RAPID TOOLING FOR CARBON FIBRE COMPRESSION MOULDING

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DECLARATION

I, Cornelis Marthinus Potgieter, do hereby declare that this research project submitted to the Central University of Technology, Free State for the degree MAGISTER TECHNOLOGIAE: ENGINEERING: MECHANICAL, is my own independent work that has not been submitted before to any institution by me or any other person in fulfilment of the requirements for the attainment of any qualification.

CM Potgieter Date

Student

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In a project like this there are normally a number of people to thank and this project is no exception. Various people helped me over the years and I would like to thank them. I would like to thank my family who supported me during the study. Secondly I would like to thank every one at the Central University of Technology that stood by me and helped me. I would like to thank the personnel at the Centre for Rapid Prototyping and Manufacturing and the Product Development Technology Station who helped me extensively on this project and showed me the way to go forward. They were available whenever I needed advice. I would like to thank Mr Nick du Toit and Mr Ludrick Barnard that helped me at the start of the project. They laid the foundation for the project. I want to thank my study leader Mr Gerrie Booysen. I would like to thank the Leatt Company who provided assistance at the start of the project and the Advanced Manufacturing Technology Strategy (AMTS) who funded the project.

UITTREKSEL

Die doel van die studie is om meer bekostigbare koolstofvesel onderdele te vervaardig. Om dit moontlik te maak, moet daar materiaal-, arbeid- en tydbesparings wees. Dus word daar ‘n produksiemetode benodig om bekostigbare koolstofveselgietstukke te vervaardig wat tyd en geld bespaar. Die proses moet toegepas kan word vir klein tot medium produksiereekse. Aangesien die veselindustrie een van die vinnig-groeienste industrieë ter wêreld is, dus hoe vinniger gietstukke vervaardig kan word, hoe vinniger sal die eindprodukte die mark bereik. Die navorsingsprojek stel vas of dit moontlik is om koolstofveselgietstukke goedkoper en vinniger op die “Electro Optical Systems (EOS) Laser Sintering (LS)” masjien te groei, eerder as om die gietstukke deur die konvensionele rekenaar numeries-beheerde (computer numerical control (CNC)) masjienering te vervaardig. Die oppervlakafwerking van die gegroeide onderdeel is nie van dieselfde kwaliteit as die van die gemasjineerde onderdeel nie, maar daar is metodes om die oppervlakgehalte te verbeter sodat dit vergelykbaar is met die gehalte van die gesnyde onderdeel. Koolstofvesel word op baie verskillende maniere gegiet maar dit is nie moontlik om LS gegroeide onderdele vir al die gietmetodes te gebruik nie. In die studie sal daar net een koolstofveselgietmetode ondersoek word, naamlik kompressiegieting. Die gietstuk sal ontwerp word om so goedkoop en vinnig as moontlik vervaardig te kan word. Verskillende metodes van gietstuk aanpassing om die goedkoopste en mees aanvaarbare metode van ontwerp vir die LS proses moontlik te maak is ondersoek.

SYNOPSIS

The aim of this study is to produce more cost effective carbon fibre (CF) parts. To achieve this there must be a saving on materials, labour and time. Thus, a production process to produce cost effective CF moulds while saving time and money is required. This procedure must be suited for the incorporation in the small to medium production ranges. The composite industry is one of the fastest growing industries in the world. Therefore, the faster a mould can be produced, the faster the end product will reach the market. This research project investigates the possibility to sinter CF moulds on the Electro Optical Systems (EOS) Laser Sintering (LS) machine cheaper and faster than the conventional method using computer numerically controlled (CNC) machining. The surface finish produced on the LS machine is not of the same quality as a CNC machined mould, but there are ways to enhance the surface quality of a LS part to the point that it is compatible to the surface quality of a CNC machined mould. The CF moulding process uses many different types of moulding processes. However, it is not possible to use LS parts for all of the available processes to produce CF parts. In this study only one CF moulding process will be investigated, namely compression moulding. The moulds will be designed to be manufactured as cheaply and as quickly as possible. Different methods of mould adapting have been studied to find the cheapest most suitable method of mould design for the LS process.

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LIST OF ABBREVIATIONS

2-D	Two-dimensional
3-D	Three-dimensional
AM	Additive Manufacturing
ABS	Acrylonitrile-butadine-styrene
AMT	Advanced Materials Technology (Pty) Ltd
CAD	Computer Aided Design
CF	Carbon Fibre
CMM	Co-ordinate Measuring Machine
CNC	Computer Numerical Control
CRPM	Centre for Rapid Prototyping and Manufacturing
CTE	Coefficient of Thermal Expansion
CUT	Central University of Technology
EOS	Electro Optical Systems
LS	Laser Sintering
PAN	Polyacrylonitrile
PTFE	Polytetrafluoroethylene
RM	Rapid Manufacturing
RP	Rapid Prototyping
RTM	Resin Transfer Moulding
Tg	Glass Transition Temperature
VARI	Vacuum Assisted Resin Injection
VARTM	Vacuum Assisted Resin Transfer Moulding
SFF	Solid Freeform Fabrication
.stl	Standard Triangulation Language

CHAPTER 1

INTRODUCTION

1.1 Foreword

"Stop giving the people straw for making bricks. Make them go and find it for themselves." Exodus 5:7

The Israelites used clay and straw to produce bricks which is an early example of composites. The individual constituents of clay and straw could not serve the function by themselves but could perform it when put together to form bricks [1].

Carbon fibres (CF) are the stiffest and strongest reinforcing fibres for use in polymer composites and are the most used after glass fibre [2]. CF can refer to carbon filament thread, felt or woven cloth made from those carbon filaments. By extension it is also used informally to mean any composite material made with carbon filament. Each carbon filament is made out of long, thin sheets of carbon similar to graphite. Two methods are used to produce CFs, i.e. the PAN or the pitch methods. The PAN method name is derived from the material used to obtain separated chains of carbon atoms, polyacrylonitrile (PAN). This is done through a heating and oxidation process. The pitch method is where graphite threads are drawn out through a nozzle from hot fluid pitch [2].

The worldwide demand for PAN-based CFs for 2004 was estimated at approximately 22 000 tons and the demand is forecast to grow at an annual rate of more than 10% in the future and exceeded 30 000 tons in 2007 [3]. Table 1.1 shows how PAN CF production has increased during the period from 2005 to 2008. Excess capacity shows the surplus produced for that year.

Table 1.1: CF used per year (Tons/year) [3]

Manufacturer	**2005**	**2006**	**2007**	**2008**
Toray Industries	9100	10 900	13 100	13 100
Toho Group	6300	7800	7800	7800
Mitsubishi	5200	5700	5700	7700
Others	5900	5900	5900	5900
Produced	26 500	30 300	32 500	34 500
Excess capacity	9800	9800	9800	9800
TOTAL	36 300	40 100	42 300	44 300

1.2 Problem statement

Today, more and more parts in cars, aeroplanes, boats, spacecrafts, sports goods, etc. are made with composite materials.

The composite industry is one of the fastest growing industries in the world and there is a need for cheaper/faster mould manufacturing to be used for production or prototyping - the faster a finished mould can be produced, the faster the end product will reach the market.

1.3 Aim of the study

The aim of this study is to produce more cost-effective composite moulds. In order to achieve this there must be a saving on materials, labour and time. Thus, a production process to produce cost-effective composite moulds must save both time and money. This procedure must be suited to incorporation in the small to medium production ranges.

1.4 Hypothesis

Cost-effective composite moulding tools can be manufactured on a Laser Sintering (LS) machine.

1.5 Study field

This research project aims to investigate whether it is possible to manufacture moulds to be used for CF moulding on the Electro Optical Systems (EOS) laser sintering (LS) machine, cheaper and faster than the conventional method of using computer numerically controlled (CNC) milling. The surface finish produced on the LS machine is not of the same quality as a CNC machined mould, but there are ways to enhance the surface quality of a LS part to the point that it is compatible to the surface quality of a CNC machined part. The CF moulding process uses many different types of moulding processes. It is however not possible to use LS parts for all of the available processes to produce CF parts. In this study only one process will be investigated, namely compression moulding. The moulds will be designed to be manufactured as fast as possible. Different mould features will be studied to find the cheapest, most suitable method of mould design for the LS process.

For the purpose of this study, a manufacturing process is investigated for composite moulding. A composite mould design is obtained from a company who already used compression moulding to manufacture CF parts. Quotes for the cost of traditional tools were obtained from tool making companies. The actual tooling cost to produce a mould (as if for a client) by means of Rapid Prototyping (RP) on the EOS P380 LS machine will be obtained from the Centre for Rapid Prototyping and Manufacturing (CRPM) at the Central University of Technology Free State (CUT). This data will be analysed and compared to establish to what extent it is feasible to sinter composite moulds instead of using CNC milling to machine the moulds.

The moulds will be designed and evaluated according to compression moulding applications. The mould surface will be sealed and smoothened by applying coats of clear lacquer to the surface. The moulds will be tested to establish how many parts can be produced per mould without losing its geometry, surface finish or accuracy. The cost of the sintered mould will be compared with the cost of a mould that was machined by a CNC machine.

Chapter 2

INTRODUCTION TO CARBON FIBRE AND LASER SINTERING

2.1 Introduction

The four basic categories of structural materials can be divided into metals, polymers, ceramics and composites. Composites are combinations of metals, polymers or ceramic materials that are combined in a macroscopic structural unit. Fibre-reinforced composite components are manufactured by embedding rigid fibres in a comparatively soft matrix. The fibres can be long or short, directional or non-directional. The individual fibres are joined together by the matrix to make the fibres resistant to shear forces [5]. Many man-made materials have two or more constituents, but are generally not referred to as composites if the structural unit is formed at the microscopic level rather than the macroscopic level. Thus, metallic alloys and polymers blends are not classified as composites [4].

Composites are used because of the desirable properties they have. These properties could not be achieved by either of the constituent materials acting alone. The most common example is reinforcing fibres embedded in a binder, or matrix material [4]. The polymeric matrix normally used is a thermoset resin or thermoplastic. Glass, carbon and aramid fibres are mainly applied as reinforcements. Fibre-reinforced composites are mainly applied in load-bearing structures, because the parts are often lighter than if they were made from conventional lightweight construction materials. CF parts have a good combination of strength, stiffness and energy absorption capacity. Another advantage is design freedom, particularly for shell-like structures [5].

It is not known when or where humans discovered fibrous composites, although nature provides us with numerous examples. Wood consists mainly of fibrous cellulose imbedded in a lignin matrix, whereas most mammalian bone is made up of layered and oriented collagen fibrils in a protein-calcium phosphate matrix [4].

Fibrous reinforcement is so effective because many materials are much stronger and stiffer in fibre form than the material would have been in bulk form. It is believed that Griffith, who measured the tensile strength of glass rods and glass fibres of different diameters, first demonstrated this phenomenon scientifically in 1920 [4]. Griffith found that the thinner the rods and fibres, the stronger the rods were. The smaller the diameter of the fibre, the smaller the chances that failure-inducting surface cracks will be generated during fabrication and handling [4]. Materials also have an actual strength which is lower, by some margin, than the theoretical strength. The reason for this is the inherent flaws in the material. By removing these flaws, the strength of the material can be improved. The smaller the diameter of the fibre, the smaller the chance of inherent flaws. A steel plate can have a tensile strength of 689 MPa, while a wire made of the same material can have a tensile strength of 4100 MPa [1].

There is no doubt that fibres allow us to obtain the maximum stiffness and tensile strength of a material, but there are obvious disadvantages of using a material in fibre form alone. Fibres without a binder or matrix material cannot support longitudinal compressive loads and the fibres' transverse mechanical properties are generally not as good as the corresponding longitudinal properties. Fibres are generally useless as structural materials unless the fibres are held together in a structure with a binder or matrix material and unless some transverse reinforcement is provided [4].

There are three main advantages of making the fibre diameter as small as possible. Firstly, the thinner the fibres, the closer the fibre properties get to the strongest theoretical stress properties of the material. This is due to the fact that fibres with a small diameter will have less chance of having inherent flaws in the material. Secondly, the same volume fraction of fibres in a composite has a larger fibre/matrix interface with small diameter fibres than bigger diameter fibres. This improves the toughness, ductility (the ability of a material to deform without fracturing) and better transfer of loads from the matrix to the fibre. The third advantage of having smaller diameter fibres is the ability of smaller fibres to bend further without breaking. The ability to bend increases with a decrease in the fibre diameter and is measured as flexibility [1].

2.1.1 Carbon fibre (CF)

Carbon fibre (CF) is the most frequently used fibre after glass fibre and is the stiffest and strongest reinforcing fibre for polymer composites [2]. CF is made of pure carbon in the form of graphite. It has a low density and a negative coefficient of thermal expansion. CF can cause galvanic corrosion when brought into contact with metals. CF is very expensive and is generally used together with an epoxy resin, where high strength and stiffness is required, i.e. race cars, automotive and aerospace applications and sports equipment [2].

Two methods are used to produce CF, i.e. the PAN or pitch methods. The PAN method separates a chain of carbon atoms from polyacrylonitrile (PAN). These fibres are then heated in the range of 200°C to 300°C in an atmosphere containing oxygen. Treating PAN fibres prior to heat treatment with diethanolamine or triethanolamine solutions substantially reduces the time needed for the oxidation process. Carbon heated in the range of 1500 – 2000°C exhibits the highest tensile strength (5650 MPa). This process is called carbonisation and takes place in an inert or mildly oxidative atmosphere. Research has shown that if carbonisation is done in an oxidising atmosphere, the optimal atmosphere should contain between 50 – 170 parts per mol of oxygen. CF heated from 2500 – 3000°C exhibits a higher modulus of elasticity (531 GPa). This process, where non-graphitic carbon is changed to graphitic carbon, is called graphitisation. Tensioning the fibre during graphitisation improves the ultimate mechanical properties and reduces any residual shrinkage. The result is usually 93 – 95% (mass fraction) carbon [2,6 – 8].

The pitch method is where graphite threads are pulled through a nozzle from hot fluid pitch. This process is faster than the PAN process. Pitch fibres are more brittle than those derived from PAN, and have a higher density, leading to lower specific properties. The basic process is a distillation of residual oils left over from the thermal or catalytic cracking of crude oil. These oil-based products are introduced into a reactor where the oil products are heated to temperatures ranging between 350°C and 500°C. Thermal cracking, polymerisation and condensation occur. The gases and light oils that are released during the heating of the oil-based products are taken out of the reactor through a condenser. The remaining material is a heavier, high carbon content material; which is the basis for pitch fibres. Heat treatment of this material causes the carbon percentage to rise. When the carbon content of the raw material reaches 91 – 96.5% and the mean molecular weight is at least 400, the pitch can be melt-spun to produce pitch CF. Additives are sometimes used to increase the molecular weight or to promote better fibre-spinning characteristics. There are various types of spinning techniques such as extrusion, centrifugal-type, pressure-extrusion, spraying and jet-type. When the melt viscosity is high and long continuous fibres are desired, the extrusion process is used. Polymers are added to improve yield and handling characteristics. After pitch fibres are spun, the fibres are subjected to an oxidising gas at a temperature below the spinning temperature, or the fibres are subjected to another chemical treatment that renders them infusible. This process is critically important to guarantee that the pitch fibres will retain their shape under heat treatment during carbonisation and graphitisation [8].

The attraction of CF components and structures is primarily due to their reduced weight, increased tensile strength and deflection properties as compared to steel. CF structures can be up to 75% lighter and 10 times stronger than steel for a given weight, as seen in Table 2.1.

Table 2.1: Properties of CF versus steel [9]

	ULTIMATE TENSILE STRENGTH (UTS) (MPa)	**DENSITY (ρ) (kg/dm)**	**SPECIFIC STRENGTH (UTS/ρ)**
CARBON FIBRE	780	1.75	0.446
STEEL	400	7.90	0.051

The first moulding process developed was the hand lay-up method. This method was labour intensive and it was difficult to control the part quality. As composites became more popular, better moulding processes were developed. These included resin transfer moulding and compression moulding.

2.2 Carbon fibre moulding methods

There are numerous methods which can be used in composite moulding and many variations on these moulding methods. However, not all the methods are suited to the use of LS moulds. The hand lay-up, resin transfer moulding, spray lay-up and compression moulding processes are the most suited to the Rapid Prototyping (RP) process, because of the simplicity of a hand lay-up and spray lay-up mould and the male/female tooling of compression moulding and resin transfer moulding.

2.2.1 Hand lay-up method

This process is also known as the wet lay-up process [10]. The hand lay-up process (Figure 2.1) is the sequential lay-up of fibres and resin in an open mould [11]. Resins are impregnated into fibres by hand, usually by means of a roller or brushes. The fibres are in the form of woven, knitted, stitched or bonded fabrics. There is an increase in the use of nip-roller type impregnators for forcing resin into the fabrics by means of rotating rollers and a bath of resin. Laminates are left to cure under standard atmospheric conditions. Any resin can be used with this moulding process e.g. epoxy, polyester, vinylester and phenolic. A limiting factor with the hand lay-up process is that the fibre volume fractions are less than 35%. Since the fibre bears most of the load, the excess resin just adds weight [11].

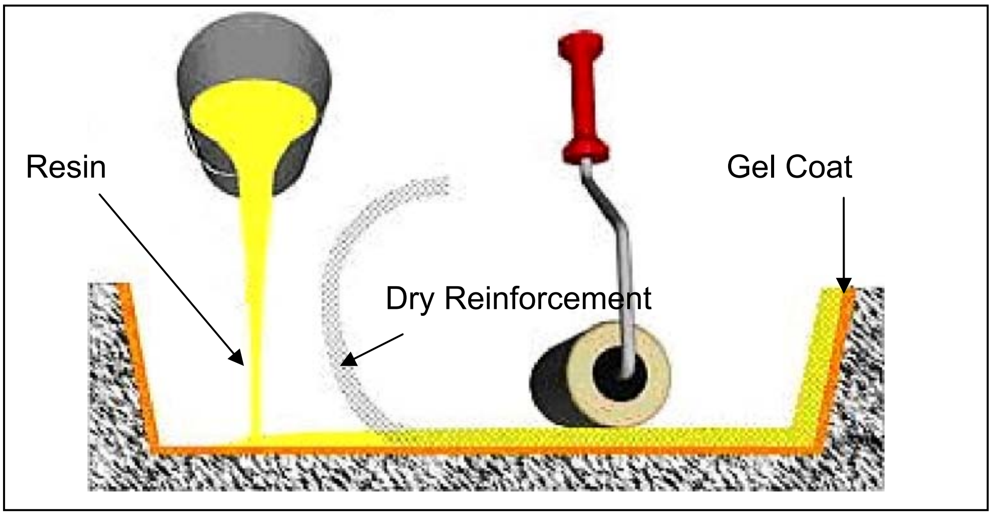

Figure 2.1: The hand lay-up process [2]

All kinds of fibres (glass, carbon and aramid) are used in this process although heavy aramid fabrics can be hard to fully wet by hand. This kind of moulding process leaves the mould side of the part smooth and the other side rough [10]. Hand lay-up moulding can be used for the production of any size of parts, for example small technical parts with a surface area of a few square centimetres right up to parts as big as swimming pools. This method is generally limited to the manufacturing of parts with relatively simple shapes and is recommended for small and medium volumes, where the investment in moulds and equipment must not be too high [13].

