full melting of the material, which was stainless steel 316 in this instance. This machine fabricates parts with a layer thickness of 50 µm, (the greatest layer thickness in case 1) and it has a laser power of 100 W. The layer thickness is related to the laser beam diameter, and large laser beam diameters generally have a negative effect on dimensional and geometric accuracy.

4.3.1.2 Sample 2

The second sample in case 1 was manufactured using an EOS (DMLS) machine. Direct Metal Laser Sintering processes partially melt the powdered material with no aid of an added binder polymer. This sample was made of a bronze based material, so it was expected to have had a faster manufacturing time than the rest of the benchmarks, which were made of steel based materials. The layer thickness is only 20 µm and the laser power is 221 W (slightly higher than the other machine laser powers in case 1). This machine scans the core of the sample much faster than it scans its outer surface to save time. Some inner layers are not scanned at all.

4.3.1.3 Sample 3

The final sample in case 1 was a Laser CUSING manufactured part. This process also involves the full melting of the powder particles (as previously mentioned, Laser CUSING and SLM processes are the same). The material used to manufacture sample 3 was hot work tool steel, the layer thickness is 30 µm and the laser power is 100W. An ultrasonic filing post process was done on this benchmark.

4.3.2 Case Study 2

Case study 2 examined the process capabilities of an SLM machine, a DMLS machine, a Laser CUSING machine and an EBM machine, as well as some other additive manufacturing machines that were irrelevant to this literature study, by using the part shown in Figure 9 as a benchmark. Unfortunately the EBM machine was incapable of manufacturing the benchmark part. This was believed to be because its electron beam has a larger diameter than the laser beams of the other machines, making it impossible to create the fine details such as the fine holes, thin walls and sharp edges.

The benchmark dimensions were 200 x 100 x 40 mm. It was the design for one half of a glass bottle die with complex geometrical features like holes and cylinders with diameter ranges of 0.5 to 2mm and text with sharp edges (which can be seen in Figure 9). The curved surface of the benchmark indicated any signs of the stair effect. In case 2, only a visual inspection was done to determine the dimensional and geometric accuracy of the benchmarks, and an overall dimension change of the benchmark was stated.

Mechanical properties were measured on slices cut off the benchmark. Again, the Archimedes principle was used to measure the density benchmarks however in this case water was used in the tests instead of ethanol. Hardness tests also uses a Vickers indentation and measurements were taken from unfinished inside surfaces once the parts were cut. The surface roughness measurements were taken from the finished surfaces of benchmarks 2 and 3, whilst the surfaces of benchmark 1 were unfinished and its surface roughness measurement was therefore much higher. Again, only Ra values were taken into account for this literature study. Manufacturing and finishing times were also measured. Manufacturing times included setup times.

There were no iterations of the benchmark manufacturing process performed to obtain optimum results for each additive manufacturing machine, as in case 1. The processing parameters recommended by the manufacturers were applied and the benchmarks were produced accordingly (Abdel Ghany *et al*. 2006).

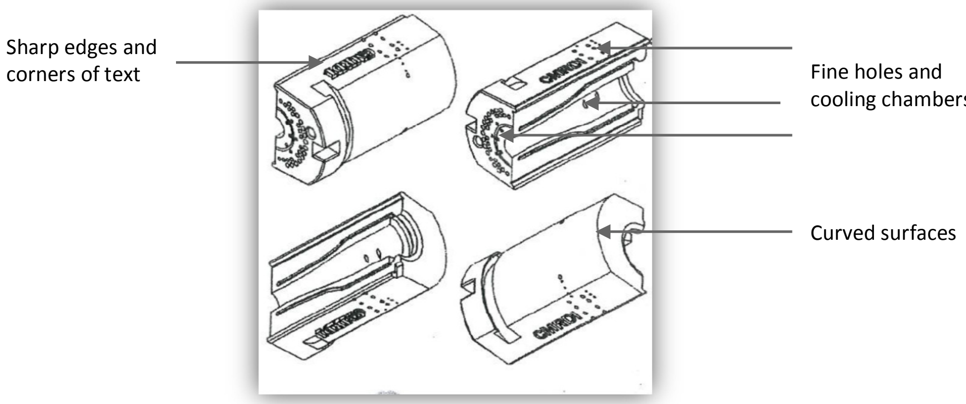


Figure 9: Benchmark for case 2

Source: (Abdel Ghany *et al*. 2006)

4.3.2.1 Sample 1

This first sample was manufactured by an SLM machine (more specifically a MCP-HEK Realizer). It was composed of stainless steel powder which has been fully melted. The layer thickness was 50 µm and at the time of the study, the material required for sample 1 cost $170 and the power consumed during the manufacturing process was 4 KW. Both the material cost and the power consumption of sample 1 were low compared with those of the other three samples, making it the cheapest one to produce. This sample was an unfinished part, which may explain higher surface roughness measurements than the rest of the samples.

4.3.2.2 Sample 2

Sample 2 was a DMLS-produced part which means the powder material was partially melted, but no polymer binder was required either (only Selective Laser Sintering processes require a polymer binder for the manufacturing of solid parts). Sample 2 was composed of DSH20 material which is a high strength steel. Boron and copper were also present in the material to aid the sintering of the metal particles at low temperatures. It was manufactured by an EOSM250X machine with material layer thickness specifications of 20 µm, this was the thinnest layer thickness of all of the samples in case 2. The cost of sample 2's raw materials was $252 and its manufacturing process consumed 6 KW of power.

4.3.2.3 Sample 3

This sample was manufactured by a M3 Linear Laser CUSING machine that was manufactured by the company Concept Laser. The Laser CUSING process also involves the full melting of powdered particles to produce a high density part. This particular part was made of CL 50 WS (hot work steel) and the machine's sample had a layer thickness of 30 µm and a raw material cost of $551 (this is by far the highest sample material cost in case 2). The power consumed during the manufacturing process was 7.5 KW (this is also the greatest recorded power consumption of the samples in this case).

4.3.2.4 Sample 4

Interestingly, sample 4 was not successfully manufactured. Sample 4 was supposed to be manufactured by an ARCAM EBM machine. The major difference between the Electron Beam Melting machine and the machines used to produce the other benchmarks was that it used an electron beam instead of a laser beam and this electron beam has a much greater beam spot diameter than laser beams do. EBM machines also utilise a high electron beam power source of 3000 W compared to the 200 W laser beam power source. The powerful energy source enables the machine to manufacture parts much quicker than machines that utilise laser beams, but it may have been part of the reason why this particular sample could not be manufactured. The heat generated by this powerful electron beam energy source may have caused the loose powder that is not intended to be solidified to form part of the sample, to melt. This would cause major shape distortions, making the sample impossible to manufacture. Also, the high manufacturing speed of the EBM machine may not be conducive to the fabrication of parts with fine details such as the small holes and cooling chambers, wall details and the sharp-edged text evident in case 2's sample. (Eyers *et al*. 2010, Bourell *et al*. 2009, Petrovic *et al*. 2011)

Further, the lack of iterative benchmark studies during case 2 may also have contributed to the failure of this manufacturing process.