The main advantages of the process are:

- It has been widely used for many years.
- It has simple principles to teach.
- The process has low tooling costs if room-temperature cure resins are used.
- There is wide choice of suppliers and material types [12].

The main disadvantages are:

- The resin mixing, laminating resin content and laminating quality are very dependent on the skills of laminators.
- Low resin content laminates cannot usually be achieved without the incorporation of excessive quantities of voids.
- The lower molecular weight of hand lay-up resins generally means that the resins have the potential to be more harmful than higher molecular weight products.
- Limiting airborne styrene concentrations from polyesters and vinylesters to legislated levels is becoming increasingly more difficult without expensive systems.
- The resins need to be low in viscosity to be workable by hand. This generally compromises the resins' mechanical/thermal properties due to the need for high diluent/styrene levels [12]. The lower viscosity of the resins also means that the resins have an increased tendency to penetrate clothing etc.

Typical applications for the hand lay-up process are standard wind-turbine blades, production boats, swimming pools and architectural mouldings.

2.2.2 Resin transfer moulding

The automotive industry has used Resin Transfer Moulding (RTM) for decades. RTM (as shown in Figure 2.2) can produce parts more rapidly with lower labour expenses than with the hand lay-up process. The RTM process cycle can be divided into two operations. The first is open mould operations which includes actions such as mould cleaning, release agent application, gel coat spraying, fibre loading and part finishing. The second is closed mould operations involving mould filling and curing stages. Fabrics are laid up as a dry stack of materials. These fabrics are sometimes pre-pressed to the mould shape and held together by a binder, which is called a preform, making it easier to lay into the mould. A second mould is then clamped over the first and resin is injected into the cavity. Vacuum can also be applied to the mould cavity to assist in drawing the resin into the fabrics. This is known as Vacuum Assisted Resin Injection (VARI) or Vacuum Assisted Resin Transfer Moulding (VARTM) [12]. Once all the fabric has been wetted throughout, the resin inlets are closed and the laminate is allowed to cure. Both injection and cure can take place at either ambient or elevated temperature.

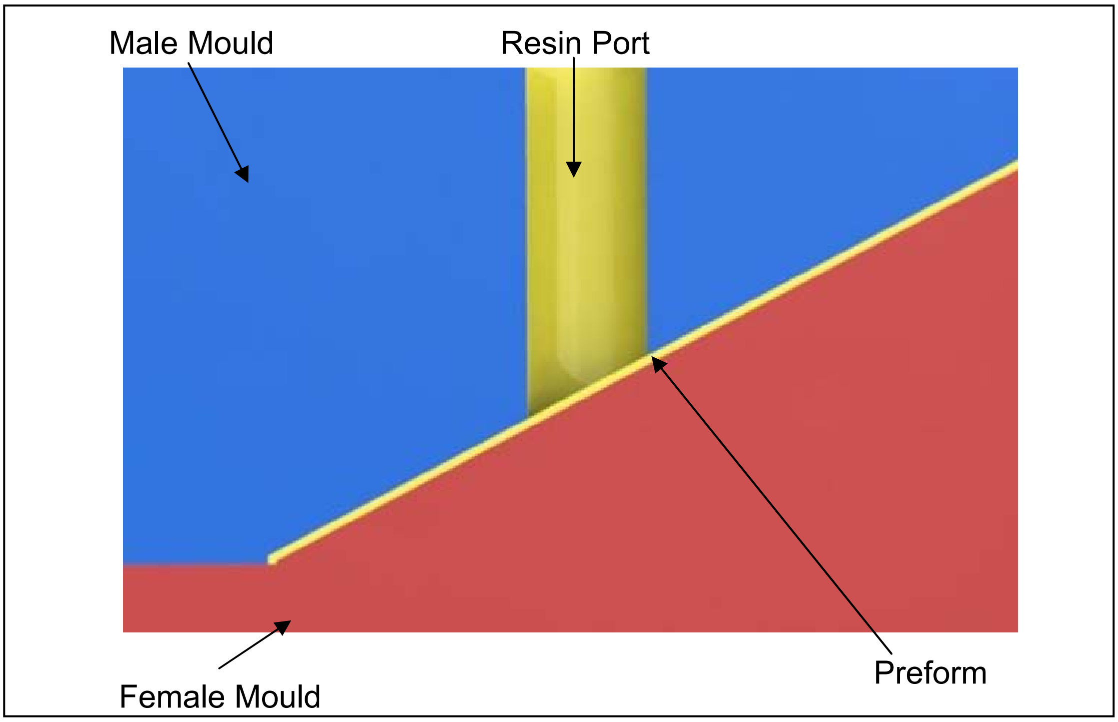

Figure 2.2: The resin transfer moulding process

RTM has been studied extensively over the last few years. Its advantages are well established as it is considered a versatile process, able to efficiently produce fibre-reinforced polymeric composites of different shapes and high structural performance for intermediate volume production runs. In fact, RTM was originally introduced in the mid 1940's. RTM was met with little commercial success until the 1960's and 1970's when it was used to produce commodity goods like bathtubs, computer keyboards, and fertiliser hoppers [14]. As a result, RTM has many current and potential applications in a variety of industries such as automotive, aerospace and sports equipment.

RTM appears to be uniquely capable of satisfying the low-cost/high-volume 500 – 50 000 parts per year in the automotive industry as well as the high performance/lower volume 50 – 5000 parts per year in the aerospace industry [14]. Under certain processing conditions, such as low injection pressure and high fibre-volume fraction, the microscopic flow of resin within the fibre bundle or tow and the fibre being wetted fully can influence the overall flow considerably. In these cases, capillary pressure, P_c, presents a significant driving force for resin impregnation and it should be taken into account to optimise the use of RTM by reducing, for example, the presence of dry spots and macro- and micro-voids.

Each step in the process affects both the processing of the part and the performance of the final part, i.e. the microstructure of the preform must be designed based on two factors. The first is the influence of the proposed microstructure on the permeability (resistance to flow in the fibres) and therefore the time to fill the mould. The second is the effect it will have on the thermo-mechanical loading the part is expected to undergo. Therefore, the microstructure designs of the preform also affect resin selection, viscosity, and processing temperature. These in turn affect selection of tooling material and demoulding time of the final part. Injection must reflect the delicate balance between the following:

- The desire for a short cycle time.
- Avoiding the movement of the fibres due to the resin flow in the mould.
- Fully wetting the fibre bundles, and
- The removal of entrapped air.

Therefore, resin selection, pressure, moulding temperature and viscosity must be controlled to preserve the integrity of the preform. Similarly, tooling must be designed not only for the shape and features of the part but also for the specifics of injection, permeability, cure, and demoulding [14].

Generally epoxy, polyester, vinylester, and phenolic are used in this process, although high temperature resins such as bimaleimides can be used at elevated process temperatures. Stitched materials (material weaves that are stitched in a three-dimensional (3-D) arrangement) work well in this process since the gaps allow rapid resin transport. Some specially developed fabrics can assist with resin flow. Honeycombs and foam cores are not used in the RTM process since honeycomb cells would fill with resin and the pressures involved could crush some foams [12].

Perhaps the greatest benefit of RTM relative to other polymer composite manufacturing techniques is the separation of the moulding process from the design of the fibre architecture. By having the fibre preform stage separate from the injection and cure stage, the designer is able to create uniquely tailored material to fit a specific demand profile precisely. This is accomplished by combining a variety of fibre types and forms. In fact, liquid moulding enables high levels of micro-structural control and part complexity to be attained compared with processes like injection moulding and compression moulding [14]. Other benefits of RTM moulding are:

- High fibre volume laminates can be obtained with extremely low void contents.
- Low capital investment
- Good health and environmental control due to enclosure of the resin.
- There is a possibility of labour reduction.
- Both sides of the component have good moulded surface finishes [12].
- Good tooling flexibility and large complex shapes can be achieved.
- It is easy to add ribs, cores and inserts.
- Part integration is easily achieved.
- A large range of resins and reinforcements can be used.
- The fibre volume fraction is easily controlled [14].

The main disadvantages of RTM moulding are:

- Matched tooling is expensive to manufacture through CNC machining and the tooling is heavy in order to withstand pressures.
- This process is generally limited to smaller components.

- Un-impregnated areas may occur because of the difficulty in predicting the resin flow in the mould and the difficulty in filling the whole mould of intricate parts, resulting in very expensive scrap parts [12].

2.2.3 Spray lay-up

Spray lay-up process uses a hand-held spray gun that chops the fibres and then feeds them into a spray of resin into the mould. The materials are left to cure under standard atmospheric pressure. The spray lay-up process can only make use of glass fibres. Carbon and aramid fibres are too tough for the chopper in a spray lay-up gun. Polyester resin is primarily used [15]. This technology produces low specific strength structures which usually are not desirable on the end product. Spray lay-up has few applications in aerospace and is normally used for developmental work, prototype manufacturing and production of large components in relatively small quantities [4]. Spray lay-up is used to join back-up structures to composite face sheets on composite tools.

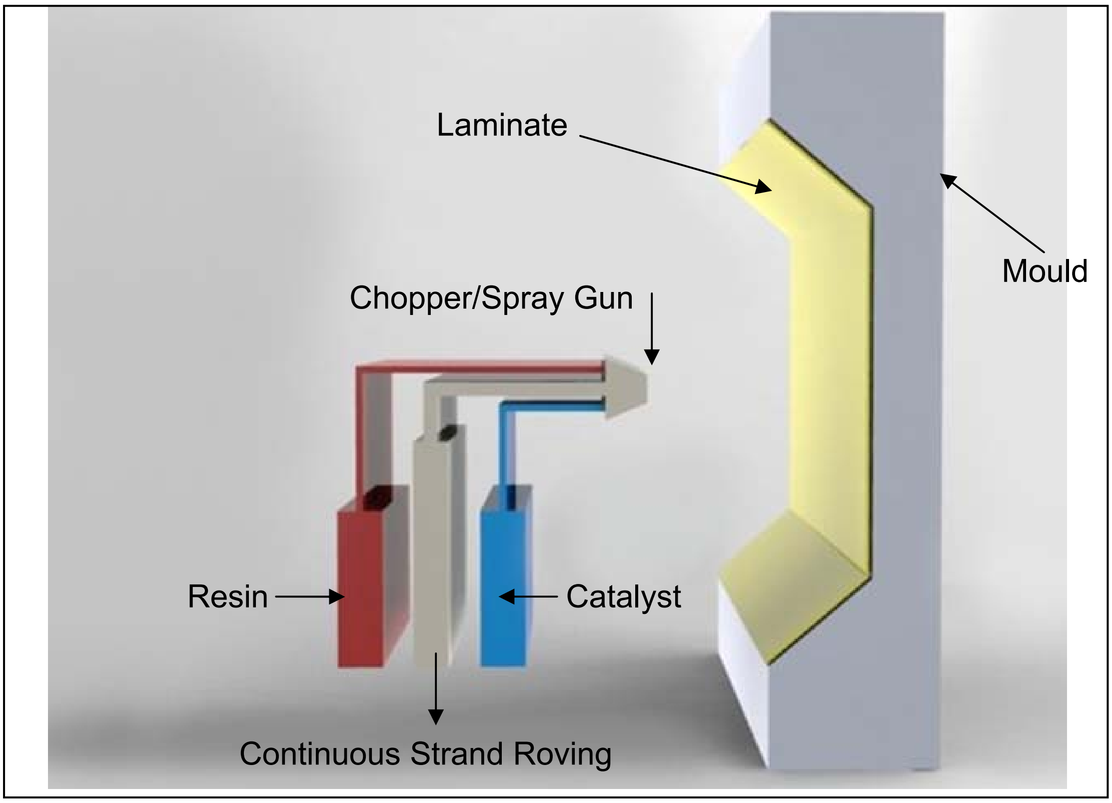

Figure 2.3: The spray lay-up process

The advantages of spray lay-up moulding are:

- Low moulding or tooling costs.
- It is widely used to produce low-cost prototypes, possibly for large products and small series [15].

The disadvantages of spray lay-up moulding are:

- Laminates tend to have a low fibre volume fraction and therefore are excessively heavy;
- Mechanical properties are limited by the use of short fibres;
- Health and safety precautions during processing are necessary;
- The resin needs to be low in viscosity for spraying. This generally compromises the spray lay-up parts' mechanical properties [15].

2.2.4 Compression Moulding

Compression moulding (Figure 2.4) is also called matched metal die moulding or press moulding. In appearance, a composite compression mould resembles a plastic injection mould. It also resembles a RTM mould. The difference is that the compression mould does not have the injection ports that are found on RTM moulds.

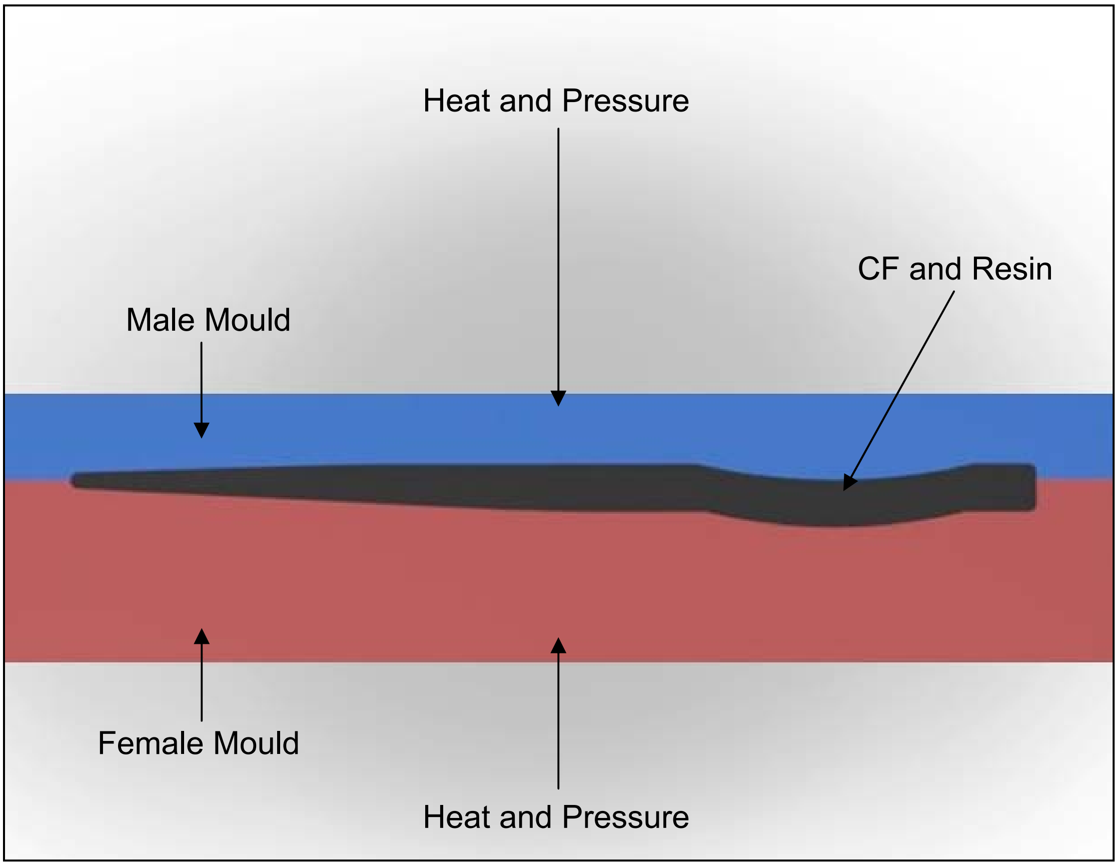

Figure 2.4: The compression moulding process

The resin used in a compression mould is not injected but is poured into the mould before it is closed and placed under compressive pressure. Material that is pre-impregnated with resin (prepreg) is regularly used in this process.

In the pouring process, the two halves of the mould (male and female) are separated, the raw material is placed in the mould by hand and the mould is closed. The compression moulding tool is normally made of fibreglass, aluminium or tool steel [18]. Compression moulding composites are created by building a nest of composite material approximating the finished shape of the product (preform) and laying it in the mould cavity. A proportional amount of thermoset resin is poured over this composite preform and the mould is closed to force the resin around the composite preform, thus filling the mould. The material fills the cavity by means of compression [19]. The benefit of this is that once the mould is closed, it is relatively clean and can be moved around or stored without a vacuum until after curing [18]. Thermoset resin is the most widely used in the compression moulding process. Compression moulding is a high-volume, high-pressure method suitable for moulding complex, high-strength composite parts. The advantage of compression moulding is the ability to mould large and/or fairly intricate parts [20].

The main disadvantages of compression moulding are the cost of the mach tooling and the weight of the tooling to withstand pressure. Another disadvantage is the time it takes to heat up the tooling if a thermosetting resin is used.

2.3 The wetting of fibres

2.3.1 Wetting

According to the thermodynamic definition of wetting, wetting occurs when the contact angle between the liquid and the fibre surface is less than 90° [21]. The thermodynamic definition of wetting is rooted in the concept of surface energy or surface tension. Surface tension results from an imbalance of molecular force in a liquid. At the surface of the liquid, molecules are attracted to each other and exert a net force pulling the molecules together. At the resin/fibre interphase, if the molecules of resin have a stronger attraction to the fibre surface molecules than to each other (the adhesive forces are stronger than the cohesive forces), wetting of the fibre surface occurs. If the resin molecules are more strongly attracted to each other and not to the fibre surface molecules (the cohesive forces are stronger than the adhesive forces), the resin beads-up and does not wet the surface of the fibre [26]. Water has a very high value of surface tension because it has a high degree of hydrogen bonding. Organic molecules with polar groups such as iodide and hydroxyl have a slightly lower surface energy than water. Pure hydrocarbons are even lower, while fluorinated compounds are very low because the fluorine atom does not share electrons and thus only dispersion interaction occurs [14]. This helps a liquid to wet a solid.

Surface energy decreases with the increase in temperature. The surface energy goes to zero at the boiling point of a liquid. In solids, surface energy stays relatively constant with temperature fluctuations. The value of surface tension at the melting point of the solid is also the value for the solid [14].

A few exceptions occur with polymeric liquids. The surface tension value does not reach zero, since polymers do not boil. The surface energy decreases with temperature, but not as dramatically as it does for small molecule liquids. Furthermore, the solid surface energy is approximately equal to that of the melt. Freezing locks the molecules at whatever orientation the molecule had just before freezing. Polymer structure also affects the surface energy. In the molecular structure of lower surface energy polymers there are weaker interacting atoms, whereas high surface energy values arise from strong interactions in polar materials [14].

2.3.2 Zisman plot of critical surface energy

It is time-consuming to measure the surface free energy of liquids. The Zisman plot (Figure 2.5) summarises wetting behaviour and allows predictions of an interpolative nature using liquids.

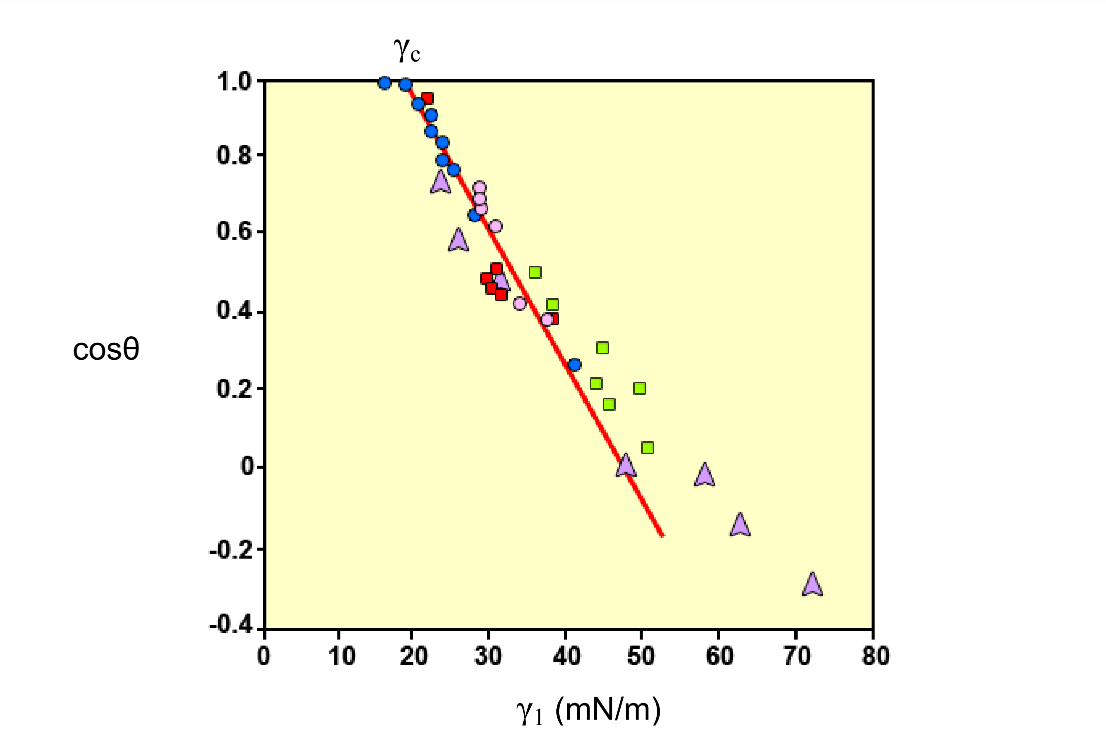

Figure 2.5: Zisman plot of a Polymer [23]

This plot was developed by Zisman at the Naval Research Laboratory, and is created by plotting the cosine (cosθ) of the contact angle versus the surface free energy of various liquids (γ_l) on a given solid [23]. The resulting plot is a straight line. Each polymeric solid has a unique value for where the cosine of the contact angle is in unison. If the contact angle of many different liquids are measured on a surface, and a plot is made of cosθ against γ_l, a curve that can be extrapolated to cosθ = 1 is obtained [23]. This value is known as the "critical" surface free energy of the solid surface, γ_c. The term critical is used because a liquid with surface free energy above the critical value might wet but will not spread, whereas a liquid with surface free energy below the critical value will wet and spread over the solid surface [24]. A liquid with surface energy above the critical value will leave micro-voids at the fibre-matrix interphase because complete molecular wetting may not occur [14].

There are two problems:

- The line of the plot is not really straight, it is more hyperbolic;
- γ_c is not the same as γ_{sl}. (Only if $\gamma_{sl} = 0$ when θ = 0)

γ_{sl} = interfacial free energy between the solid and liquid

The concept of critical surface energy enables one to characterise a polymer and correlate the critical surface energy with polymer structure. Fluorinated materials have low values of critical surface energy, where hydrogenated materials, such as polyethylene and polypropylene, have slightly higher values. For other substituents (Cl, O, N) the critical surface free energy is a little higher. Resins used in composite moulding, such as vinyl esters and epoxies, have a fairly high liquid surface free energy, which can make it difficult to wet fibre substrates. Critical surface energy data shows that fluorinated and hydrogenated materials will be among the materials that will wet fibres the least [14]. Zisman's empirical prediction fails for liquids that form acid-base interactions or hydrogen bonds with the surface. These liquids spread spontaneously on the substrate [24].

2.3.3 Contact angle

The concept of contact angle is rooted in the concept of surface energy. Figure 2.6 shows what is meant by the term “contact angle”.

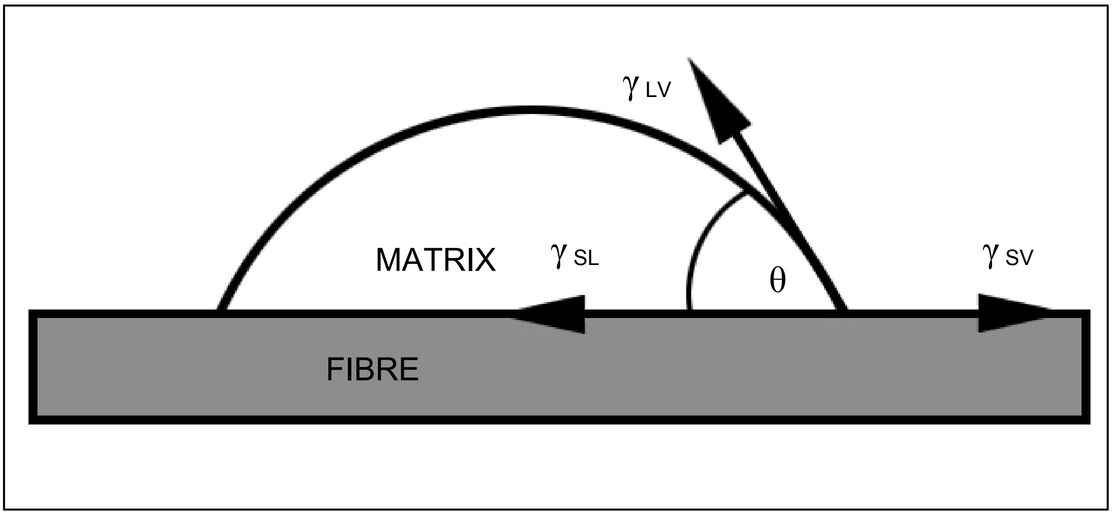

Figure 2.6: The contact angle [22]

Contact angle, θ, is a quantitative measure of the wetting of a solid by a liquid. It is defined geometrically as the angle formed by a liquid at the three phase boundary where a liquid, gas and solid intersect, as shown above in Figure 2.6. When liquid droplets interact with a solid surface, the droplet attains an equilibrium shape. The droplet can be characterised by the angle formed at its edge where the liquid contacts the solid surface. This angle is called the contact angle [14]. The measurement of a single static contact angle to characterise the interaction is no longer adequate. There are a range of contact angles for any given solid/liquid interphase. The value of static contact angles are found to depend on the recent history of the interaction. The drop expands and contracts. When it expands the angle represents the advanced contact angle. When it contracts the angle represents the receding contact angle. This gives a maximum and minimum contact angle [25].

The concept of the contact angle can be used quantitatively to measure interaction between any liquid and solid surface. The surface free energy components of the liquid and solid can be modelled as vectors. The so-called Young equation (Equation 2.1) may be obtained by equating the components of the surface energy as shown in Figure 2.7.

$$\gamma_{sv} - \gamma_{sl} = \gamma_{lv} \cos\theta \qquad [2.1]$$

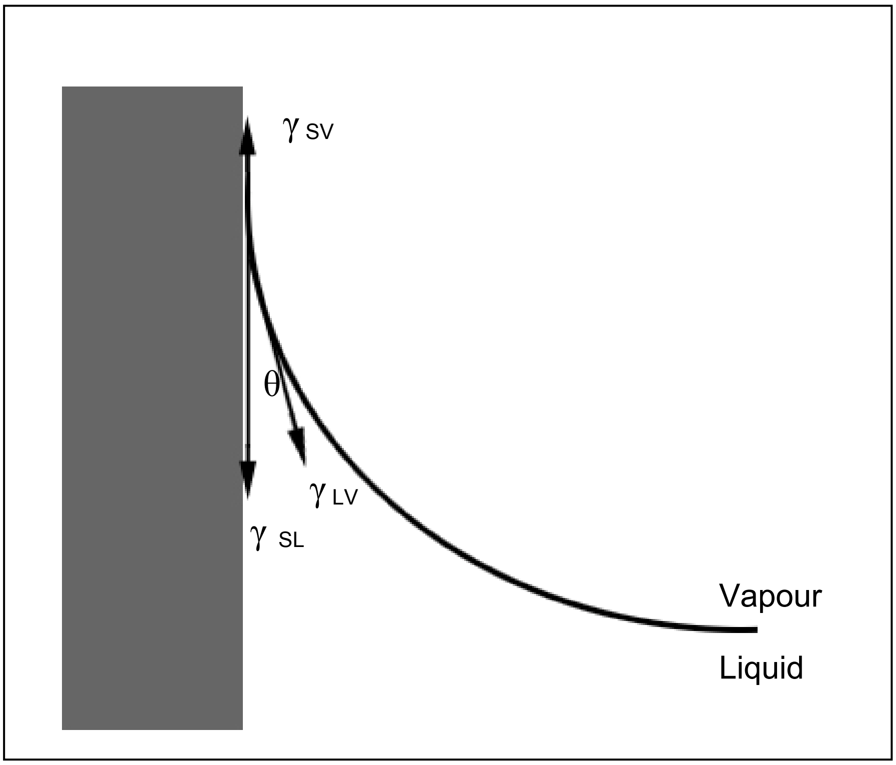

Figure 2.7: Schematic illustrating a suspended fibre in contact with a liquid [22]

where,

- γ_{lv} or γ_l = surface free energy of the liquid
- γ_{sl} = interfacial free energy between the solid and liquid
- γ_{sv} or γ_s = surface free energy of solid

This equation states that the surface free energy of the solid minus the interfacial free energy between the solid and the liquid is equal to the surface free energy of the liquid times the cosine of the contact angle. This equation is derived simply from an energy balance in the horizontal direction [21]. To determine γ_{sl} from γ_{sv} and γ_{lv}, Equation 2.2. can be used.

$$\gamma_{sl} = \gamma_{lv} + \gamma_{sv} - 2\Phi(\gamma_{lv}\gamma_{sv})^{1/2} \qquad [2.2]$$

Combining Equation 2.1 and 2.2, along with some algebraic rearrangements, yields equation 2.3.

$$\cos\theta = 2\Phi\sqrt{\frac{\gamma_{sv}}{\gamma_{lv}}} - 1 \qquad [2.3]$$

The value of Φ is close to 1, so it can be ignored.

Wetting can be defined based on the contact angle:

θ = 0º for spreading

0º < θ > 90º for wetting

90º < θ > 180º for non-wetting

In reality there is no lower limit, although zero is the lowest measurable contact angle. It is not possible to measure an angle less than zero, but it is possible to have a greater thermodynamic driving force. This greater force can be characterised by the spreading coefficient, which is defined as follows:

$$S_{l/s} = \gamma_{sv} - \gamma_{lv} - \gamma_{sl} \qquad [2.4]$$

$S_{l/s}$ = Spreading coefficient

For proper wetting, the contact angle must be 90º or less. From the defining equation, it is expected that low contact angles will be associated with low liquid surface energy and high solid surface energy. Thus, for the best condition for spreading and wetting in composite manufacturing, the surface free energy of the fibre should be high while the surface free energy of the matrix should be low [14].

2.3.4 Measuring contact angle

Fibres present a unique problem in measuring contact angle because of their size (5 – 15 µm). Microbalances which are sensitive to about 10^{-7} grams can be used. In the gravimetric method of contact angle measurement, the fibre is immersed in the liquid of interest and the microbalance is used to measure the force that the liquid exerts on the fibre, as indicated in Figure 2.8.

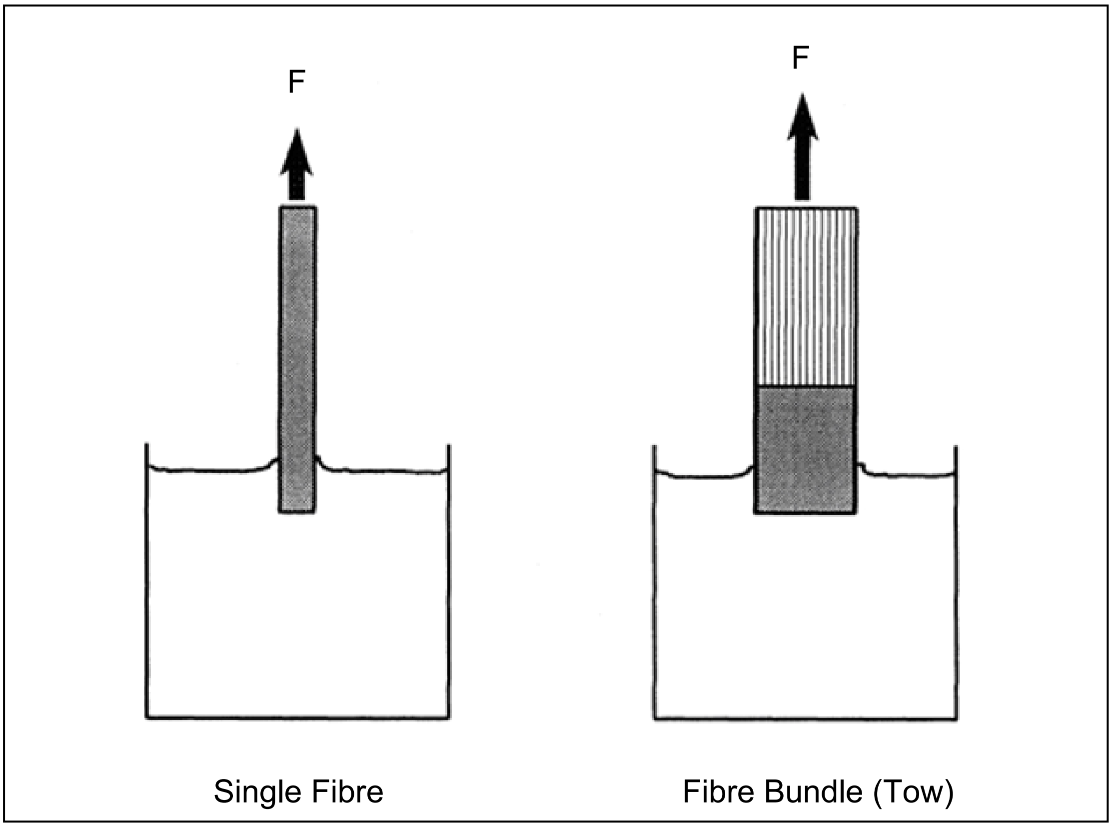

Figure 2.8: Measuring the contact angle of a single strand and a fibre tow [14]

A contact angle will form at the surface of the fluid in the same way as when a liquid droplet is placed on a flat surface. The force exerted on the liquid is related to the contact angle, the wetted perimeter *P*, and the liquid surface energy (γ_{lv}).

$$F = \gamma_{lv} P \cos\theta \qquad [2.5]$$

and;

$$P = \pi d \qquad [2.6]$$

d = diameter of the fibre.

The work of adhesion of the fibre W_A is calculated from the expression [26]:

$$W_A = \gamma_{lv}(1 + \cos\theta) \qquad [2.7]$$

2.3.5 Measurement of contact angle for fibre tows

The mathematical analysis for the contact angle of a fibre tow is relatively easy. Capillary forces caused by change in the interfacial free energy of the system provide the driving force for Poiseuille flow of liquid up the packed bed. This overcomes viscous, gravitational and inertial forces. The capillary equation relates the pressure driving force (Δ*p*) for a single cylindrical channel:

$$\Delta p = \frac{4\gamma_{lv}}{D_e}\cos\theta \qquad [2.8]$$

D_e is an equivalent hydraulic channel diameter [27].

The penetration distance (*L*) of liquid into a capillary tube for a time (*t*) is described by the Poiseuille equation combined with mass balance:

$$L = \frac{D_e}{4}\left(\frac{t\Delta p}{2\mu}\right)^{\frac{1}{2}} \qquad [2.9]$$

Where μ is the liquid viscosity. The gravitational and inertial forces are negligible, allowing considerable simplification in the analysis. The change in surface free energy as a function of time (*t*) may be monitored using an electrobalance. The bundle contact angle (*θ*) may be calculated as a function of time from an energy balance as follows:

$$\Delta\gamma = \gamma_{lv}\cos\theta_b = \gamma_{sv} - \gamma_{sl} = \frac{128(1-\varepsilon)^2 H^2 \rho_f \mu \alpha m^2}{K^2 \varepsilon^3 V_t W_f \rho_t^2 d_f t} \qquad [2.8]$$

where,

- ε = porosity of the fibre bundle
- *H* = height of liquid rise at *t*

- m = weight of liquid in the fibre bundle at t
- ρ_f = fibre density
- α = slope of the wicking rate data on a log-log plot
- K = hydraulic constant
- V_t = volume inside of the tube
- W_f = fibre weight in the bundle
- ρ_t = liquid density
- d_f = fibre diameter

2.4 Composite material selection

There are two basic materials available when selecting materials for composite moulding, i.e. reinforcing fibres and resins (matrix). These materials are available separately or as fibre mats which have already been impregnated with the resin. This is called a pre-impregnated material or prepreg. Prepregs are stored in a freezer to prevent the curing of the resin.

2.4.1 Fibre selection

Every type of fibre has different properties and therefore affects the properties of the composite in different ways. Selection of the reinforcing fibre is based on the mechanical requirements of the moulded component, its environmental requirements and cost. Many types of fibres can be used for composite moulding, including carbon (pitch-based or PAN-based), several types of glass (E, S, S2, or A) and aramid (Kevlar®). Kevlar® is the brand name given to an aramid fibre by DuPont industries. Kevlar® is one of the most widely used aramid fibres. Fibres are available in standards known as rovings or twisted into yarns. The fibres used in composite moulding may be stitched or woven into various two-dimensional (2-D) architectures, as shown in Figure 2.9 or 3-D architectures as shown in Figure 2.10 [14].