4.3.3 Case Study 3

Case study 3 examines the process capabilities of a SLM machine and a Laser CUSING machine, as well as some other additive manufacturing machines that were irrelevant to this literature study, by using the part shown in Figure 10 as a benchmark.

The benchmark dimensions were 60 x 100 x 81 mm. This benchmark design had a number of planes positioned at different angles in the shape of an open book. This feature enabled the study of angle accuracy of 0, 15, 30, 45, 60, 75 and 90 degree angles. Angle accuracy was tested because many additive manufacturing machines have difficulty building features at specific angles. The planes themselves had varying thicknesses and this enabled the study of wall thickness accuracy and minimum wall thickness capability. Different sized circular towers and holes with various different diameters were also included in the design and these dimensional accuracies were analysed. These circular towers also tested the samples' tendency to crack. Internal stresses due to layer defects in high parts can cause cracks. Holes with various diameters were added to the benchmark model in the XY, XZ and YZ plane to test the machines' ability to build differently oriented features. The building of features in the XY plane is easier than building the same features in the XZ or YZ plane because of layer slicing in the Z direction. An overhang feature was present in this benchmark as labelled in Figure 10. The warpage of a sample was tested in the benchmark base's table shape. There is a wall thickness transition in the base from 10 mm to 15 mm which has an influence on the heat transfer within the part and thus the tendency of the part to undergo warpage. The dimensional accuracies of these samples were measured using a digital calliper.

The samples' mechanical properties were tested on the angled planes (the pages of the open book) which were sliced off for this purpose once the measurements for the dimensional and geometric accuracy have been taken. Hardness Vickers tests were performed on a Wolper V-Testor 2 and tensile tests were performed according to standard ISO 6892 by cutting the detached angled planes from the benchmark into the specified size. The building time of each technique is also measured, but this does not include finishing time or support removal time (Castillo. 2005).

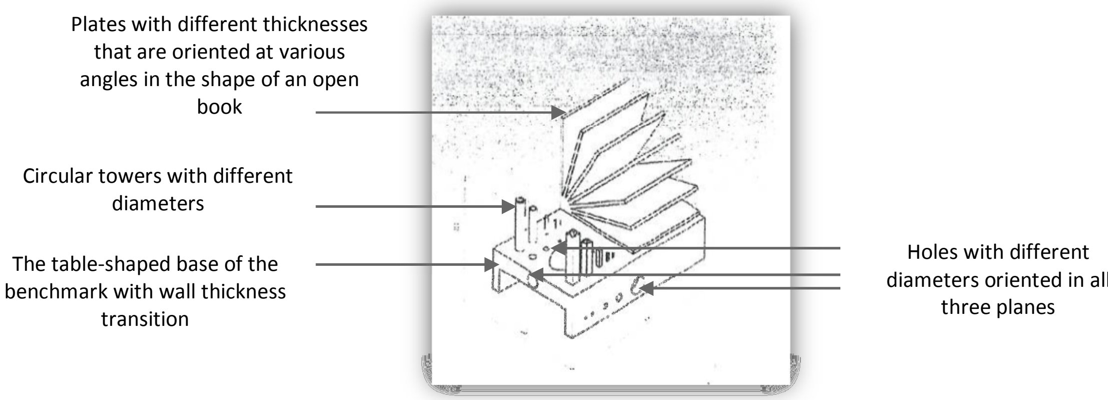


Figure 10: Benchmark for case 3

Source: (Castillo. 2005)

4.3.3.1 Sample 1

Sample 1 was manufactured by a SLM machine, namely the MCP Realizer machine. The material used to make the sample is AISI 316L stainless steel. This machine manufactures parts with a layer thickness of 75 µm. Supports were required in order to manufacture the overhang and all of the angled planes positioned at angles below 45 degrees. These supports needed to be removed after the manufacturing process and the sample also had to be removed from the building platform that was used during the manufacturing process.

4.3.3.2 Sample 2

A Laser CUSING machine, namely the Concept Laser M3 Linear machine, was used to manufacture sample 2. The material used to make the sample was also AISI 316L stainless steel. The layer thickness of parts manufactured by this machine is 30 µm. Sample 2 was built at a 135 degree angle and it also required the addition of supporting structures to build the overhang feature and some of the angled plates. The 135 degree building orientation of the sample means that warpage can't be studied. This sample was finished using the micro blasting process.

Table 2: Summary of the benchmark process parameters of all three cases

Case Number	1			2				3	
Sample Number	1	2	3	1	2	3	4	1	2
Machine Type	MCP-HEK (SLM)	EOS (DMLS)	Concept Laser (Laser CUSING)	MCP-HEK Realizer (SLM)	EOSM250X (DMLS)	Concept Laser M3 Linear (Laser CUSING)	ARCAM (EBM)	MCP-HEK Realizer (SLM)	Concept Laser M3 Linear (Laser CUSING)
Material	Stainless steel 316	Bronze based material	Hot work tool steel	Stainless steel	DSH20 (hi strength steel)	CL 50 WS (hot work steel)	N/A	AISI 316L stainless steel	AISI 316L stainless steel
Layer Thickness	50 µm	20 µm	30 µm	50 µm	20 µm	30 µm	N/A	75 µm	30 µm

4.4 Discussion and Results

The process capabilities of the machines evaluated in case 1, case 2 and case 3 are shown in tables 3, 4 and 5 respectively. No process capability data has been collected for EBM machines because, as discussed in section 2.3.2.4 above, the benchmark in Figure 9 couldn't be manufactured by the EBM machine.

Generally speaking, the SLM, Laser CUSING and DMLS additive manufacturing machines performed well in two of the three cases that were analysed. The manufactured samples were good quality parts with high dimensional and geometric accuracies, adequate mechanical properties, acceptable surface roughness measurements and acceptable minimum wall thicknesses and hole diameters. However, in case 2, both the DMLS and SLM benchmarks were not built well. These results could have been improved by selecting processing parameters based on an iterative benchmark manufacturing procedure in which different combinations of processing parameters were tested.

Although no total manufacturing costs have been calculated for any of the three cases, the manufacturing times give some indication of the variable costs incurred during the manufacturing process.

The process capabilities were further analysed to determine the limitations and advantages of each machine type and these were then used to identify appropriate industrial applications that are suited to these capabilities.

4.4.1 Dimensional and Geometric Accuracy

The average length variation values were calculated for the benchmarks in all of the case studies using the measured dimensions of the different lengths, hole diameters, cylinder diameters and angle accuracies. The original measured dimensions are shown in Appendix A. Figure 11 shows the average (absolute) dimension deviation in graphical form. It is clear that the SLM machine is slightly more limited in dimensional accuracy capability than the Laser CUSING or DMLS machines.

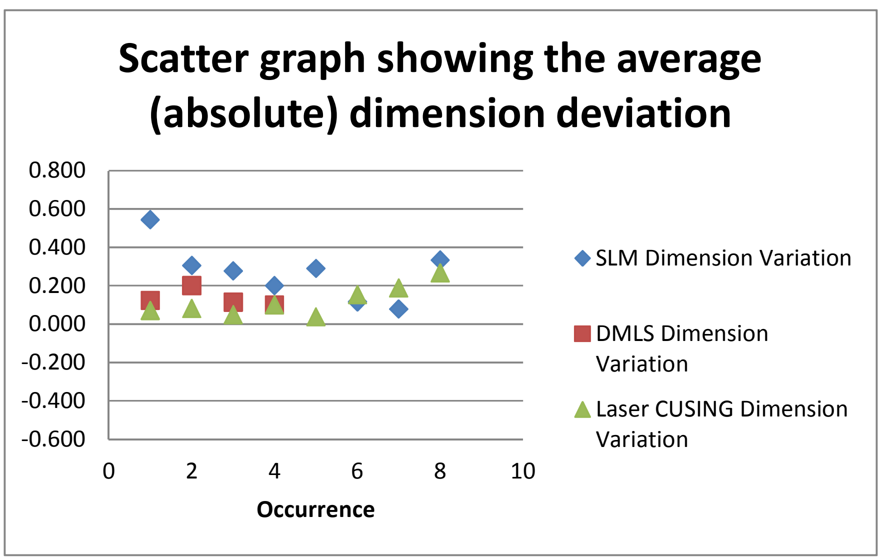


Figure 11: Dimension deviation graph

In case study 1 the average hole diameter variation only included the measurements of diameters greater than 1mm because not all of the machines were able to accurately create holes with diameters of 1mm and below. This is because the loose powder enclosed within the small area of the hole is melted by the surrounding heat, distorting the hole's shape (Kruth *et al*. 2005).

The dimensional and geometric accuracy of the benchmarks in case 2 have not been measured, they have been classified into categories according to the writers' judgement and this must be taken into account when including these results in the project conclusion. As mentioned, iterations of the benchmarks with differing processing parameters were not performed in case 2. Instead, the processing parameters recommended by the manufacturer were used and these recommended processing parameters were not ideally suited to case 2's benchmark for the SLM and DMLS machines. One processing parameter in particular that could have caused the vast discrepancies between the Laser CUSING machine's benchmarks (benchmark 3) and the SLM and DMLS machines' benchmarks (benchmark 1 and 2) is the production speed. As shown in Table 4, the manufacturing time of benchmarks 1 and 2 was nearly half that of benchmark 3. If the production speeds of the SLM machine and the DMLS machine had been reduced, perhaps the benchmarks would have been more successful.

SLM

In case 1, the SLM machine produced a sample (Sample 1) with slightly less accurate dimensions than the DMLS or Laser CUSING machines. The stair effect was visible in sample 1. The stair effect varies proportionally with the layer thickness and the SLM machine had the greatest layer thickness parameter of the three machines, as can be seen in Table 2. Bad overhangs were built, however this is believed to be due to the process's metal melting binding mechanism, since all of the overhangs in the samples in case 1 were badly built. The theory is that the high power lasers used in machines with metal melting binding mechanisms don't allow the bottom surfaces to solidify properly causing the near-horizontal overhangs to collapse without the aid of supporting structures. Sample 1 also had badly built (i.e. blunt) sharp corners. Sharp corners are difficult to build because heat accumulates at the points and the feature does not solidify properly as a result. Sharp corners require successful scanning strategies to avoid this heat accumulation and in this case the SLM procedure didn't include a scanning strategy that could adequately prevent the formation of a blunt corner (Kruth *et al*. 2005).

In case study 2, the SLM machine produced a sample (Sample 1) with incomplete cylinders and holes and rough edges and corners. The initial visual inspection resulted in sample 1 being declared "unacceptable" because it was missing numerous details. No fine details were visible, the stair effect was evident in the curved surface of the part and there were surface & deep cracks in the benchmark. Since this SLM machine uses the same technology as the Laser CUSING machine, which performed well in case 2, the sample's problems can be attributed to the adjustment of the machine's processing parameters.

Although the overall results of sample 1 (manufactured on a SLM machine) in case 3 were good, the sample showed alarming signs of warpage, and this is due to inhomogeneous material shrinkage and it is subject to material properties, benchmark geometry and process conditions. Again, since the design of the sample is not being studied in this project and the Laser CUSING machine's sample (sample 2) was free of distortions and both systems utilised the same powder material, the warpage of sample 1 can only be blamed upon the lack of iterative benchmark testing or at least the inaccurate selection of processing parameters.

DMLS

Sample 2, which was manufactured on a DMLS machine, had relatively accurate lengths, holes and cylinders in case study 1.

In case study 2 the DMLS and Laser CUSING machines' samples again had the smallest overall dimension changes, however the initial result of sample 2's visual inspection was unsatisfactory because the sample was missing fine details like thin walls, grooves and text details and there was a separation between the surface layers and the core. The inability of the machine to create these fine details may also be due to non-ideal processing parameters. Again, since the processing time of sample 2 was so much shorter than that of sample 3, one possible cause for this limitation may be a production speed that is too fast.

Laser CUSING

In case study 1, the length, hole and cylinder variations of the Laser CUSING machine's sample were relatively accurate.

The DMLS and Laser CUSING machines' samples had the smallest overall dimension changes in case study 2 and had good initial visual inspection results. Of the three benchmarks studied in case study 2, only the Laser CUSING machine's sample (sample 3) had very accurate fine details (Abdel Ghany *et al*. 2006).

In case study 3, the dimensional and geometric accuracies of the samples manufactured by the SLM and Laser CUSING machines (sample 1 and 2 respectively) were similar, with low dimensional variations. Both the SLM and Laser CUSING machines produced samples with fairly accurate angles and all the critical geometries were well built in both cases.

Overall, the Laser CUSING machine consistently produced samples with good dimensional and geometric accuracies. The DMLS machine also produced samples with acceptable accuracies and unfortunately the SLM machine's dimensional and geometric accuracies were the worst of the three. In each case the SLM machine had the greatest layer thickness (50 µm in case 1 and 2 and 75 µm in case 3) and this helps to explain the samples' inaccuracies. In addition, both the DMLS and the SLM machines had much quicker manufacturing speeds than the Laser CUSING machine in all three cases. Manufacturing speeds that are too fast cause scanning errors, and these might have contributed to the inaccuracy of some of the dimensions. Despite this, all three machines produced acceptable samples in case study 1, and both the SLM and Laser CUSING samples in case study 3 were very accurate.