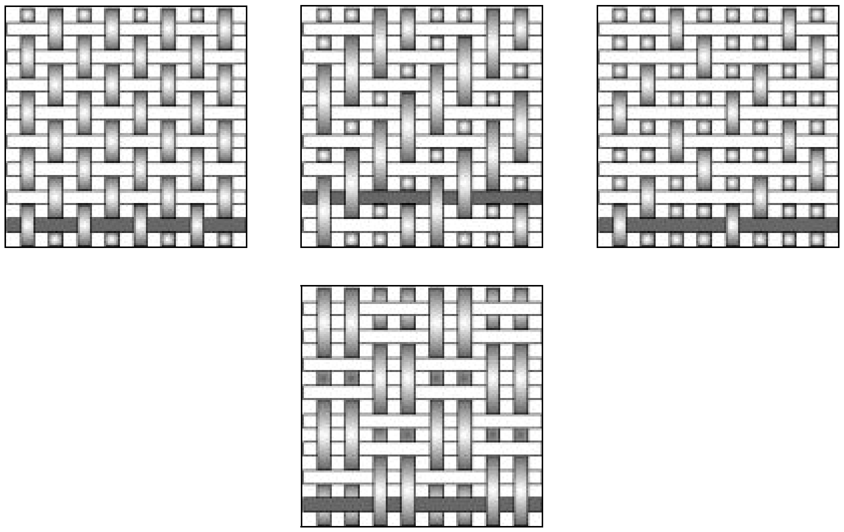

Figure 2.9: Various 2-D fibre weaves [2]

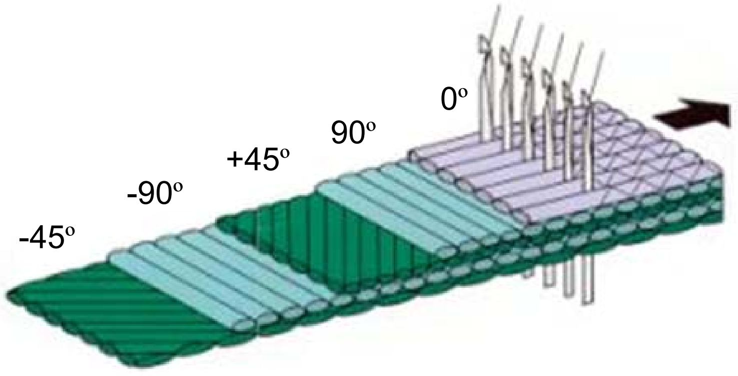

Figure 2.10: Construction of 3-D weave [12]

Glass fibre has good tensile and compressive strength and stiffness. It has good electrical properties, like insulation, and is relatively cheap, although glass fibre's impact resistance is relatively poor. Aramid fibres are fibre filament with high strength and low density, giving them good specific strength. All grades have good resistance to impact and lower modulus grades are used extensively in ballistic applications. The compressive strength of aramid fibres is similar to that of glass fibres. CF has the highest specific stiffness of any commercially available fibre. It has very high strength in both tension and compression and a high resistance to corrosion, creep and fatigue. CF impact strength is lower than that of glass or aramid, with particularly brittle characteristics exhibited by the high modulus and ultra high modulus fibres [12].

Fibre architecture selection depends on performance issues such as modules, strength, durability, compressibility during the manufacturing of the preform and drapability to ensure proper placement of the reinforcement during preforming operations [14].

2.4.1.1 2-D woven fabrics

2-D woven fabrics are made from at least two sets of fibre tows that are interwoven. Balanced properties in the plane of the fabric are thus achieved. Woven fabrics exhibit good resistance to impact. On the other hand, these woven fabrics have poor conformability for placement in complex-geometry moulds. Also, the weave introduces crimping (undulation) of the yarn, which decreases the strength and reduces the effective stiffness of the lamina.

Weaves can be classified according to the spacing between the tows and the overlapping ratio of the tows (Figure 2.9). Fibre weaves with large open spaces in the weave are termed open weaves, while weaves with no space between the tows are termed closed weaves [14]. A normal mat weave can have different orientation of fibres. The fibres seen in Figure 2.9 are orientated 0/90. This is an indication to the angle the fibres have to one another. The 0 indicates the first angle of the fibres. The 90 indicates that the second direction of the fibres is 90° to the first. There can also be a third or fourth direction.

2.4.1.2 Preform

In composite moulding a variety of forms of reinforcing fibres is available. Selection of a preform fibre architecture directly affects the mechanical performance and processability of the part being manufactured and is a critical step in the concurrent engineering process of applying composite moulding to component fabrication. A preform is the assembly of reinforced fibres that is preshaped and orientated by placement in the composite mould prior to the introduction of resin.

Selection of a material and design of the preform are based on criteria for the desired structural performance, balanced against the requirements for processability, long-term durability and cost. The impact on the processability is the need to fully wet out the preform with resin. The factors affecting the wetting of the fibres in the preform are:

- The degree of compaction of fibres
- The orientation of the fibres.

This directly affects the ability of resin to flow through the preform to wet all the fibres in the mould [14].

Another issue of preform design is the potential for placing structural foam cores, metallic inserts or attachment points, or other dissimilar reinforcing material in the mould. Preforms may be constructed with any combination of fibre architecture like continuous fibres, fibre mats, woven fabrics and cores.

2.4.1.3 Selection of fabric architecture

The properties of a part and its processability are dependent on material selection and material architecture. The practical aspect of the choice of the material for a preform includes a number of issues:

- Permeability, which is a measure of the ability of resin to flow through the pores in the preform. Permeability can be highly directional (anisotropic), which is of serious concern for mould design in terms of the placement of a preform in the mould. Permeability is directly affected by the degree the preform is compacted in the mould as well as the preform architecture.

- Compressibility. Some compressibility of the preform is desirable and necessary so that the reinforcing fibres are properly compressed to improve the fibre volume in the final part. However, a high degree of compression improves the mechanical properties of the part at the expense of resin flowability in the mould.
- The ease of handling, (in terms of cutting, stacking and insertion of preform plies) is a serious concern in moderate to high-volume production modes. The easier the fibre handles, the easier and faster it is to produce the preform for composite moulding.
- Drapability or the ability of the reinforcing fibre to conform to curvature in the mould is a factor in the choice of reinforcement form. Drapability must be considered for moulds with intricate curves.
- Strength, stiffness and fibre volume fraction must be considered. A very high fibre volume fraction might be desirable for the final part, particularly for strength and stiffness. The preform must be compacted more in order to achieve a higher volume fraction. The permeability of the preform decreases when this is done. These impacts on the manufacturing possibility and the part properties [14].

Permeability is a very important feature of the preform that influences the selection of the preform architecture, tool design and mould filling during the moulding step. Basic issues related to the role of permeability and methods for determining permeability are:

- Fibre preform consist of solid fibres surrounded by open spaces;
- Adjacent open spaces are connected to form conduits for the passage of fluid;
- Porosity is the fraction of volume that is open;
- A high viscosity fluid will take more force to push through the pores than a low viscosity fluid;
- Open weave results in higher porosity and higher permeability;
- Closed weave mats are difficult to penetrate, but offer higher strength and moduli;
- Effect of preform structure on flow is represented by permeability, κ. The more porous or openings the preform structures have the higher values of κ and are easier to fill [14].

Important points to remember with permeability are:

- Permeability has units of area;
- Permeability does not change by changing the fluid as long as it is a constant viscosity fluid [14].

Permeability, κ, is dependent upon the preform architecture and the resin viscosity and is a measure of the ease of flow through the preform. Permeability may be directional. For anisotropic preforms, three values for the permeability may be required; κ_{xx}, κ_{yy}, κ_{zz}. For isotropic preforms, one value is sufficient; $\kappa_{xx} = \kappa_{yy} = \kappa_{zz} = \kappa$ [3].

Fabric compressibility is a concern which affects both processing and performance of the composite part. During the moulding process, the pressure of the tool closing can compress or deform the fabric, changing the volume fraction and the permeability of the preform. These changes can also affect the performance of the final part. Thus compressibility is an issue that ties processing and performance together [11].

When a preform, that is thicker than the mould cavity, is placed in a mould, and the mould is closed, the preform is compressed and the fibre architecture is changed. A number of changes may occur:

- Changes in the amount of nesting between layers;
- Changes in the fibre packing within individual bundles;
- The aspect ratio of the fibre bundles can change;
- Fibre re-orientation.

When a fabric is compressed in a mould the permeability drops, but the strength increases because of the higher fibre volume the final part will have. The compressibility varies from fabric to fabric, based on yarn bundle size, fibre type, and other factors. There are some points to consider when compressing the preform to elevate the fibre volume fraction. The mechanical properties improve with increasing fibre volume fraction, but not always linearly, and sometimes only to a certain critical point [4]. At 60 – 70% fibre volume fraction, although tensile stiffness continues to increase, the laminate’s strength will reach a peak and then begin to decrease due to the lack of sufficient resin to hold the fibres together properly [12].

2.4.2 Resin selection

Numerous resin systems, sometimes referred to as polymers, are available for the composite moulding process. The resin must satisfy several requirements to be included in the compression moulding category. For processing considerations, the resin should have low viscosity throughout the process. Resins are classified in two types; thermoplastic and thermosetting resin. Following the closing of the mould, the resin should gel quickly and “snap” cure should occur. This means that resin cure cycle tailorability is important. Some important processing characteristics are:

- extended pot-life compatibility,
- low volatility,
- low outgassing during cure, and
- fibre-resin compatibility.

For better performance, characteristics such as strength, modulus, toughness, adhesion to fibres, service temperature and resistance to environmental agents must meet the requirements for the application [12,14].

Thermosetting resins are used most often in compression moulding. Generally, low-performance resins are easier to process and cost significantly less than high-performance systems. The automotive and infrastructure industries tend to use low-cost systems, while aerospace and military applications employ higher-cost systems.

2.4.2.1 Thermoset resin

Thermoset resins, or thermosets, are the most common type of resin used for composite materials [8]. In 1906, Dr. Leo Bakeland experimented with the polymerisation of phenolic resins [28]. Bakeland found that by adding formaldehyde and heat, a chemical cross linkage took place. Modern thermoset resin is formed when a resin and hardener or a resin and catalyst are mixed to form a non-reversible reaction which forms a hard, infusible product. Acid anhydrides and multifunctional amines are the most common hardeners used for thermoset resins. Aliphatic amines yield fast cure times, whereas aromatic amines are less reactive but result in higher glass transition temperatures (Tg) [8]. Bakeland discovered that cotton cloth and paper materials could be impregnated with the resin mixture. This composite could be semi cured and then made into a stack of sheets or wrapped around a mandrel. Subsequently, when put into a hydraulic press, heat and pressure could be applied. Full polymerisation took place rendering hard, dense, reinforced thermoset polymer.

Thermoset polymer can be compared to cement; once cured the thermoset polymer is set, hence the name thermoset. Although thermoset resins will not become liquid again when heated, the mechanical property of the thermoset changes drastically when heated. This softening temperature is known as the Tg, and varies widely from one resin system to the next. Some thermoset resins emit a volatile gas when curing. Thermoset resins, like polyester and epoxy, do not emit a volatile gas and are thus easier to produce.

Thermoplastics can be compared more to wax in as much as the thermoplastic can be remelted and reshaped upon the re-application of heat [12,28]. Thermoset resin is popular because it has a low melt viscosity, good fibre impregnation and fairly low processing temperatures. Thermoset resins are also cheaper compared to thermoplastic resin [8].

Thermoset polymers are uniformly dense and structurally strong materials that will not soften appreciably when heat is re-applied. Thermosets are extremely durable resins that are lightweight and moisture resistant. Thermosets have high mechanical and insolating properties and include a wide range of materials [28]. Some examples are: acrylics, alkyds, amino resins, bismaleimides, epoxy, furane, phenolics, unsaturated polyesters, polyurethanes and vinyl esters. The new materials that are being developed are: cyanate esters, silicones and arylzene resins, together with hybrid resins [29]. The majority of structural parts are made with three kinds of resins, namely polyester, vinyl ester and epoxy [12]. Epoxy resins are predominantly used for advanced composite materials. Epoxy resins are used because of their excellent mechanical properties, retention of mechanical properties when operating in hot and moist environments and good chemical resistance. The other advantages of epoxy resins are that they have good dimensional stability, are easily processed, are low in cost and have good adhesion to a variety of fibres. The reaction between epichlorohydrin and bisphenil A is the basis for the most common epoxy resin. Epoxies cure slowly and several hours are needed to cure completely. Once an epoxy is cured it is very brittle. A second class of thermosetting resin is addition-polyamide resins. It is primarily used in high-temperature applications. Addition-polyamide development has given polymer composites a new opportunity for high temperature applications (250°C) [8].

2.4.2.2 Thermoplastics

Thermoplastics are not cross-linked. Thermoplastics derive their strength and stiffness from the degree of entanglement of the polymer chains and the built-in properties of the monomer units. Amorphous and crystalline are the two types of thermoplastic resins available. Amorphous thermoplastics polymer chains exhibit a high degree of entanglement. The chains disentangle and the resin becomes a viscous fluid when heated. The resin can then be formed and cooled down to form the part. The crystalline thermoplastics show a high degree of molecular order and alignment. When the resin is heated the crystalline phase melts to form an amorphous, viscous liquid. Crystalline resins are actually semi-crystalline with both amorphous and crystalline phases present. This process of crossing the melting or softening point on the temperature scale can be done as often as desired without any affect on the material properties in either state. Nylon, polypropylene and Acrylonitrile-butadine-styrene (ABS) are typical thermoplastic resins [8,12].

Thermoplastic resins offer the potential of reducing manufacturing cost, because thermoplastics are produced faster than thermosetting resin. As no cross-linking occurs, there is no reason to maintain elevated temperatures for an extended period of time. Some thermoplastic resins have much higher glass transition and maximum-use temperatures compared with epoxies and bismaleimides. Thermoplastic resins are far tougher than thermosetting resins, because thermoplastics yield and undergo large deformations before final fracture. One problem with thermoplastics is that thermoplastics exhibit time-dependent deformation, or creep, under sustained load conditions [8].

Thermoplastic moulding is where an uncured laminate consisting of thermoplastic prepreg tape layers, is passed through an infrared oven where it is heated to near melting point. The heated material is then placed in a matching metal die mould for final forming [4].

2.5 Tooling

As all composite fabrication methods require tools to provide the shape of the composite part, the design and manufacturing of the mould is a very important part of the manufacturing process [8]. Tooling must be designed for the shape and features of the final part, and must also include specifics of injection, number and location of gates and vents, permeability, and heat transfer characteristics that affect the cure [14].

The key to success in composite moulding is the tooling design and manufacturing. It is difficult to produce poor quality parts with well designed tooling. It is impossible to produce high quality parts if under designed tooling is used. There is little or no middle ground in the manufacturing process. In contrast to closed moulding, open moulding has the potential to produce varying degrees of acceptable part quality depending on the skill of the person moulding the composite [14].

The tooling requirements include the following: the number of parts, the tool life expectancy, cost-effectiveness, the clamping method, the tool faces must match accurately, it must be stiff (minimum deflection with clamping, injection and opening) and heat resistant (exothermal, heating for cure) [14].

2.5.1 Tooling materials

Common tooling materials include tool steel, electroplated nickel, aluminium, laminate, ceramics, and mass cast materials. Important criteria in selecting a tooling material are the cost of the tool, number of parts per tool, thermal conductivity, coefficient of thermal expansion (CTE), durability, surface quality, and temperature tolerance [14]. The choice of moulding material is especially critical, because the mould will be pressurised and heated. The closest CTE to composite material is tool steel. Tool steel has good thermal conductivity and is durable. The problem with tool steel is that it is extremely heavy and takes a long time to heat and cool. Aluminium tools are easy to machine and are less expensive than steel or ceramic tools. It is lighter than steel tools and are heated up and cooled down faster. Also, they are not as durable as tool steel and their thermal expansion is excessive compared with that of composite material. Graphite or glass-reinforced fibres can also be used to produce a composite mould. Moulds used for composite moulding have excellent surface finish and the mould material CTE can match the moulded material exactly. The only disadvantages are that a master is needed to produce the mould and it can only be used for open moulding methods [8].

Economics is the overriding concern in industry. When selecting a tool, durability must be balanced against cost. These two factors are affected by the cycle time, the number of parts per year and the tooling material itself. Thermal conductivity of the tooling material is important because it controls the heat-up and cool-down time of the tool. This property determines the process time of bringing the mould up to curing temperature and the time it takes the mould to cool down to remove the part. Thermal expansion properties are important because thermal expansion controls the shrinkage and the final dimensions of the mould and part [14].

2.5.2 Important tooling features

2.5.2.1 Clamping

Clamping is a very important feature that a mould designer should incorporate into the design. The most common clamps are: the G clamp, the perimeter clamp, air bags, pneumatic press (30 – 50 tons) and hydraulic press (>100 tons). To select a clamping method the designer should look at a few criteria:

- The surface area of the mould;
- The clamping pressure;

- The cycle time;
- The surface requirement (appearance);
- Thickness uniformity considerations [14].

2.5.2.2 Alignment

Guide pins are typically used to bring male and female mould halves together and ensure that no misalignment will occur.

2.5.2.3 Mould heating methods

- Plate heating: This method relies on heat transfer (conduction). Electrical elements are imbedded in the mould which heats the mould up, but it can take a long time for the tool to heat up. The benefit of this method is that the tool itself does not have to be specially manufactured. There are no extra channels or features manufactured into the tool.
- Integral heating: This kind of heating is the most common method used for composite tool heating. Tubes are machined in the tool and hot water or oil is pumped through the tubes to heat the tool. The spacing of the tubes in the mould must be uniform to ensure uniform heating and cooling of the mould. Heat distribution is better in this method than the plate method.
- Oven: In this method the whole tool is placed in an oven. While this saves machining cost, the cycle time is very slow because the system

relies on convection to heat the tool. The tool takes longer to heat up and cool down.

2.6 Hand equipment required for composite moulding

2.6.1 Brushes

Smooth-haired brushes should be used for the resin application in CF moulding. New brushes should be used with care as a brush tends to shed bristles which stick to the surface of the mould during resin applications. However, this should not be a problem once the brush has been used a couple of times.

2.6.2 Rollers

After applying the resin in CF moulding, ribbed rollers (metal or plastic) may be used to remove entrapped air bubbles in the resin. The roller is rolled over the impregnated reinforcement with mild pressure to remove air bubbles. This consolidation of the laminate can also be done with a brush to eliminate air-bubbles. A brush works best to consolidate the reinforcement in sharp internal corners.

2.7 Flow resistances

The resin encounters two different types of resistance in a woven fabric or preform, i.e. resistance in the fibre tows (which are called throats) and resistance between the tows (called junctions). The resistance caused by the throats is the latent resistance in the woven fibre. Each tow may contain up to 3000 fibres. The tows are very densely packed and resist the flow of resin much more than the junctions.

2.8 Mould filling

The typical composite mould has many curves and corners, making the wetting of all the fibres in the mould difficult. If the mould was a flat plate, the filling of the mould would be easy. However, the more complicated the mould, the more difficult it becomes to wet the fibres completely without any dry spots in the fibre mat.

Most composite mould designers come from an injection mould design background. The injection mould designers do not always take the anisotropic flow in a mould into consideration and their intuitions can be quite wrong [14].

2.8.1 Transverse flow

Most composite parts are thin compared to the parts' length and width, variations in flow through the thickness will have no effect and the part can be moulded as 2-D parts. Multi-layer preforms' thickness permeability can be obtained by averaging the permeability. To obtain the average permeability, assuming several layers with permeabilities $\kappa_{ij\ 1}$, $\kappa_{ij\ 2}$, $\kappa_{ij\ 3}$, and so on through $\kappa_{ij\ n}$, and with total thickness H and individual thicknesses designated by h, the average permeability can be calculated as:

$$\overline{K_{\bar{v}}} = \frac{1}{H}\sum_{k=1}^{n} h^{k} \kappa_{\bar{v}}^{\ k} \qquad [2.9]$$

The averaging of the permeability is not perfectly accurate, because the variation in permeability through the thickness of the part leads to non-uniform flow profiles and the averaging of the permeability is based on the assumption that the fluid undergoes uniform flow through the preform.

2.8.2 Non-uniform filling

A variation in both permeability and resin viscosity leads to non-uniform filling in the mould. Once the preform is placed inside the mould, design factors, preform manufacturing techniques or wall and edge effects can lead to spatial variations in permeability. The resin viscosity is heavily dependent on temperature and degree of cure. The heating of the mould wall and polymerisation during the filling of the mould may lead to large spatial and temporal variations in viscosity. The dissolution of the binder also effects resin viscosity significantly. The variations in resin viscosity are due to factors such as the resin polymerising. This causes the viscosity of the resin to increase as time passes. The gel time of a resin is when there is a sharp rise in the viscosity of the resin as it starts to solidify into a cross-linked structure.