4.4.2 Surface Roughness, Material Density and Minimum Dimension Capabilities

It is difficult to make fair comparisons of the surface roughness measurements in each case because some samples were finished and others were not. However, the samples had to be evaluated in the state they were found, so those that have been post processed were simply at an advantage.

In case study 1, whilst sample 3 had its surfaces finished and had the best surface roughness results, sample 1 (SLM) and sample 2 (DMLS) do not have finished surfaces. Sample 3 also had the best material density measurement of the three. None of the machines could produce the 0.5mm diameter holes and the 1mm holes were badly built. The 0.5mm diameter cylinder in sample 3 (the Laser CUSING machine's benchmark) could not be fabricated because the thin cylinder was not strong enough to withstand the force of additional powder layer depositions. Sample 3 was the only benchmark with this problem. Sample 3 had the largest minimum wall thickness, minimum hole diameter and minimum cylinder diameter measurements of all the samples in case study 1.

In case study 2, sample 1 (SLM) had an unfinished surface roughness value which was greater than that of sample 2 (DMLS) and benchmark 3 (Laser CUSING). Sample 2 had the best surface roughness results. Sample 1's material density was remarkably low at 82.6%. Material density is dependent on layer thickness, particle size and distribution and production speed. Again the implementation of non-ideal processing parameters can be held responsible for this negative outcome. Sample 1 and 2 could manufacture walls with a minimum wall thickness greater than 1mm, whilst sample 3 was able to create walls with a 1mm thickness.

In case 3, the material density and surface roughness was not measured and sample 1 (SLM) was able to manufacture walls with a thickness of 2mm, whilst sample 2 (Laser CUSING) was not able to create walls that were that thin.

Overall, the Laser CUSING machine's samples had the best material densities and surface roughness values. Sample 3 (Laser CUSING) did have the smallest minimum wall thickness in case study 2, but the creation of features with small dimensions still appears to be one of the Laser CUSING machine's limitations, whilst the SLM and DMLS machines were more capable of creating these smaller features. The surface roughness values were largely dependent on whether or not the sample's surfaces had been finished, but the consistently better material densities of samples manufactured by Laser CUSING machines is due to the implementation of optimum process parameters. The Laser CUSING machine's limitation with regards to the creation of small features could be a result of the machine's laser properties.

4.4.3 Mechanical Properties

In all three cases the Laser CUSING machine's sample had far superior mechanical properties to the mechanical properties of the SLM and DMLS machines' samples. The results are shown in tables 3, 4 and 5. The low HV hardness measurements of samples 1 and 2 in case study 2 can again be blamed on the use of sub-optimum process parameters. In case study 3, the tensile strength and HV hardness measurements of the SLM and Laser CUSING samples were similar, however in case study 1 the Laser CUSING sample has yield strength and HV hardness measurements that were much higher than those of the other samples. The DMLS sample in case study 1 was made of a bronze based material which explains its low hardness and yield strength measurements. Also, since the Laser CUSING sample was made of tool steel which is hard and strong and the SLM sample was made of stainless steel, the lower hardness and yield strength measurements for the SLM benchmark could have been expected.

4.4.4 Manufacturing Time and Cost

In all of the case studies, the Laser CUSING machine had the longest manufacturing times, but this may be necessary for the achievement of its good results.

In case study 1 the short manufacturing time of the DMLS benchmark could be explained by the use of a bronze based material to manufacture the part, but the DMLS scanning strategy, which is explained in section 4.3.1.2, also aims at reducing manufacturing times by scanning the core of the part very quickly.

The manufacturing time of 121 hours of the Laser CUSING sample in case study 2 does seem excessive, especially since the other machines produced the same benchmark in half the time. However, when the dimensional and geometric accuracy results for that case are re-examined, it is clear that the Laser CUSING sample was of the highest quality and it must therefore be assumed that this benchmark simply requires that length of time to be manufactured properly.

In case study 3, the SLM and Laser CUSING samples had similar dimensional and geometric accuracies, minimum wall thicknesses and mechanical properties and the Laser CUSING machine still took 22 hours longer to manufacture the benchmark. However, it is incorrect to assume that the long manufacturing time of the Laser CUSING machine is a limitation of the machine. As discussed in section 4.4.1, signs of warpage could be seen in the SLM sample of case study 3 and this could again be partly due to a production speed that is too high.

Table 3: Process Capabilities of the SLM, DMLS and Laser CUSING machines from case 1

Case study	*Process Capability*		*Benchmarks*		
			SLM: Benchmark 1	**DMLS: Benchmark 2**	**Laser Cusing: Benchmark 3**
	Material used		**Stainless steel 316**	**Bronze based**	**Hot work tool steel**
Case 1	**Dimensional and geometric accuracy**	**Average length variation (mm)**	0.543	0.123	0.070
		Average hole diameter variation (mm)	0.305	0.200	0.080
		Average cylinder diameter variation (mm)	0.277	0.113	0.047
		Stair Effect	Bad	Good	Good
		Curling	Good	Good	Good
		Sharp corners	Too short	Good	Good
		Overhangs	Badly built	Badly built	Badly built
	Surface roughness - Ra (µm)		10.08 (unfinished)	10.585 (unfinished)	5.82 (finished)
	Material density (kg/m³)		7900	7650	8025
	Minimum hole diameter (mm)		2	1	2
	Minimum cylinder diameter (mm)		0.5	0.5	1
	Minimum wall thickness (mm)		0.25	0.25	1
	Mechanical properties	**Micro Hardness (HV)**	233 ± 5	185 ± 20	398 ± 12
		Young's Modulus (Gpa)	54	30	62
		Yield Strength (MPa)	598	320	1410
	Manufacturing time (hours)		8.5	4.5	9

Table 4: Process Capabilities of the SLM, DMLS, Laser CUSING and EBM machines from case 2

Case study	*Process Capability*		*Benchmarks* SLM: Benchmark 1	DMLS: Benchmark 2	Laser Cusing: Benchmark 3	EBM: Benchmark 4
	Material used		**Stainless steel**	**DSH20 (hi strength steel)**	**CL 50 WS (hot work steel)**	*Benchmark could not be made*
Case 2	**Dimensional and geometric accuracy**	**Overall Shape**	Bad/ incomplete	Missing details	Complete	-
		Dimension change	0.200	0.100	0.100	-
		Accuracy of holes	Incomplete depth, near circular	Correct depth, near circular	Correct depth, near circular	-
		Accuracy of cooling tubes	Blocked	Incomplete	Very accurate	-
		Sharp edge/corner accuracy	Blunt	Blunt	Very sharp	-
		Stair effect	Layers are visible	Layers are not visible	Layers are not visible	-
		Accuracy of fine details	Poor	Poor	Very accurate	-
		Cracks	Layer separation	Internal cracks	No cracks	-
	Surface roughness - Ra (µm)		>10.0 (unfinished)	3.0 - 5.0 (finished)	5.0 - 7.0 (finished)	-
	Material density (%)		82.6	93.75	95.2	-
	Minimum wall thickness (mm)		>1	>1	1	-
	Mechanical properties	**Hardness (HV)**	140	180	325	-
	Manufacturing time (hours)		60	58	121	-
	Finishing time (hours)		Not finished	1	1	-

Table 5: Capabilities of the SLM and Laser CUSING machines from case 3

Case study	*Process Capability*		*Benchmarks*	
			SLM: Benchmark 1	**Laser Cusing: Benchmark 2**
	Material used		**AISI 316L Stainless Steel / DIN 1,4404**	**CL 20ES (similar to the material used by SLM)**
Case 3	**Dimensional and geometric accuracy**	**Average length variation (mm)**	0.290	0.037
		Average hole diameter variation (mm)	0.115	0.153
		Average cylinder diameter variation (mm)	0.078	0.188
		Average angle variation (°)	0.333	0.266
	Minimum wall thickness (mm)		2	>2
	Mechanical properties	**Hardness (HV)**	212.4	232.6
		Tensile strength (MPa)	626.82	648.76
		Elongation at break (%)	20.84	30.52
	Manufacturing time (hours)		38	60

4.5 Industrial Applications

Electron Beam Melting machines should not be regarded as unreliable as a result of the ARCAM machine's inability to manufacture the benchmark in case study 2. In fact, according to literature, because of the high production speeds, adequate accuracy and good material properties of EBM processes, they are used principally for the production of medical implants and the middle volume production of titanium parts that are used in the aerospace and military industry (Eyers *et al*. 2010). EBM machines can also manufacture mould inserts with cooling channels (Petrovic *et al*. 2011). Further development of the EBM process is expected in these industries because of the consistency and efficiency of the beam power transferral rate to the substrate and the flexibility in beam control in comparison with other laser-based additive manufacturing processes (Bourell *et al*. 2009).

The applicability of the SLM, DMLS and Laser CUSING machine types to different industries is assessed using a tailored parameter rating method. The chosen industries are the Tooling, Medical and Aerospace and Motor Industries.

Firstly, the results tables (Tables 3, 4 and 5) were scrutinized and the performances of the different machines were rated according to the measured parameters. A machine scores a 3 if its benchmark has the best parameter measurement, a 2 if it has the second best measurement or a 1 for the worst measurement of the group. The ratings table for case 1 are shown in Table 6 to demonstrate the procedure and the ratings tables for case study 2 and case study 3 are shown in Appendix B.

Table 6: Parameter ratings table for case study 1

Case study	*Process Capability*		SLM: Benchmark 1	DMLS: Benchmark 2	Laser Cusing: Benchmark 3	
			Benchmarks			
Case 1	**Linear and geometric accuracy**	**Average length variation (mm)**	1	2	3	
		Average hole diameter variation (mm)	1	2	3	
		Average cylinder diameter variation (mm)	1	2	3	
		Stair Effect	1	3	3	
		Curling	3	3	3	
		Sharp corners	1	3	3	
		Overhangs	1	1	1	
			9	**16**	**19**	**Total Linear and geometric accuracy rating**
	Surface roughness - Ra (µm)		**2**	**1**	**3**	**Surface roughness rating**
	Material density (kg/m³)		**2**	**1**	**3**	**Material Density rating**
	Minimum hole diameter (mm)		1	3	1	
	Minimum cylinder diameter (mm)		3	3	1	
	Minimum wall thickness (mm)		3	3	1	
			7	**9**	**3**	**Total minimum dimensions capability rating**
	Mechanical properties	**Micro Hardness (HV)**	2	1	3	
		Young's Modulus (Gpa)	2	1	3	
		Yield Strength (MPa)	2	1	3	
			6	**3**	**9**	**Total mechanical properties capability rating**
	Manufacturing time (hours)		**2**	**3**	**1**	**Manufacturing time rating**

Next, total scores were calculated for each machine for linear and geometric accuracy, surface roughness, material density, total minimum dimensions capability, total mechanical properties capability and manufacturing time as shown in Table 7.

Table 7: Preliminary scores for each machine for each parameter

	SLM	DMLS	Laser CUSING
Total Linear and geometric accuracy rating	25	30	51
Surface roughness rating	3	4	5
Material Density rating	3	3	6
Total minimum dimensions capability rating	11	10	7
Total mechanical properties capability rating	10	5	21
Manufacturing time rating	7	6	3

Since the DMLS machine is not tested in case 3, these scores need to be equalised by dividing the calculated scores by the number of measurements taken from that particular machine multiplied by 3 (the maximum score attainable for each measurement). These new scores were then multiplied by 100 to give each machine a final equalised score out of 100 for each parameter. These scores are shown in Table 8.

Table 8: Final equalised scores out of 100

	SLM	DMLS	Laser CUSING
Total Linear and geometric accuracy rating (out of 100)	44	67	89
Surface roughness rating (out of 100)	50	67	83
Material Density rating (out of 100)	50	50	100
Total minimum dimensions capability rating (out of 100)	73	83	47
Total mechanical properties capability rating (out of 100)	48	42	100
Manufacturing time rating (out of 100)	78	100	33

Finally, the applicability of the SLM, DMLS and Laser CUSING machines to selected industries is assessed in Tables 9, 10 and 11 and this is also shown graphically in Figures 12, 13 and 14. The selected industries are the tooling, medical and aerospace and motor industries. The applicability of the machines to the industries is calculated using different weightings for each parameter. The weightings can be seen in Tables 9, 10 and 11.

For the tooling industry the accuracy, strength and density parameters are given high weighting because they are the most important parameters of tooling products. Surface roughness is given a lower weighting since the cooling channels in tooling parts actually require rough surfaces to aid process cooling when the tool is in use. Since thin walls are not likely to be a requirement for tooling products, this parameter is also given a low weighting.

The accuracy of products that are manufactured for the medical industry is not important, and is therefore given a low weighting. The accuracy is not the most important parameter involved in manufacturing medical implants and the like since human bones are not created with highly accurate dimensions to begin with. The strength of medical implants is of great importance to ensure that the implants are durable. The surface roughness is also not important since the attachment of human bones onto the implant is assisted by its rough surfaces. The density parameter is also given a low weighting since a lattice structured implant is more likely to be fully integrated into the human body's structure (Petrovic *et al.* 2011). The minimum dimension capability is given a higher weighting than the accuracy, surface roughness and density capabilities since some medical industry-related products like hearing aids are complex in shape and may require the creation of thin walls, holes and tubes (Petrovic *et al.* 2011).

Products that are manufactured for use in the aerospace and motor industry need to be strong, accurate and light weight with smooth surfaces for the improved aerodynamics of the aircraft or motor vehicle (Petrovic *et al*. 2011). For these reasons, the strength, accuracy and surface roughness capabilities are given high weightings while the density and minimum dimension capabilities are given lower weightings.