Gelation sets the time available for filling large parts. The resin formulation may be changed to suit processing conditions.

Polymerisation begins when reaction components first come into contact with one another. At this point, the viscosity of the mixture is a mean value of the resin and hardener viscosities and is denoted by μ_u. The subscript “u” denotes that the mixture is still uncross-linked or the initial viscosity of the resin/hardener mixture. The reaction of the two substances has not yet begun. At the beginning, the resin viscosity is very low. Viscosity begins to rise and shoots up rapidly just before the gel time because of the progression of the chemical reaction. The resin impregnation of the preform must be completed well before gelation of the resin occurs [14].

2.9 Microscale flow

Micro-voids occur when the resin does not completely fill the tow. This happens more frequently with higher fibre volume fraction parts. Figure 2.11 shows the tows as circles and the junction as the areas around the tows. The flow in the mould can move past the tows without fully impregnating the tows.

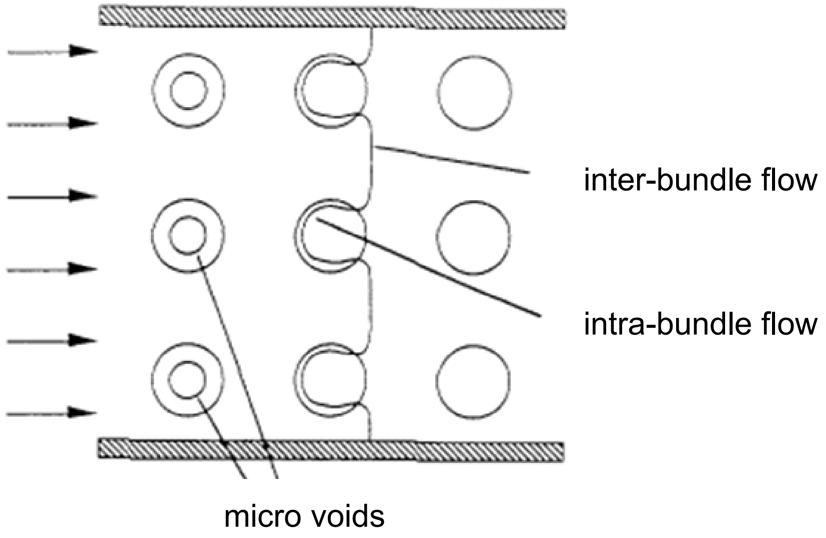

Figure 2.11: The forming of micro-voids in composite materials during composite moulding [14]

Micro-voids are formed when the resin flows around fibre bundles before it can penetrate them, trapping some air inside. Figure 2.12 shows the resin just reaching a tow containing many fibres. The flow front moves around the tow and actually passes it. The fluid keeps on impregnating the tow after the flow front has passed, but if the air was not evacuated at the beginning of the filling process, air is trapped in the tow and so a micro-void is formed at the centre of the tow.

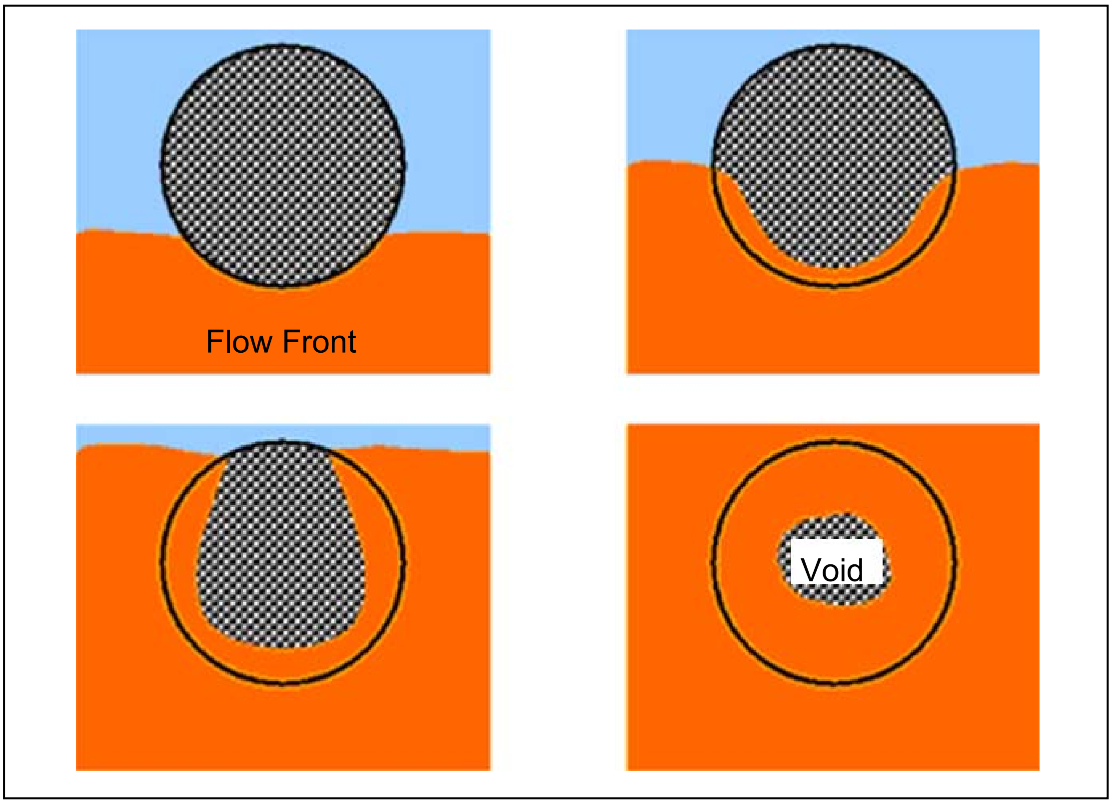

Figure 2.12: Micro-void formation in composite materials [14]

2.10 The fibre/resin interphase

The boundary between the matrix and fibre is not necessarily a simple 2-D boundary. A 3-D boundary called an interphase can develop. In the interphase, properties can vary from the bulk properties (e.g. viscosity, polymer properties, sizing, and concentration). In addition, surface treatment can affect local cure of polymer near the fibre surface.

Fibre-matrix interaction is usually considered in terms of equilibrium values, but it is important to remember that the entering resin will swell and dissolve the surface treatment system and form an interphase over a period of time, not instantaneously. Fibre-matrix interaction is really a time dependent process. For example, if a part is filled from multiple injection ports, both old and new interphases could exist. Local properties could vary depending on how long the interphase has been forming and whether it has reached its equilibrium value.

2.11 Fibre/resin interface optimisation

Although a composite is made from a strong fibre and a well-suited resin, the result may not necessarily be a strong material. The reason is that the fibre-matrix interphase is also very important in determining the mechanical strength of the composite material. The first attempts to improve the fibre/resin interaction were chemical modifications to the resin system. Ultimately, the successful manufacturing of a composite part depends on the quality of the fibre-matrix interphase. The suitability of using a particular resin system with CF reinforcement depends on the wetting ability of the resin. Unfortunately, some resins, such as aromatic polyphenylene resins, have poor wetting ability but possess other desirable characteristics that dictate the use of aromatic polyphenylene resins in composite structures. There was a need to overcome the poor wetting ability by developing techniques to alter the fibre surface. This promoted an increase in fibre–matrix adhesion. Several surface treatment methods exist, the most common of these techniques are: acid treatment, oxidation treatment, plasma treatment, carbon coating, resin coating, ammonia treatment, and electrolytic treatment.

Acid treatment: Acid is used to improve the interfacial bond between CFs and resins with poor wetting ability. Fibres are wetted with a sulfonic acid solution, dried to drive off the solvent, heated to allow the acid to react with the surface or with itself, washed to remove any unreacted acid, and then dried to remove the washing solvent. Hypochlorus acid has also been used, and the resulting composite shows a significant increase in shear strength.

Ammonia treatment: Heat treating CFs in an ammonia atmosphere at 1000°C prior to impregnation with resin shows an increase in the shear strength. Heating is accomplished by passing a current through the fibres as the CF passes through a controlled atmosphere containing 10 – 100% ammonia. A non-oxidising gas like nitrogen, argon, hydrogen, or helium is used to achieve the balance. The exposure time is normally from 1 – 60 seconds. As the concentration of ammonia increases, the shear strength of the composite increases. The problem with this is that the tensile strength of the fibre decreases. For optimal properties a balance must be found between the ammonia content of the atmosphere, exposure time, and fibre temperature. Resins that bond well with CFs treated this way are those that bond to amine functions during cure. This class of resins include epoxies, polyamides, polyethylene, and polypropylene.

Carbon coating: Low-modulus CF has high shear strength. Compared with high-modulus CF, low-modulus shows superior bonding ability with resin. This is due to an isotropic surface layer of carbon on the low-modulus CF. The exposed surface is believed to bond chemically with epoxy resins. In contrast, high-modulus CFs are more ordered due to graphitisation and orientation of crystallites. The surface is anisotropic and there are large areas of crystallite basal planes which have low reactivity and show poor bonding with most resins. One technique to improve interfacial bonding for high-modulus CF is to deposit a layer of isotropic carbon on the surface. The two methods of doing this are:

- CFs are electrically heated to approximately 1200°C and then exposed to an atmosphere containing methane and nitrogen. A uniform carbon coating is formed when the methane decomposes onto the surface. CF made this way shows a twofold increase in shear strength with a small loss in tensile strength compared to untreated fibres.
- CFs are impregnated with thermally carbonisable organic precursors such as phenylated polyquinoxaline. The precursor is then pyrolysed at a high temperature and is carbonised on the surface of the CF. Wikipedia states that, “Pyrolysis is the chemical decomposition of organic materials by heating in the absence of oxygen or any other reagents, except possibly steam” [6].

Electrolytic treatment: CFs can be electrolytically treated to improve the CF surface characteristics for improved bonding to resin. Electrolysis is used to change the reactivity of the fibre surface or to deposit chemical groups on the fibre that will bond to the resin. Electrolysis is accomplished by pulling the fibre through a series of rollers that are electrically charged in positive/negative pairs. After the fibre has passed through the rollers, it is dried before being wound onto a take-up reel. The electrolytic solution is normally an aqueous-based caustic mixture. If the fibre is used as the cathode and vinyl monomer is added to the electrolysis solution, the fibre will be covered with a vinyl polymerisation product. This greatly improves the bond strength between the fibre and some resins [14].

Oxidation treatment: A fibre surface roughening process is also used. This is achieved by exposing the fibre to formats, acetates and nitrate salts of copper, lead, cobalt, cadmium and vanadium pentoxide. The fibres are oxidised by exposing them to air or oxygen in the range of 200 – 600°C. The increase in surface area leads to greater bond strength compared to untreated fibres [14].

Plasma treatment: Plasma treatment of the fibre surface significantly improves the interfacial bonding. Fibres are drawn through a plasma chamber in which thermal plasma of argon, oxygen, or a mixture of hydrogen and nitrogen or carbon fluid and oxygen is generated. Argon plasma introduces active sites that react subsequently with atmospheric oxygen. Oxygen plasma introduces oxygen both by direct reaction and by active sites. Carbon fluoride/oxygen plasma essentially results in an etching and oxidation of the fibre surface. Nitrogen/oxygen plasma introduces amine-like groups on the fibre surface that are able to participate in cross-linking reaction for epoxies. The plasma can reach temperatures of up to 8000°C. The time that the fibre spends in the plasma must be closely controlled to ensure that the fibre surface temperature does not rise too high [14].

Resin coating: A polymer coating can also be applied to increase the interfacial bonding. Thermoplastic polymers like polysulfone or polycarbonate are coated onto the surface of the fibres before the fibres are impregnated with a thermosetting resin. The resultant material shows a significant increase in shear strength. Elastomers, like urethane polymers, can also be used to achieve this. The elastomer can be applied as a sizing or it can be blended with the resin. The development of an interphase region provides for a more efficient distribution of stresses and reduces the tendency for cracks to develop at the interphase. Adding compatible elastomer and matrix material combinations results in a gradual transition of properties within the interphase. These composites have enhanced toughness and high impact strength. A significant improvement in composite mechanical properties can be provided by tailoring the interphase properties [14].

There are many techniques that can be used to improve fibre-matrix bonding strength. Whiskers can be grown on the surface of the fibres. These whiskers help with the mechanical interlocking of the resin around the fibre. Irradiation by neutrons during curing also improves fibre-resin bonding. Oxides, organometallics, isocyanares, and metal halides have all been used with some success by suitably coating the CF surface and then impregnating the fibre to form the composite [14].

2.12 Fibre tows

Fibre bundles behave differently to single fibres. Single fibre contact angles reflect expectations based on surface free energies. It is possible to compute a wicking time from single fibre data. The wicking time values obtained via calculations are about the same for all the surface treatments [14].

The data obtained for actual fibre tows differs from the single fibre data. This is because the physical act of applying surface treatment to fibre tows does not create perfect arrays of uniformly coated separate fibres. In reality, the surface treatment creates a bridge, intertwined network with open and closed capillary channels. The act of wicking can involve swelling, dissolution, and maybe an increase in fluid viscosity as the liquid moves through the network [14].

2.13 Cure

The cure process is governed by the physical-chemical processes of mass transfer with chemical reaction, heat transfer with internal heat generation and the fluid dynamics of the flow of the polymer. These features are characteristic of traditional chemical processes that have been modelled by application of principles of chemical reactor engineering. The cure process models may be generated through the linking of three sub-models. The heat generation, extent of cure and the viscosity can be generated by the thermokinetic model which requires physical and chemical data specific for the materials under consideration. The output from this model may be used as input to first, a heat transfer model to generate temperature/time profiles and second, a flow/compaction model to investigate the influence of pressure-time cycles. The heat transfer and flow/compaction models are specific to the geometry of the part and characteristics of the tooling assembly. Consequently, the part must be specified in terms of shape (e.g. flat plate), dimensions, geometry and composition of the preform [14].

2.14 Additive Manufacturing

Additive Manufacturing (AM), or Solid Freeform Fabrication (SFF), is a process where parts are created by continually adding material. The information to create the part is obtained from Computer-aided Design (CAD) data. The CAD data is “sliced” in layer thicknesses that the AM machine can process. These slices vary from 0.02 mm to 0.2 mm depending on which AM machine is used. The slices are added in sequence on top of one another to create the part [34].

There are several AM processes available [34]. Some of the AM processes used are: Laser Sintering (LS), Fused Deposition Modelling, Stereolithography and 3-D Printing.

LS is suitable for composite moulding as the materials are strong enough to withstand the related temperatures and pressure. The processes where metals are sintered or sprayed in AM are too expensive and time-consuming to justify use for composite mould manufacturing.

2.14.1 Laser Sintering

The Laser Sintering (LS) process was developed in 1986 and was patented in 1989 [33]. The manufacturing technique is an increasingly important method for creating complex shaped prototypes for use in automotive, medical and other industries [35]. LS is a method to produce working models of parts that can be analysed, tested or used to construct mouldings for cast parts [36]. LS are being used more and more for rapid manufacturing (RM) of usable parts. The LS process is where a CO_2 laser beam, either in continuous or pulse mode is used as heat source for scanning and joining powders in predetermined sizes and shapes of layers. The geometry of the scanned layers corresponds to the various cross-sections of the CAD models or Standard Triangulation Language (.stl) files of the object [37]. The LS machine can use a number of different powders to build parts. Polymers are mostly used in the sintering process, many of which are thermoplastics such as nylon, elastomer, or polycarbonates. This is because a thermoplastic can be melted using much lower temperatures than most metals and the thermoplastics can easily be re-melted to create a bond between each layer [36]. The material density produced in the LS process is on average 85% of that which can be obtained using other production methods such as injection moulding [38]. A schematic of a LS machine can be seen in Figure 2.13.

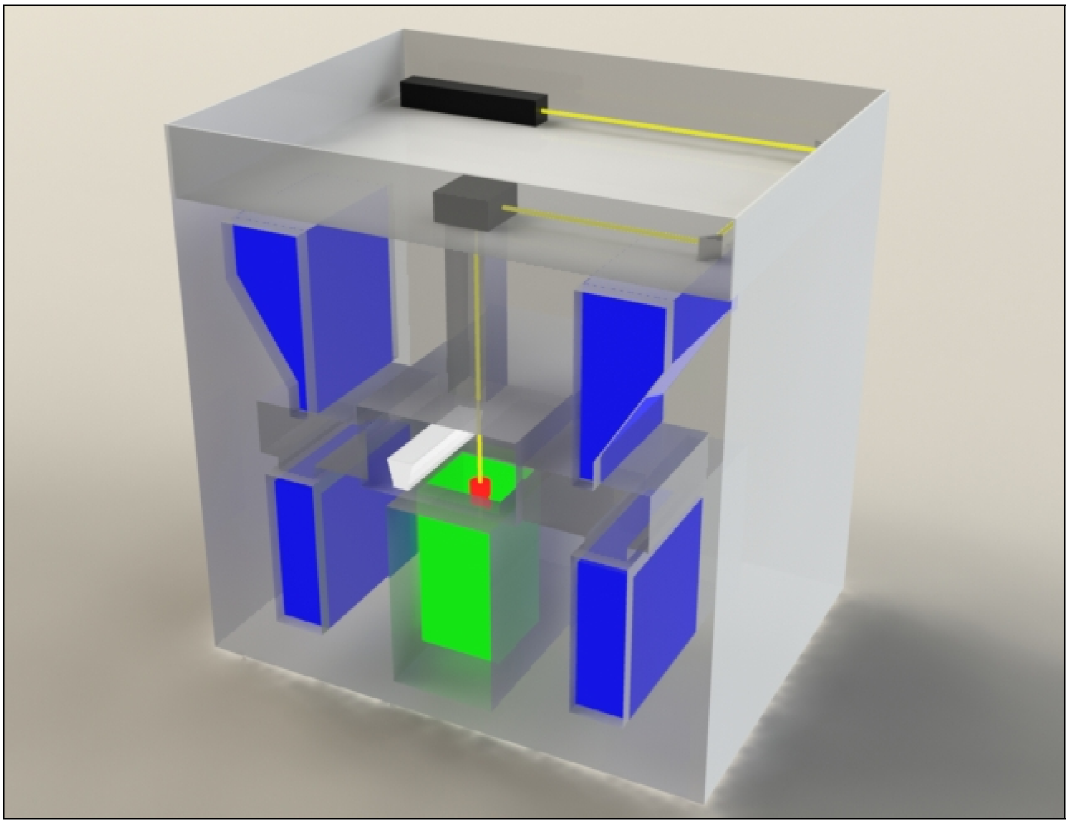

Figure 2.13: Laser Sintering Machine

In Figure 2.13, the green box is the building bin where the building platform is to be found. The building platform is the part that moves a layer thickness down after each layer is sintered. The red component is the part being sintered. The top blue parts are the powder supply bins. The powder is stored in the powder supply bins and is deposited into the recoater (white component) which deposits a new layer after the building platform is lowered down a layer thickness. The bottom blue components are the overflow bins. Any excess powder in the recoater is dumped into the overflow bins. The laser that sinters the powder can be seen at the top and is directed into the building chamber. A detailed view can be seen in Figure 2.14.