Figures 12, 13 and 14 show that of the SLM, DMLS and Laser CUSING machines, the Laser CUSING machine is best suited to all three of these industries according to this study. The weighted parameters are shown in different colours in these figures and they can be compared individually.

Table 9: Table showing the applicability of the machine types to the tooling industry

	Tooling Industry					
Capability:	**Accuracy (Weighting = 30%)**	**Strength (weighting = 30%)**	**Density (weighting = 30%)**	**Minimum dimension capabilities (weighting = 5%)**	**Surface roughness (weighting = 5%)**	**Total**
Weighting	30.00	30.00	30.00	5.00	5.00	**100.00**
SLM	13.16	14.29	15.00	3.67	2.50	**48.61**
DMLS	20.00	12.50	15.00	4.17	3.33	**55.00**
Laser CUSING	26.84	30.00	30.00	2.33	4.17	**93.34**

Table 10: Table showing the applicability of the machine types to the medical industry

	Medical Industry					
Capability:	**Accuracy (weighting = 5%)**	**Strength (weighting = 50%)**	**Density (weighting = 5%)**	**Minimum dimension capabilities (weighting = 35%)**	**Surface roughness (weighting = 5%)**	**Total**
Weighting	5.00	50.00	5.00	35.00	5.00	**100.00**
SLM	2.19	23.81	2.50	25.67	2.50	**56.67**
DMLS	3.33	20.83	2.50	29.17	3.33	**59.17**
Laser CUSING	4.47	50.00	5.00	16.33	4.17	**79.97**

Table 11: Table showing the applicability of the machine types to the aerospace and motor industry

	Aerospace and Motor Industry					
Capability:	**Accuracy (weighting = 30%)**	**Strength (weighting = 30%)**	**Density (weighting = 5%)**	**Minimum dimension capabilities (weighting = 5%)**	**Surface roughness (weighting = 30%)**	**Total**
Weighting	30.00	30.00	5.00	5.00	30.00	**100.00**
SLM	13.16	14.29	2.50	3.67	15.00	**48.61**
DMLS	20.00	12.50	2.50	4.17	20.00	**59.17**
Laser CUSING	26.84	30.00	5.00	2.33	25.00	**89.18**

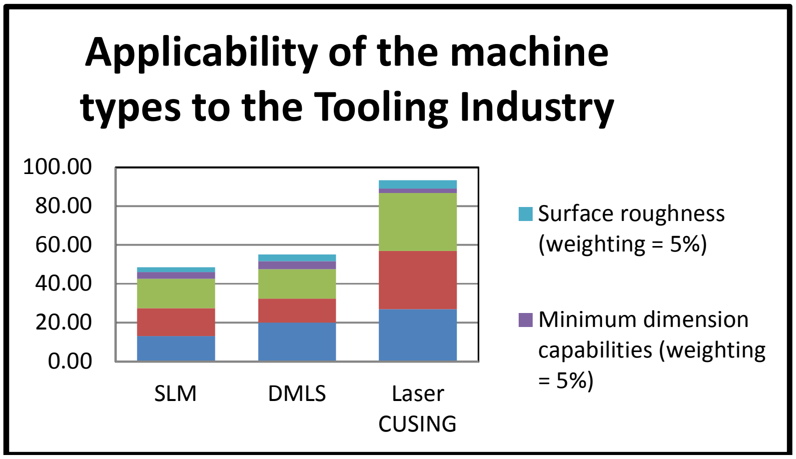


Figure 12: Tooling industry applications

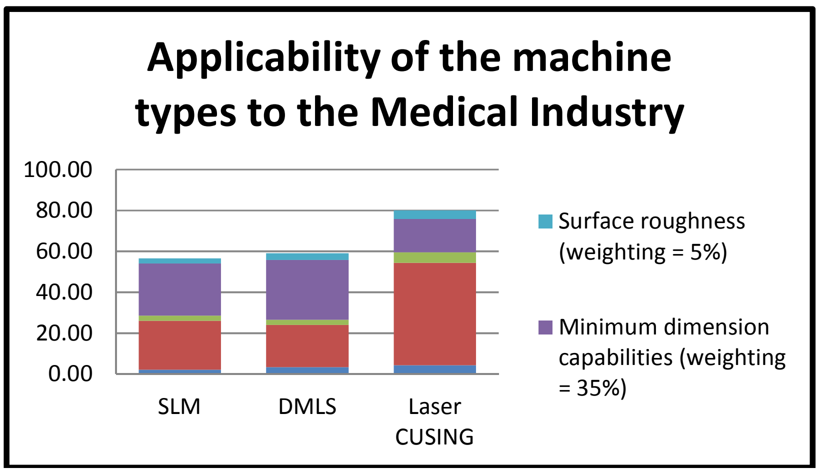


Figure 13: Medical industry applications

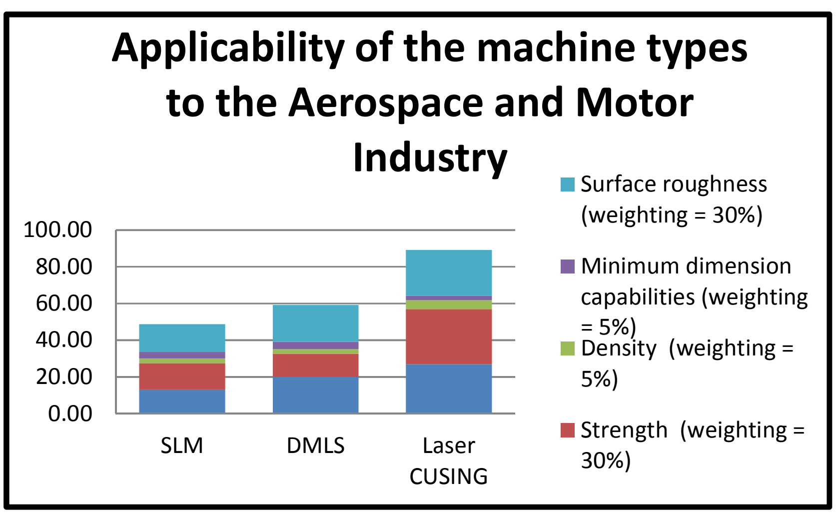


Figure 14: Aerospace and motor industry applications

5. Conclusion

The objective of this project was to create a capability profile of an Additive Manufacturing machine based on the SLM process and to identify corresponding industrial application areas using these results. This was done by constructing an Additive Manufacturing overview, evaluating various case studies in which process capabilities of different Additive Manufacturing machines were tested and finally designing a method by which the different machine capabilities could be evaluated and weighted to determine the applicability of each of them to three specific industrial applications.