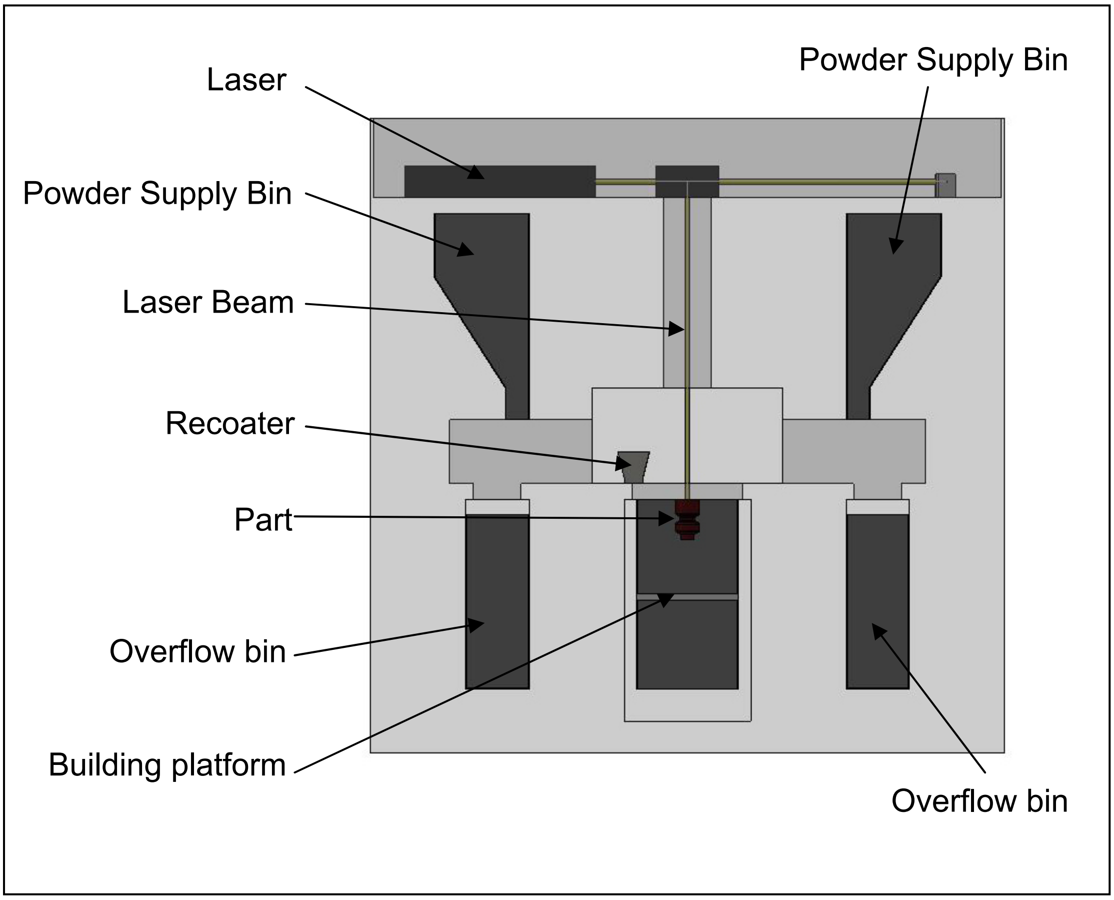

Figure 2.14: Detailed view of LS machine

Weak or low quality parts are mainly caused by poor quality powder [34]. Each time a part is built there is unsintered powder around the part. Poor quality powder is created by the re-use of powder and the refresh rate is not correctly sustained. This powder is removed and can be re-used to make other parts. As the powder is re-used, the appearance of the LS parts deteriorates. Some of these visible flows are:

- Rippling surfaces;
- Weaker material properties as a result of poor sintering;
- Densification processes [34].

The building area in plastic machines or metal machines is filled with nitrogen to keep contaminates out, reduce the risk of oxidation and to avoid potential combustion of powder particles. Laser output is minimised through maintaining the temperature of the building area just below the melting point of the build material [40]. The CO_2 laser, typically 50 watt in the case of a plastic machine, then draws each slice of the CAD model on the surface of the powder, adding just enough energy to bond the layer to the layer just below it [40]. The work platform moves down one layer thickness, typically 0.15 or 0.2 mm, and the roller or recoater then moves in the opposite direction. The process repeats until the part is complete.

In the plastic powder LS process, no support material is needed because the unsintered material supports the part. The finished part is embedded in a cake of surrounding powder, which supports it during the manufacturing process. The powder cake serves a useful purpose as it retains heat, and avoids rapid cooling, which causes internal stresses. At the end of the build, the platform on which the part rests is raised, cooled and the excess powder is removed [40].

The time needed to build a part using the LS process depends on the volume of the part and the height of the object. Because the machine builds the part layer by layer, an object with a set amount of volume, placed on its end will take longer to build than the same part placed on its side [36]. The new layer must first be heated to the desirable temperature before the layer can be scanned by the laser. This takes 10 – 20 seconds, depending on which machine and powder is used.

There are several factors causing accuracy errors in the LS process. The most common of these errors are caused by:

- The laser scanning system;
- Material shrinkage;
- The laser beam spot size and the heat affected area;
- The slicing software and the step effect caused by the layer process;
- Random errors [41].

Probably the biggest problem with any AM process is the step effect. The step effect occurs as a result of the layers that the machine sinters. The machine cannot sinter a part with an angle or a rounding exactly as the part was designed. As can be seen in Figure 2.15, the designed profile is in black, whereas the sintered profile is in red. This problem is only seen in the Z direction between layers and gets bigger as the angle between the layers decreases. At the bottom of the half circle the layers do not differ much, but the higher the profile goes, the more the layers differ which can result in a big problem in the part. The parts should be placed so that the rounds in the part show upwards to the laser. This helps to make circles round and not oval.

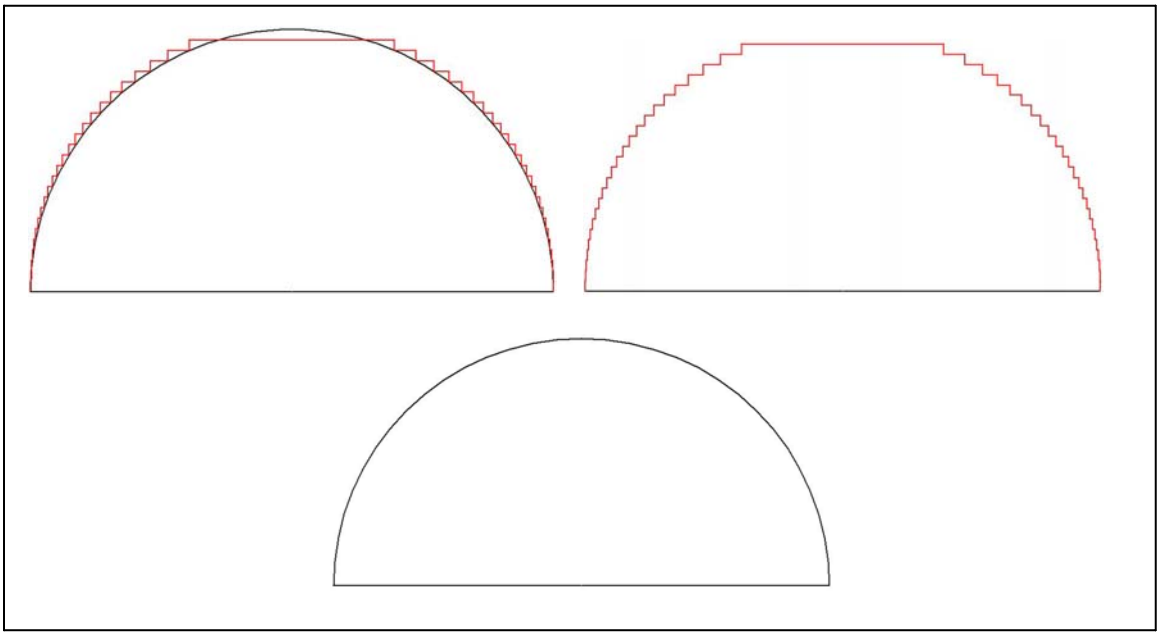

Figure 2.15: The step effect in the LS process

Another example of the step effect can be seen in Figure 2.16.

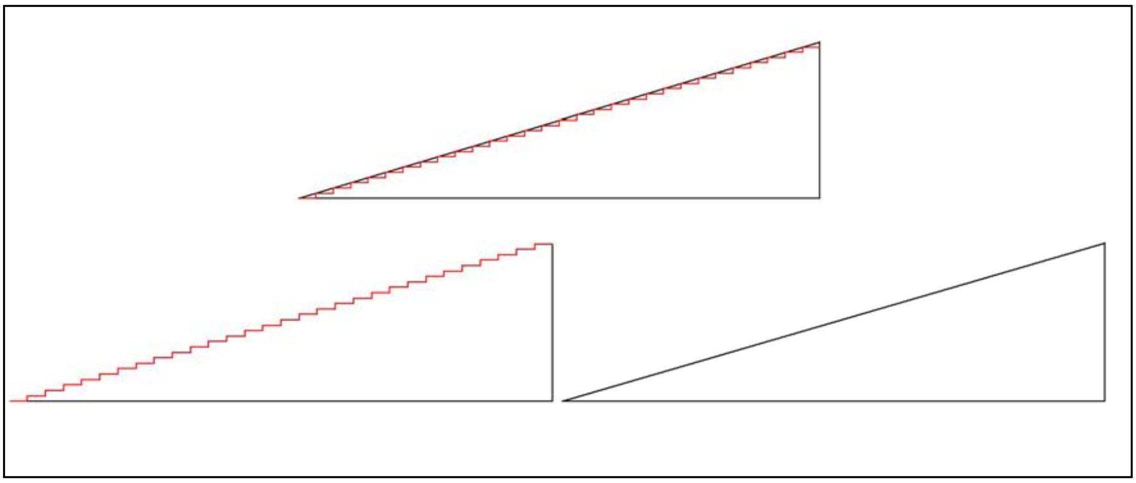

Figure 2.16: Another example of the step effect

There are various methods of improving the surface of LS parts. The parts can be sandblasted, colour impregnated, painted, covered, coated or tumbled [39].

CHAPTER 3

METHODS AND TECHNIQUES

3.1 Methods used to conduct the experiments

Suitable moulding parts were chosen or designed and the moulds were updated to suit the laser sintering (LS) process. The mould was sintered on the EOS P380 LS machine. Any excess powder was cleaned off the mould and it was then coated with a automotive clear lacquer. The mould was left to dry for two hours and thereafter a second coat of clear lacquer was applied. The mould was coated until a compatible to CNC milling surface finish was obtained for composite moulding. Composite material was cut and a preform was manufactured to fit in the mould. The preform was placed in the mould and a part was moulded as described in Chapter 4.

Thereafter the moulded part was inspected and measured to check that it was geometrically correct and accurate. Further modifications were made to the mould. This was done in order to make the manufacturing of the mould as affordable as possible. If it can be proved that this method of moulding can be effectively applied to CF moulding, ways will be investigated to reduce the cost of the mould as the sintering process is expensive. Because the LS cost depends on the volume and height of the mould, the mould was redesigned to be as small and to use as little material as possible. The possibility of using a material to fill the back of the mould was investigated. This would mean that the back could be hollowed out to save on material and cost of LS. A suitable material was tested to use as back filling material. Experiments were conducted to determine the minimum wall thickness that could be used to decrease the moulding cost and time to a minimum. The findings were applied on a new mould and parts were moulded to see how many parts could be produced from a mould. The geometry of the parts was noted to see if the parts remained geometrically stable. The conventional method of moulding and the LS moulding were compared to determine what the improvements and disadvantages were of the sintered moulding method. If the geometry of the parts remained constant, it could be assumed that the moulding method worked. If the geometry of the parts differed, a study would be done to determine how it differed from the moulding geometry.

3.2 Moulding methods

The most suitable moulding methods for LS sintering parts are RTM, hand lay-up or compression moulding. Compression moulding was chosen in this study because of the simplicity of the mould design and the ease of moulding parts using this method. A suitable way of editing the mould was examined to make the mould as cost-effective as possible, but durable enough to do a long production run. The moulding process, as developed through the research, can easily be adapted to the other composite processes.

3.3 Materials used for moulding

The composite materials most used are CF, Aramid fibres and glass fibre. These three materials were used in the study, although CF was the primary material.

3.4 Resins used in the study

Thermoset resin was used in the study. This type of resin is easy to work with and is relatively affordable and freely obtainable.

3.5 Post curing temperature

The post curing temperature depends on the resin that is used as every resin has a different curing temperature. The curing temperature should be less than the melting temperature of the material used for the mould. The melting temperature of polyamide is 180°C – 183°C, although the softening temperature of polyamide is 160°C. The temperature should not be too high as the thermal expansion of the moulding material can cause the part to be geometrically incorrect. The higher the temperature, the more the mould will expand and the part geometry will be affected.

The application of the part also affects the curing temperature. The higher the quality of the part, the higher the quality of resin which means the curing temperature is higher. There are high strength and temperature resins available, however its curing temperatures are very high.

The cycle time needed to produce a part also influences the curing temperature. The higher the curing temperature, the faster the resin cures. A higher temperature however, will lead to a higher thermal expansion and the part's geometry will be affected.

3.6 Method of measuring

The parts were measured with a 3-D scanner to obtain the parts' profiles. These profiles were compared with the CAD files and the deviations were noted. Two different methods of digitising were used:

3.6.1 The Renishaw Cyclone touch probe 3-D scanner

The Renishaw Cyclone machine, as seen in Figure 3.1, is just one of the many Co-ordinate Measuring Machines (CMMs) available on the market. These machines have evolved from simple layout machines and manually operated systems to highly accurate, automated systems for inspection, measurement and data capturing. CMMs are accurate to 0.012 – 0.014 millimetres. CMMs use a touch probe or a laser probe to capture the data needed. The touch probe is known as a contact probe, and the laser probe is known as a non-contact probe.

Figure 3.1: The Renishaw Cyclone scanner

The first CMM machine was built for Rolls-Royce who needed an accurate method to measure pipes for the Anglo-French Concorde engines. The first low trigger force touch probe was designed to do this quickly and accurately. Since then, a number of different touch probes and laser probes have been designed [30].

3.6.2 Konica Minolta 3-D non-contact scanner

This is a non-contact 3-D digitiser, which is capable of capturing 3-D shapes of objects with the simple operation of a compact camera. A 3-D digitiser is an instrument that scans an existing solid object and sends the 3-D data obtained to a computer for processing. This process is not as accurate as using a CMM, but is still accurate to 50 µm (0.05 mm). With this process it is possible to scan large objects such as cars, planes, etc. [31]. The camera can be seen in Figure 3.2.

Figure 3.2: Konica Minolta 3-D Digitiser [31]

3.7 Industrial partnership in the experiments

The mould used in the first and third experiments was designed by the company Leatt Corporation. The Leatt Corporation designs, develops and manufactures spine and neck protection equipment for all forms of motor sports. The Leatt-Brace, seen in Figure 3.3, is one of the products the company manufactures. The brace is designed to protect the neck of a motorcyclist or the driver of a car during an accident. The company has its global distribution headquarters in Nevada, USA, and operates its production and research and development facility from Cape Town in South Africa. The company distributes its products to a global customer base.

Figure 3.3: Leatt-Brace Moto-R [32]

Leatt Corporation was started in 2004 and began producing the Leatt-Brace in October 2005. During the development of the production process, the company sought a method to produce moulds cheaper and faster than the current method the company was using. A few prototypes were made at the

CRPM and when an industrial partner was needed to assist with research, the Leatt Corporation was approched. Due to the willingness of the company to be involved with research, their products were used as case studies for the research project.

The company uses compression moulding to produce the composite parts for the brace. The moulds are CNC machined from aluminium and then polished with a high speed CNC head. Most of the moulds are produced in-house. External contractors produce some of Leatt Corporation’s moulds when it is not possible to produce them in-house. This is a long process and can take up to three weeks to produce a fairly simple mould.

CHAPTER 4

EXPERIMENTS

The experiments were done in a way to determine firstly if it is possible to use the LS process to manufacture CF parts. When this was determined, a way to make this more cost-effective was determined.

4.1 Experiment 1

4.1.1 Methods used to conduct the experiment

The experiment was conducted using a compression moulding tool designed by the Leatt Corporation. The mould was sintered on the EOS P380 LS machine in PA2200 polyamide powder. The mould was coated with two layers of clear lacquer to improve the surface finish of the mould and to seal the pores in the material where after it was coated with release agent before the materials were placed in the mould. The CF and Kevlar® were cut by hand from a sheet using templates for each piece and then placed in the mould by hand. The mould was then filled with resin by hand and closed. It was placed in a jig and clamped with car jacks. The closing pressure was 1 ton. The jig was placed in an oven at 80°C for 40 min. This is the same temperature and pressure applied on the CNC moulds that the company use traditionally. The jig was then taken out of the oven and the mould was removed from the jig. The mould was opened using a chisel and wedging it open to remove the part. The mould was cleaned in preparation for the next part. Any resin that was still on the mould was removed and then it was treated with release agent again and the process was repeated.

4.1.2 Mould used to conduct the experiment

The original mould consists of five pieces (Figure 4.1). There is one piece for the bottom and four pieces for the top.

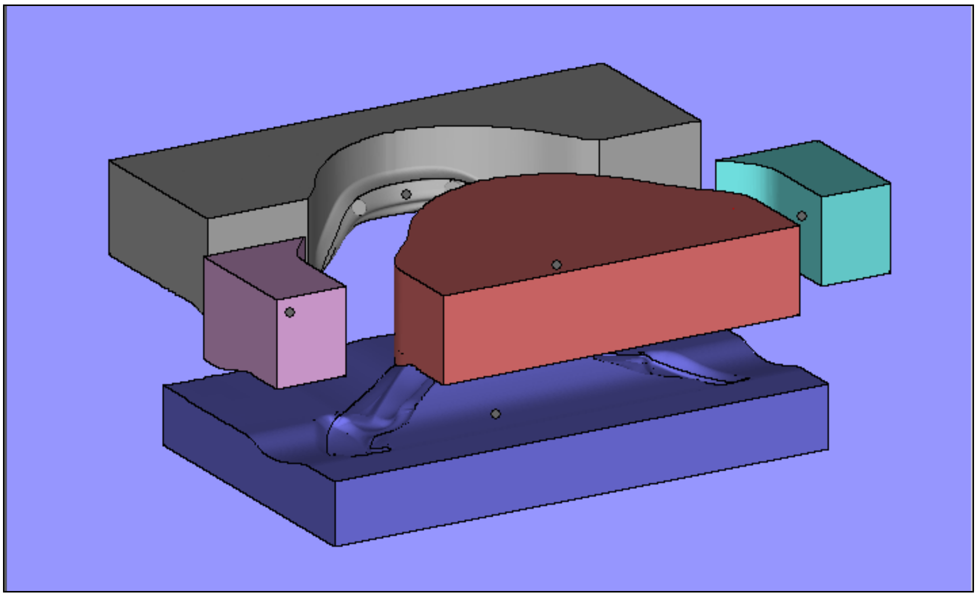

Figure 4.1: Original design of mould

The mould was initially designed to be manufactured by CNC machining out of aluminium billets and therefore blocks of aluminium are the starting point. The mould design was evaluated with the aim to reduce the cost of the mould. The original idea was a solid mould which would have been very expensive. To achieve this cost saving, the back of the mould was hollowed out and ribs were inserted in the back to decrease the material usage and to reduce the sintering time on the EOS P380 machine. The cost of a sintered part is determined by the amount of material that is used as well as the scanning time of the laser. Another factor that should be taken into account is the step effect described in chapter 2 section 2.14. This implied that the mould was sintered upright and not flat which increased the cost of the sintering process. Ribs had to be inserted to withstand the pressure of the compression moulding process. Changing the design as indicated, the building parameters changed with a subsequent change in time and cost. Table 4.1 shows the results affected by the change:

Table 4.1: Comparison between the old and new designs for the mould

	Original Design Fig. 4.1	**Changed Design Fig. 4.2**	**Difference**	**% Decrease**
Volume (mm^3)	4 995 960	4 284 860	711 100	14.23
Building time (H:M:S)	14:37:43	14:09:33	00:28:10	3.21
Cost (R)	21 534.60	19 419.90	2 114.70	9.82

The mould that was CNC machined cost R28 000 and two weeks was needed to manufacture the mould. The sintered mould can be manufactured and shipped to the client in three days at a cost of R 19 419.90. Treatment of the mould surface, before the production of the parts can start, takes a further two days. The modified mould can be seen in Figure 4.2.

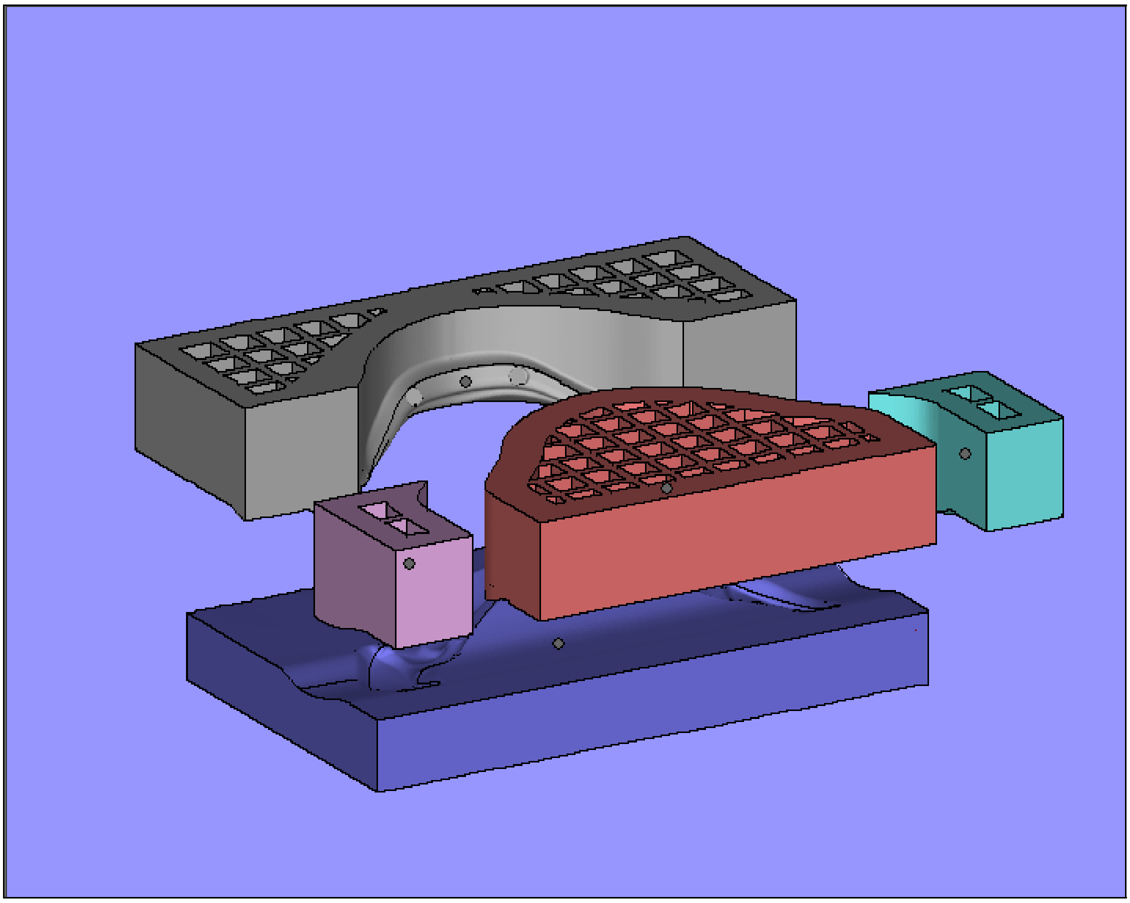

Figure 4.2: Modified mould

4.1.3 Moulding methods

Compression moulding was used in the moulding of the part. The mould was clamped in a jig with a car jack that is made to apply 1 ton of pressure. This composite moulding method is the method currently used by the Leatt Corporation. The amount of resin that is wasted is kept to a minimum and the skill needed in designing and use of the mould is elementary.

4.1.4 Materials used in the mould

There were three materials used in the part: glass fibre, CF and Aramid fibre (Kevlar®). A foam core was also used. These materials are currently used in the parts produced for the Moto GPX brace. CF provides strength, the Kevlar® provides shock absorption and the glass fibre is for filling the part in a strong, lightweight and cheap manner.

The glass fibre, CF and Carbon-Kevlar® mat is a 0/90 arrangement.

4.1.5 Resins used in the experiment

A thermoset resin was used in the experiment. This type of resin hardens when a hardener is added and it is heated past its curing temperature of 50°C. Cross linking occurs and an irreversible bond is formed between the molecules of the resin.

4.1.6 Post curing temperature

The resin was cured at 80°C for 40 minutes.

4.1.7 Method of measuring

In order to draw a conclusion on the ability to use this method of sintering a mould, the part and moulds had to be measured using a touch probe or non-contact digitiser. The moulded test piece was captured by the Konica Minolta 3-D non-contact scanner and compared with the Computer Aided Design (CAD) file, supplied by Leatt Corporation. The result in Geomagic v10 is shown in Figure 4.3.

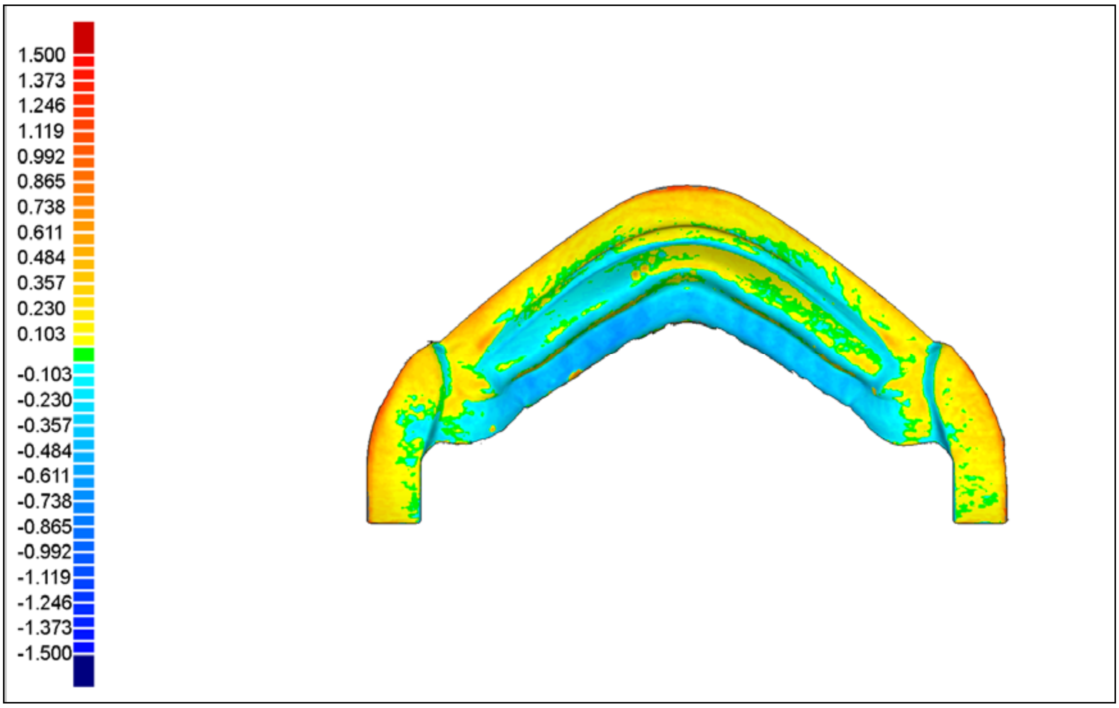

Figure 4.3: A part from the polyamide mould compared with the CAD data

A table of how many points are in each range and the percentage it represented is given in Table 4.2.

Table 4.2: Representation of points in the comparison between the part produced in the polyamide mould and the CAD data

>=Min (mm)	<Max (mm)	# Points	%
-1.5	-1.437	0	0
-1.437	-1.373	0	0
-1.373	-1.31	0	0
-1.31	-1.246	0	0
-1.246	-1.183	0	0
-1.183	-1.119	0	0
-1.119	-1.056	1	0.007
-1.056	-0.992	1	0.007
-0.992	-0.929	1	0.007
-0.929	-0.865	0	0
-0.865	-0.802	2	0.013
-0.802	-0.738	2	0.013
-0.738	-0.675	19	0.124
-0.675	-0.611	80	0.522
-0.611	-0.548	159	1.037
-0.548	-0.484	264	1.722
-0.484	-0.421	463	3.021
-0.421	-0.357	533	3.477
-0.357	-0.294	614	4.006
-0.294	-0.23	619	4.038
-0.23	-0.167	830	5.415
-0.167	-0.103	1124	7.333
-0.103	-0.04	1362	8.886
-0.04	0.04	2245	14.646
0.04	0.103	2041	13.316
0.103	0.167	1663	10.849
0.167	0.23	1114	7.268
0.23	0.294	826	5.389
0.294	0.357	493	3.216
0.357	0.421	244	1.592
0.421	0.484	144	0.939
0.484	0.548	116	0.757
0.548	0.611	85	0.555
0.611	0.675	69	0.45
0.675	0.738	46	0.3
0.738	0.802	45	0.294
0.802	0.865	29	0.189
0.865	0.929	32	0.209
0.929	0.992	22	0.144
0.992	1.056	12	0.078
1.056	1.119	7	0.046

Table 4.2 continues.

>=Min (mm)	<Max (mm)	# Points	%
1.119	1.183	7	0.046
1.183	1.246	6	0.039
1.246	1.31	0	0
1.31	1.373	5	0.033
1.373	1.437	1	0.007
1.437	1.5	0	0

A graphical representation of the comparison is given in Figure 4.4.

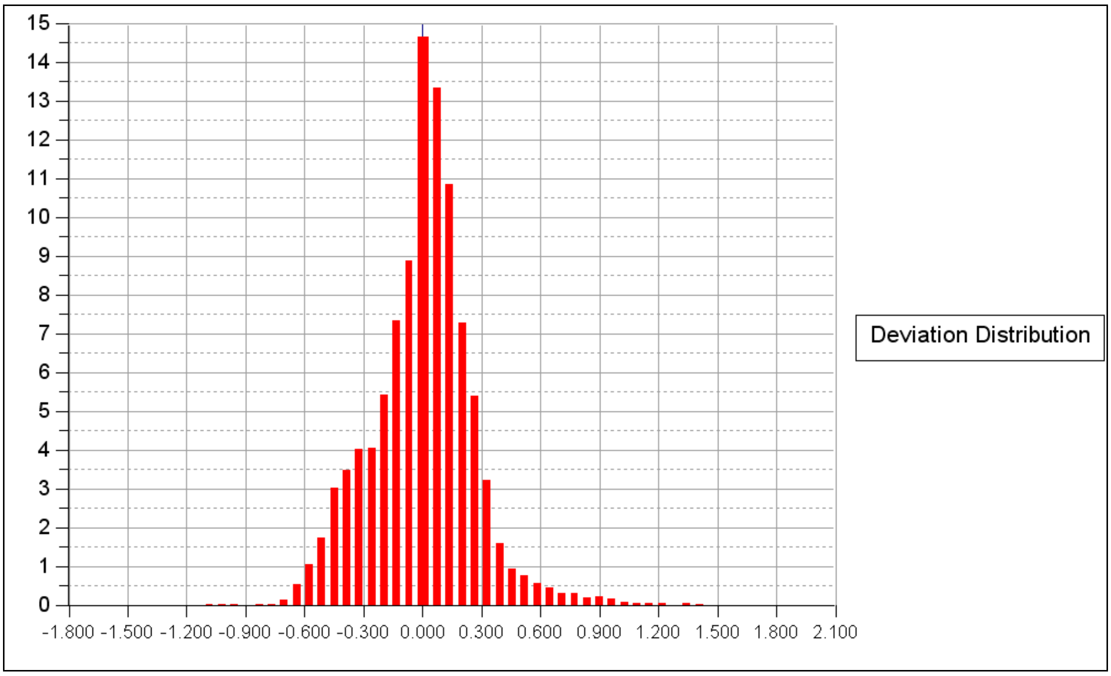

Figure 4.4: Graphical representation of the comparison between a part produced in the polyamide mould and the CAD data

Table 4.3: Percentage of points in different ranges from the CAD data for a part produced in the polyamide mould

Percentage of points (%)	Distance from CAD (mm)
39.6	-1.5 to -0.04
14.6	-0.04 to 0.04
45.7	0.04 to 1.5

Table 4.3 indicates how many of the points lie in each distance range of the CAD data. The -1.5 mm to 1.5 mm range was chosen because the points falling outside this range deviate too much to be deemed accurate. Table 4.2 shows that 97.5% of the data lies in the range between -0.6 mm and 0.6 mm deviation. The part produced in the polyamide mould is slightly bigger on average than the CAD data, because more points are in the positive deviation range.

The polyamide mould was scanned with the Konica Minolta non-contact 3-D digitiser and the mould was compared with the CAD data. The results from this comparison are shown in Figure 4.5.

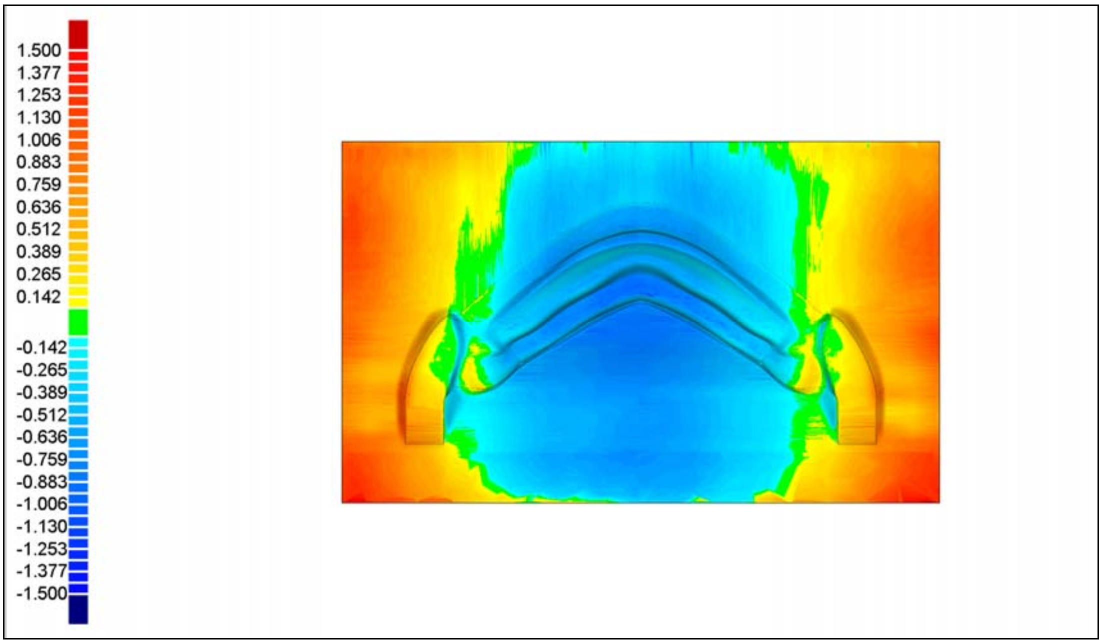

Figure 4.5: Comparison between the polyamide mould data and the CAD data

A graphical representation of the comparison can be seen in Figure 4.6.

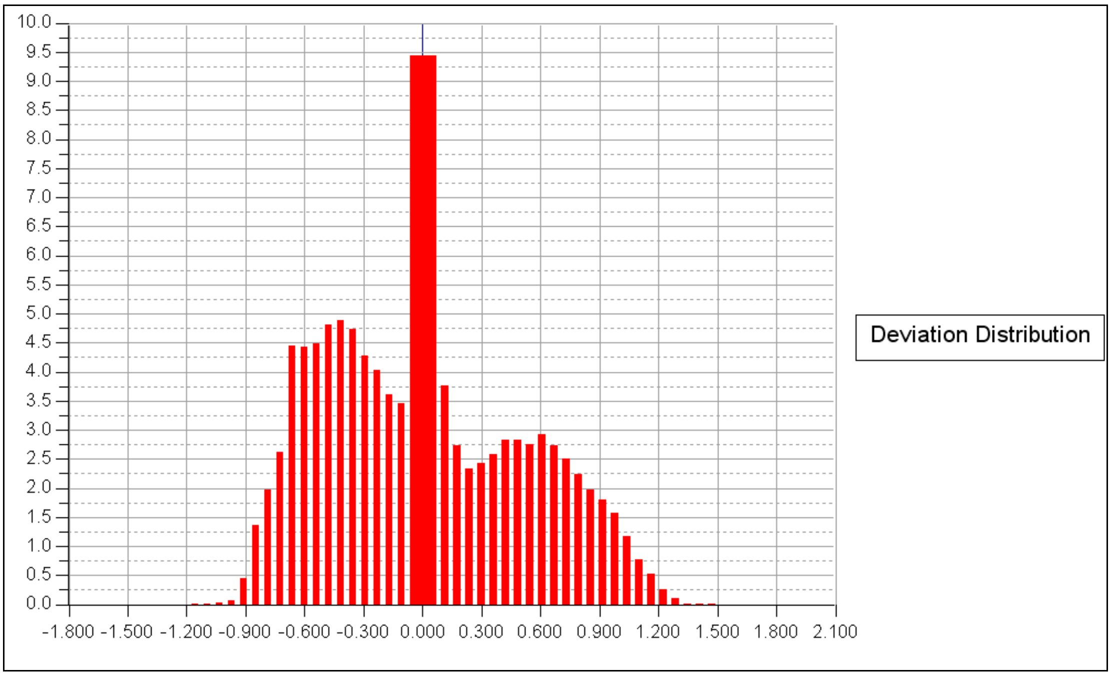

Figure 4.6: Comparison between the polyamide mould scan data and the CAD data

Table 4.4: Percentage of points in different ranges from the CAD data for the polyamide mould

Percentage of points (%)	Distance from CAD (mm)
49.7	-1.5 to -0.08
9.4	-0.08 to 0.08
40.9	0.08 to 1.5

Table 4.4 indicates the dimensional variance of the polyamide mould from the CAD master file in different regions. Only 74.9% of the data is in the region of between -0.6 mm – 0.6 mm deviation. In Figure 4.5, the curvature of the polyamide mould can be seen. The mould is smaller in the middle regions and larger on the sides. The part from the polyamide mould was also compared with a part produced in the aluminium mould and the result is shown in Figure 4.7.