The purpose of the overview in sections 2 and 3 was to outline the existing research involving Additive Manufacturing in general and SLM in particular, to gain an understanding of the manufacturing processes and to identify the advantages, disadvantages and existing industrial applications of Additive Manufacturing. It was found that the major advantages of Additive Manufacturing are the short product development phases, the elimination of the 'design for manufacture' requirement and the ability to create highly complex parts, whilst the main disadvantages included the low level of quality of additive manufactured parts, long manufacturing times compared to Subtractive Manufacturing Processes and the high cost of the required materials. The industrial applications that were identified as the most relevant to Selective Laser Melting based processes in particular were the Tooling, Medical and Motor/Aerospace Industries.

A literature study of the process capabilities of DMLS, SLM, Laser CUSING and EBM machines based on three separate case studies comparing these machine types was laid out in sections 4.1 to 4.3. The outcomes of the three case studies were evaluated and discussed in section 4.4 and various conclusions can now be drawn from these findings.

The unsatisfactory results for the SLM and DMLS machine capabilities in case study 2 allow the following conclusion to be drawn: A number of benchmark tests should be performed to iteratively determine the best possible processing parameters applicable for the manufacturing of a particular benchmark on a particular machine. This was performed in case study 1 and more successful overall study results were thereby achieved. This introduces the idea that the poor part quality disadvantage of Additive Manufacturing machines mentioned above can be eradicated or at least reduced by investigating and documenting the best process parameter setting requirements of a specified machine for the manufacturing of a specific product type.

Another interesting aspect of case study 2 was the EBM machine's inability to manufacture the benchmark shown in Figure 9. As discussed in section 4.3.2.4, the reason for this is probably the different laser strength and diameter of the EBM machine. High laser powers also limited the other three machines' abilities to manufacture small holes, cylinders and overhangs and it should therefore be taken into account when machine process parameters are being set. The EBM machine's shortcomings during this particular study are not necessarily a negative reflection on the capabilities of the ARCAM machine or the EBM process, it simply proves that products that are similar to the benchmark model used in case study 2 with fine holes and thin and sharp walls should not ideally be manufactured using this EBM machine with these specific processing parameters.

It can also be concluded that production speeds should not be increased to an extent that sacrifices the machine's ability to manufacture parts of high quality and complexity. This is proven in case study 2, where the Laser CUSING machine's manufacturing time was double the manufacturing times of the DMLS or SLM machines and the sample produced by the Laser CUSING machine outperformed the other samples in nearly every capability. This sample had the best dimensional and geometric accuracy, material density, minimum wall thickness and hardness measurements. In case study 1, the DMLS machine's manufacturing time was much faster than the other manufacturing times and the corresponding DMLS sample had the least satisfactory mechanical properties of all three samples. Again, in case study 3, the Laser CUSING machine which had a longer manufacturing time than the SLM machine produced a sample (sample 2) with better mechanical properties than the SLM sample (sample 1). Further, the long manufacturing times should not be classified as a disadvantage of Additive Manufacturing. Instead, it should be viewed as a necessary and optimal process parameter for the achievement of high quality, complex parts.

As shown in Table 2, the SLM machines' samples (sample 1) in each case study had the greatest layer thicknesses of all the machines. The corresponding dimensional and geometric accuracy capabilities for sample 1 in each case study were also the poorest. The conclusion that large layer thicknesses result in poor dimensional and geometric accuracies makes sense and this is an expected outcome.

As shown in Figures 12 to 14, the Laser CUSING machine was evaluated as being the most applicable of the three machines to the Tooling, Medical and Aerospace/Motor Industries. Since all three machines are based on similar manufacturing techniques, their applicability to these industries could be improved if process parameter alterations were made in accordance with the suggestions above.

These project outcomes are found to be satisfactory and further studies into the optimisation of the Additive Manufacturing process parameters would require a benchmark study to be conducted.

6. References

1. Abdel Ghany, K., Moustafa, S.F. 2006, "Comparison between the products of four RPM systems for metals", *Rapid Prototyping Journal,* vol. 12, no. 2, pp. 86-94.
2. Aronson, R.B. 2009, "It's a Lot More Than RP Now", *Manufacturing Engineering,* vol. 142, no. 4, pp. 67-73.
3. Bibb, R., Thompson, D. & Winder, J. 2011, "Computed tomography characterisation of additive manufacturing materials".
4. Bourell, D. L., Leu, M. C., & Rosen, D.W. 2009. *Roadmap for Additive Manufacturing, Identifying the future of Freeform Processing.* Austin: The University of Texas At Austin Laboratory for Freeform Fabrication Advanced Manufacturing Center.
5. Castillo, L. 2005, *Study about the rapid manufacturing of complex parts of stainless steel and titanium.* Aimme Instituto Tecnológico Metalmecánico.
6. de Beer, N., Dimitrov, D. & van der Merwe, A. 2008, "Manufacturing of custom-made medical implants for cranio/maxillofacial and orthopaedic surgery – an overview of the current state of the industry", *Journal for New Generation Sciences,* vol. 6, no. 2, pp. 1-15
7. Dimitrov, D., Schreve, K., de Beer, N., & Christiane, P. 2008, " Three dimensional printing in the South African environment", *South African Journal of Industrial Engineering*, vol. 19, no. 1, pp. 195-213
8. Dinda, G.P., Dasgupta, A.K. & Mazumder, J. 2009, "Laser aided direct metal deposition of Inconel 625 superalloy: Microstructural evolution and thermal stability", *Materials Science and Engineering A,* vol. 509 pp.98–104
9. Eyers, D., Dotchev, K. 2010, "Technology Review for mass customisation using Rapid Manufacturing", *Assembly Automation,* vol. 30, no. 1, pp. 39-46.
10. Hao, L., Raymond, D., Strano, G. & Dadbakhsh, S. 2010, "Enhancing the sustainability of additive manufacturing", *5th International Conference on Responsive Manufacturing - Green Manufacturing, ICRM 2010, January 11, 2010 – January 13* Institution of Engineering and Technology, Ningbo, China, 2010, pp. 390.
11. Hopkinson, J., Hague, R.J.M. & Dickens, P.M. 2006. *Rapid Manufacturing, An Industrial Revolution for the Digital Age.* England: John Wiley & Sons
12. Langer, H.J. & Shellabear, M. 2006, "Recent E-manufacturing solutions developed by EOS", *Journal for New Generation Sciences,* vol. 4, no. 1, pp. 100-110
13. Li, C.H., Fang, Z. & Zhao, H.Y. 2010, "Investigation into layered manufacturing technologies for industrial applications", *2010 2nd International Conference on MultiMedia and Information*

*Technology, MMIT 2010, April 24, 2010 - April 25*IEEE Computer Society, Kaifeng, China, 2010, pp. 213.

14. Kruth, J.P., Vandenbroucke, B., Van Vaerenbergh, J., Mercelis, P. 2005. *Benchmarking of different SLS/SLM processes as rapid manufacturing techniques*. Belgium: The Katholieke Universiteit Leuven at Division PMA of the Department of Mechanical Engineering.
15. Petrovic, V., Vicente, H.G., Jorda Ferrando, O., Delgado Gordillo, J., Ramon, B.P. & Portoles Grinan, L. 2011, "Additive layered manufacturing: Sectors of industrial application shown through case studies", *International Journal of Production Research,* vol. 49, no. 4, pp. 1061-1079.
16. Santos, E.C., Shiomi, M., Osakada, K. & Laoui, T. 2006, "Rapid manufacturing of metal components by laser forming", *International Journal of Machine Tools and Manufacture,* vol. 46, no. 12-13, pp. 1459-1468.
17. Spierings, A., Herres, N. & Levy, G. 2011, "Influence of the particle size distribution on surface quality and mechanical properties in AM steel parts", *Rapid Prototyping Journal,* vol. 17, no. 3, pp. 195-202.
18. Wohlers, T. 2010. *Wohlers report 2010, State of the industry*, *Annual worldwide progress report*. United State of America: Wohlers Associates Inc.
19. www.3trpd.co.uk. Visited on 21 February 2011
20. www.concept-laser.de/. Visited on 21 February 2011
21. Zhang, W., Lin, H. & Zhang, W. 2005, "From virtuality to reality: Individualized freeform model design and rapid manufacturing", *Human Factors and Ergonomics in Manufacturing,* vol. 15, no. 4, pp. 445-459.

Appendix A: Tables Showing the Original Dimensional Measurements of Each Case Study's Samples

Table 12: Case Study 1's measured dimensions

Case 1	SLM	DMLS	Laser CUSING
50mm length	50.78	50.16	50.08
50mm width	50.73	50.18	50.09
7 mm height	7.12	7.03	6.96
5mm diameter hole	4.67	4.83	4.87
2mm diameter hole	1.72	1.77	1.97
1mm diameter hole	Badly built	0.9	Badly built
0.5mm diameter hole	Not built	Not built	Not built
5mm diameter cylinder	5.35	5.12	5.03
2mm diameter cylinder	2.23	2.1	2.05
1mm diameter cylinder	1.25	1.12	1.06
0.5mm diameter cylinder	0.64	0.63	not built

Table 13: Case Study 2's measured dimensions

Case 2	Total shape	Dimension change	Fine details	Holes	Cooling tubes	Sharp edges	Sharp corners	Overall
SLM	Bad/ incomplete	-0.2	Poor	Incomplete depth, near circular	Incomplete	Rough	Very rough	Poor
DMLS	Missing details	±0.1	Poor	Correct depth, near circular	Incomplete	Blunt	Blunt	Good
Laser Cusing	Complete	±0.1	Very accurate	Correct depth, near circular	Very accurate	Very sharp	Very sharp	Very good
EBM	Could not produce the benchmark accurately							

Table 14: Case Study 3's measured dimensions

Case 3	SLM	Laser Cusing
100mm length	100.040	99.990
60mm width	60.060	60.090
81mm height	80.230	80.990
5mm diameter cylinder	5.100	5.200
4mm diameter cylinder	4.150	4.180
2mm diameter cylinder	2.040	2.160
1mm diameter cylinder	1.020	1.200
0.5mm diameter cylinder	0.580	0.700
0° angle	0.160	0.090
15° angle	14.200	14.970
30° angle	29.900	29.970
45° angle	44.900	44.850
60° angle	59.600	59.930
75° angle	74.800	74.930
90° angle	89.430	88.580
10mm diameter hole	9.825	9.919
4mm diameter hole	3.880	3.803
3mm diameter hole	2.883	2.809
2mm diameter hole	1.853	1.830
1mm diameter hole	0.873	0.822
0.5mm diameter hole	0.498	0.400

Appendix B: Industrial Applications Data

Table 15: Parameter ratings table for case study 2

<table>
<tr><th rowspan="2">Case study</th><th rowspan="2" colspan="2">Process Capability</th><th colspan="3">Benchmarks</th><th rowspan="2"></th></tr>
<tr><th>SLM: Benchmark 1</th><th>DMLS: Benchmark 2</th><th>Laser Cusing: Benchmark 3</th></tr>
<tr><td rowspan="14">Case 2</td><td rowspan="8">Linear and geometric accuracy</td><td>Overall Shape</td><td>1</td><td>1</td><td>3</td><td rowspan="8"></td></tr>
<tr><td>Dimension change</td><td>1</td><td>3</td><td>3</td></tr>
<tr><td>Accuracy of holes</td><td>1</td><td>3</td><td>3</td></tr>
<tr><td>Accuracy of cooling tubes</td><td>1</td><td>1</td><td>3</td></tr>
<tr><td>Sharp edge/corner accuracy</td><td>1</td><td>1</td><td>3</td></tr>
<tr><td>Stair effect</td><td>1</td><td>3</td><td>3</td></tr>
<tr><td>Accuracy of fine details</td><td>1</td><td>1</td><td>3</td></tr>
<tr><td>Cracks</td><td>1</td><td>1</td><td>3</td></tr>
<tr><td></td><td></td><td>8</td><td>14</td><td>24</td><td>Total Linear and geometric accuracy rating</td></tr>
<tr><td colspan="2">Surface roughness - Ra (µm)</td><td>1</td><td>3</td><td>2</td><td>Surface roughness rating</td></tr>
<tr><td colspan="2">Material density (%)</td><td>1</td><td>2</td><td>3</td><td>Material Density rating</td></tr>
<tr><td colspan="2">Minimum wall thickness (mm)</td><td>1</td><td>1</td><td>3</td><td>Total minimum dimensions capability rating</td></tr>
<tr><td>Mechanical properties</td><td>Hardness (HV)</td><td>1</td><td>2</td><td>3</td><td>Total mechanical properties capability rating</td></tr>
<tr><td colspan="2">Manufacturing time (hours)</td><td>2</td><td>3</td><td>1</td><td>Manufacturing time rating</td></tr>
</table>

Table 16: Parameter ratings table for case study 3

Case study	*Process Capability*		*Benchmarks* SLM: Benchmark 1	*Benchmarks* Laser Cusing: Benchmark 2	
Case 3	**Linear and geometric accuracy**	**Average length variation (mm)**	1	3	
		Average hole diameter variation (mm)	3	1	
		Average cylinder diameter variation (mm)	3	1	
		Average angle variation (°)	1	3	
			8	8	**Total Linear and geometric accuracy rating**
	Minimum wall thickness (mm)		3	1	**Total minimum dimensions capability rating**
	Mechanical properties	**Hardness (HV)**	1	3	
		Tensile strength (MPa)	1	3	
		Elongation at break (%)	1	3	
			3	9	**Total mechanical properties capability rating**
	Manufacturing time (hours)		3	1	**Manufacturing time rating**