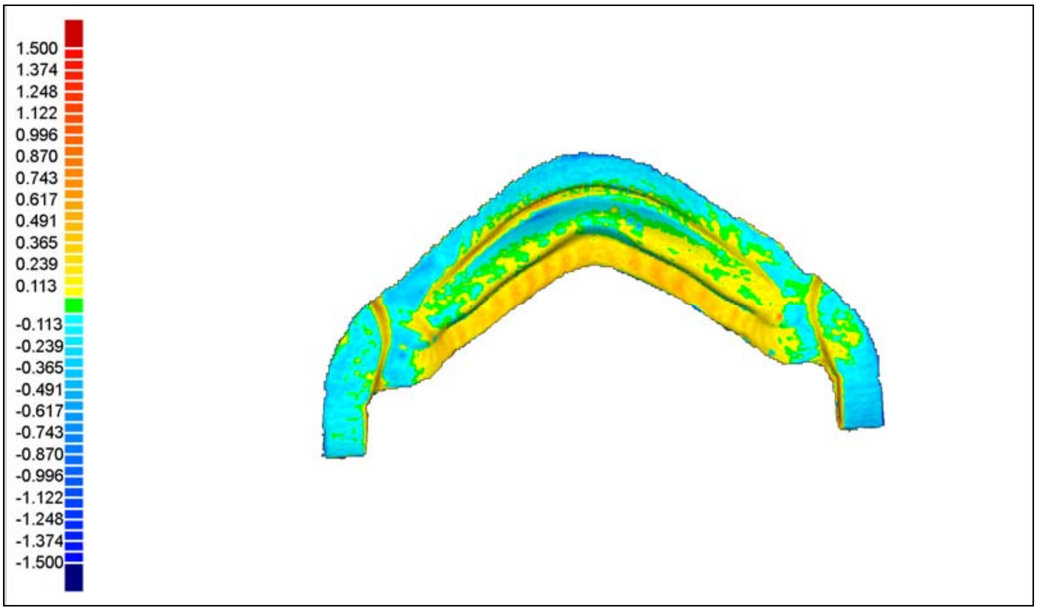

Figure 4.7: A part from the polyamide mould compared with a part from the aluminium mould

A graphical representation of the comparison between the aluminium mould and polyamide mould can be seen in Figure 4.8.

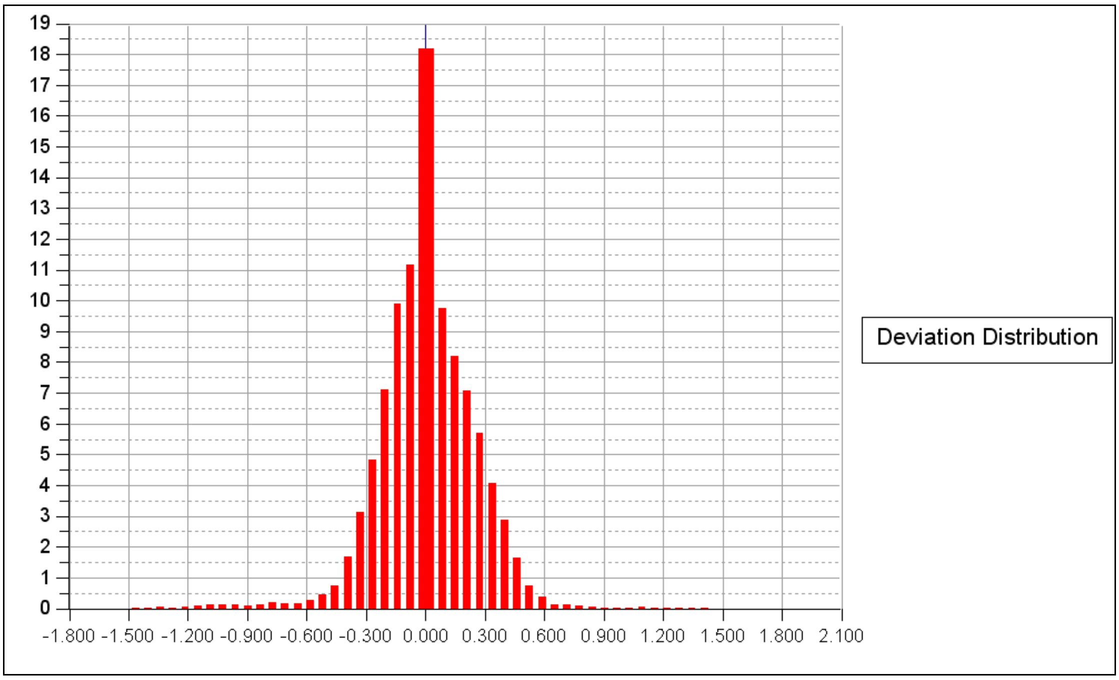

Figure 4.8: Graphical representation of the comparison between the part produced in the polyamide mould and the part produced in the aluminium mould

The parts are almost identical, with 98% of the points in a range of -0.6 mm and 0.6 mm from each other. This indicates that the part from the polyamide mould compares well with the part from the aluminium mould.

The aluminium mould part was also compared with the CAD file. The results can be seen in Figure 4.9.

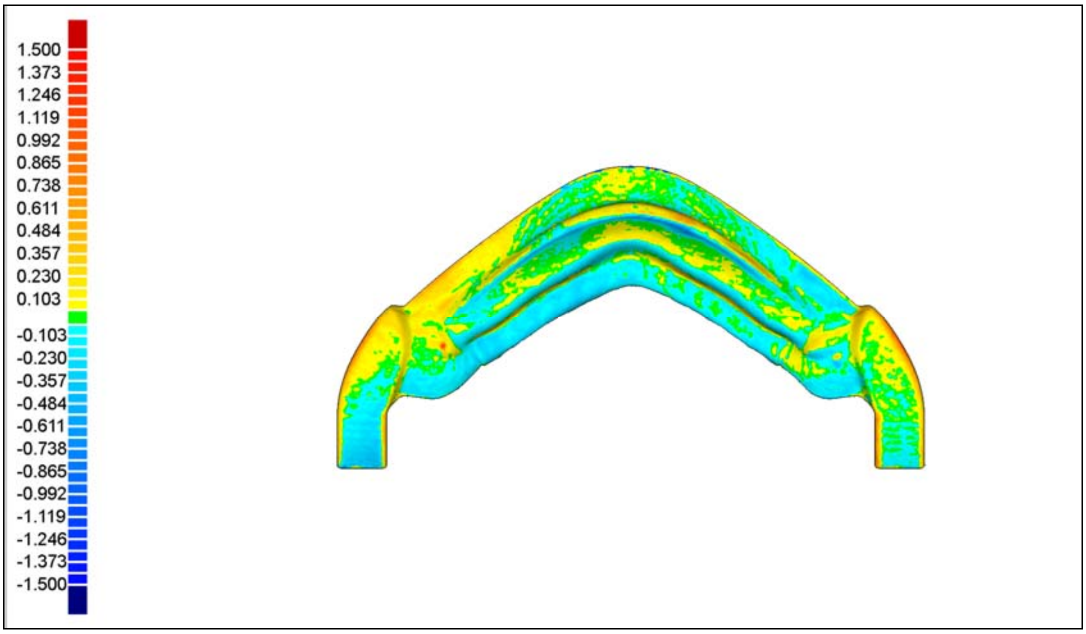

Figure 4.9: A part from the aluminium mould compared with the CAD file

A graphical representation of this comparison can be seen in Figure 4.10.

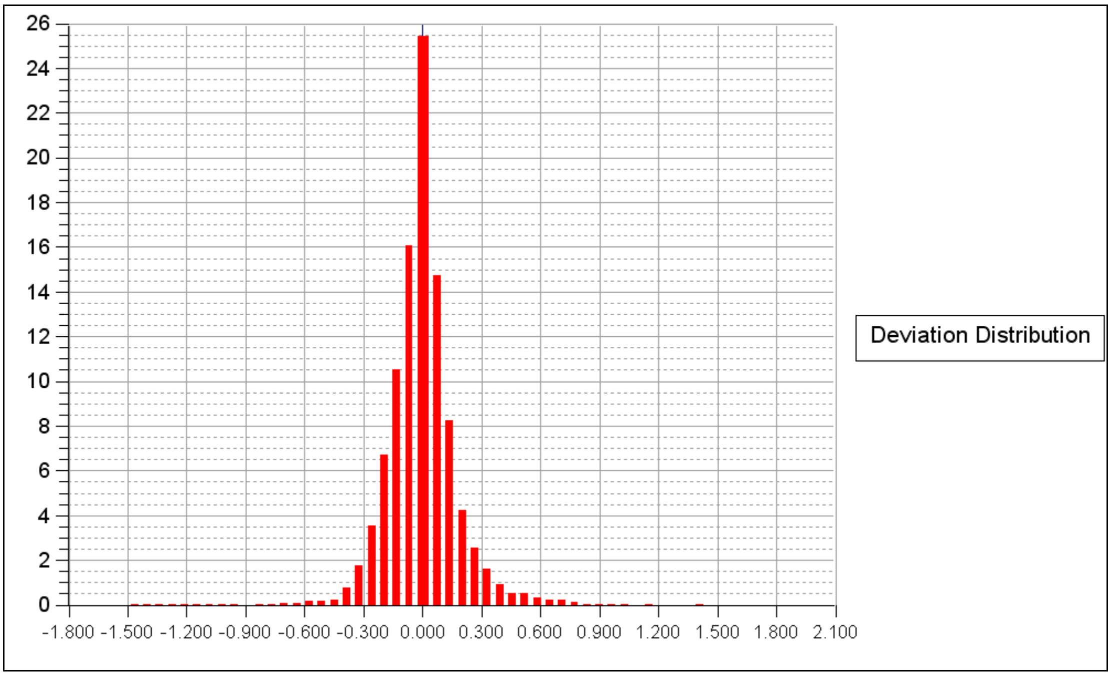

Figure 4.10: Comparison between the part produced in the aluminium mould and the CAD data

The graph in figure 4.10 shows that 99% of the points lie in the range between -0.6 mm and 0.6 mm. This is fairly accurate and 1.5% better than the part produced in the polyamide mould. The polyamide mould is not very accurate, as can be seen in Figure 4.5. Due to the inaccuracy, the part produced in the polyamide mould has 1.5% fewer points in the -0.6 mm – 0.6 mm range than the part produced in the aluminium mould. The part produced in the polyamide mould was compared with the polyamide mould. The results can be seen in Figure 4.11.

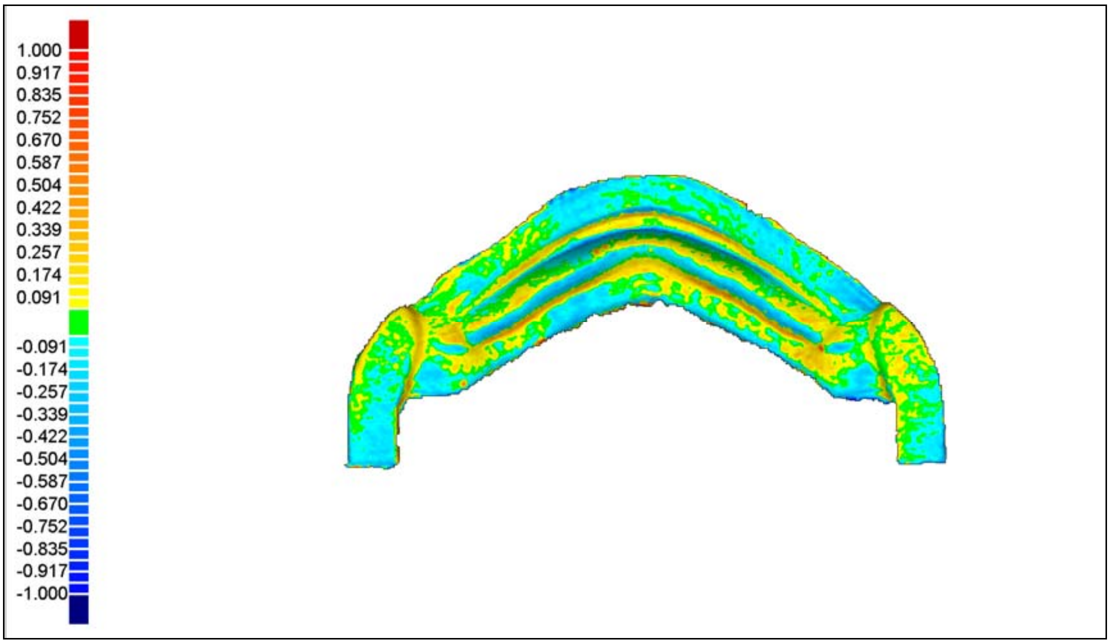

Figure 4.11: Comparison between the part produced in the polyamide mould and the polyamide mould

The results from the comparison in a graphical form can be seen in Figure 4.12.

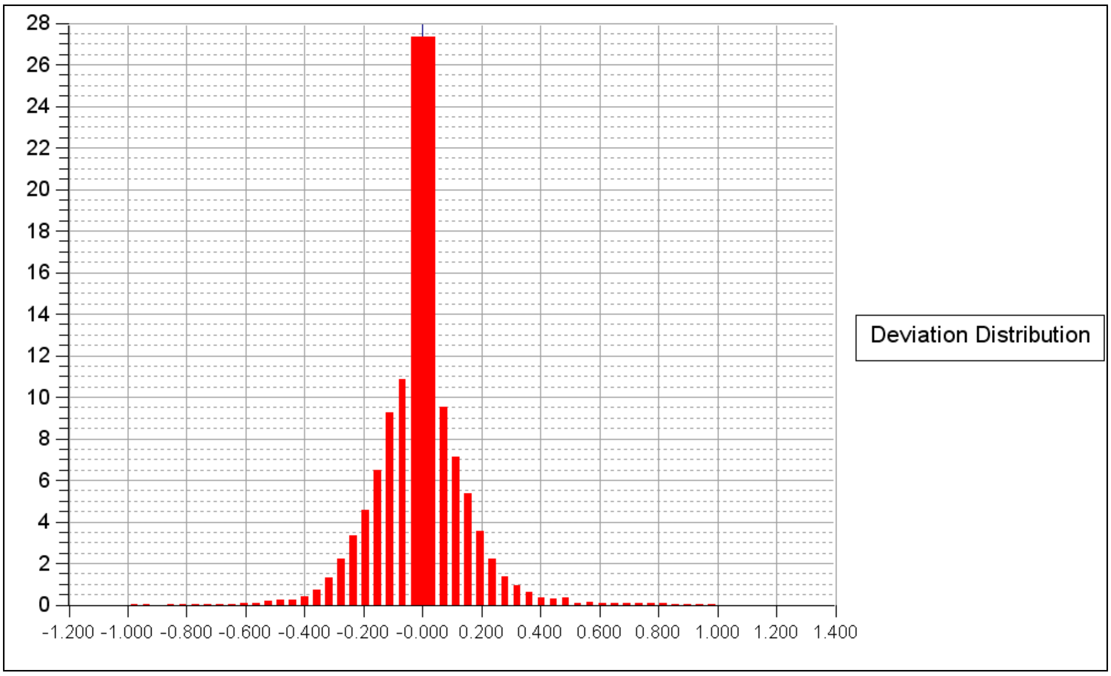

Figure 4.12: Graphical representation of the comparison between the part produced in the polyamide mould and the polyamide mould

Table 4.5: Percentage of points in different ranges from the polyamide mould data and for a part produced in the polyamide mould

Percentage of points (%)	**Distance from mould data (mm)**
40.2	-1.5 to -0.08
24.4	-0.08 to 0.08
32.4	0.08 to 1.5

99.3% of the data is in the range of -0.6 mm – 0.6 mm deviation. The part is therefore accurate.

4.1.8 Problems that occurred in the mould and moulding process

A major problem was the step effect created by the machine during sintering, as described in Chapter 2. The surface was treated with two layers of clear lacquer. This treatment smoothed the surface sufficiently for CF moulding, but compromised the accuracy.

The coating of clear lacquer also sealed the pores in the material. The sintered parts have pores due to the sintering process and if the mould is used without a sealant, the resin will flow into the pores making it very difficult to open the mould.

The polyamide mould was not very accurate. Only 74.9% of the points lie in the region of -0.6 mm – 0.6 mm to the CAD data.

4.1.9 Recommendations for the next mould

The first recommendation for the next mould was to ensure that the machine was calibrated correctly. The biggest problem with the first mould was the fact that it was not accurate. Therefore, if the mould could be sintered more accurately, it would be a significant improvement.

Experiment 1 proved that the method of sintering moulds for composite moulding does work and shows potential for further development. Cost is always a problem for companies developing products, therefore, methods must be researched to reduce the cost of CF press tooling even further. It was, therefore, decided to hollow out the whole of the back of the next mould and sinter the mould, without the ribs. By hollowing out the back, more material could be saved, which would decrease the cost even further. The hollowed out portions can be filled with a resin afterwards. By filling the hollowed out section with resin it was anticipated that the mould would be given the strength needed to withstand the pressure exerted by the clamping.

The resin used in the moulding process can be slightly heated when it is poured into the mould. This reduces the surface tension of the resin. There will be fewer air bubbles in the resin, resulting in fewer air bubbles in the part.

4.2 Experiment 2

There was no definite rule to be applied with the back filling. Therefore, an experiment was conducted to determine the filler mixture as well as the required wall thickness that is needed to contain the filler.

4.2.1 Method used to conduct the experiment

Experiments were carried out to find a suitable powder/resin mixture. Any filler powder can be used just to add volume to the resin and it was decided to use old polyamide powder as filler. 100 g of Axson F 19 resin without any powder was mixed in a container and left to cure. Four containers with the same amount of resin (100 g) were mixed and 25 g, 50 g, 75 g and 100 g of used

EOS polyamide powder were added to the resin. The mixtures were left to cure at 70°C for 30 minutes in an oven without vacuum. The same size containers were used in the experiment. The results of the volumetric experiment as seen in Table 4.6 are:

Table 4.6: Powder/resin mixture volume and height

Powder (g)	Height (mm)	Volume (mm^3)
0	20	107
25	23	129
50	26	153
75	32	200

The experiment using 100 g of powder was not successful. The mixture's viscosity was too high and the mixture was a thick paste and lost its flow properties. It was not possible to determine the height or volume of that test piece. The test pieces can be seen in Figure 4.13.

Figure 4.13: Powder/resin mixture test pieces

The container with no filler powder is seen on the right. The 25 g, 50 g, 75 g and the 100 g samples are from right to left respectively. The volume in the experiment is important as it is not possible to work with the height alone. The containers that were used in the experiment had a conical shape. The volume of the test piece increased exponentially with the increase in height. The increase in volume of the test pieces had to be determined by measuring the volume of water added to fill the container. The drastic increase in volume in the 75 g test piece is due to the vast amount of air trapped in the powder/resin mixture. Figure 4.14 shows the exponential increase in volume and small increases in the height of the powder/resin mixture. The 25 g sample had a 20.6% increase in volume. The 50 g and 75 g powder filling had a 43% and 86.9% increase in volume respectively.

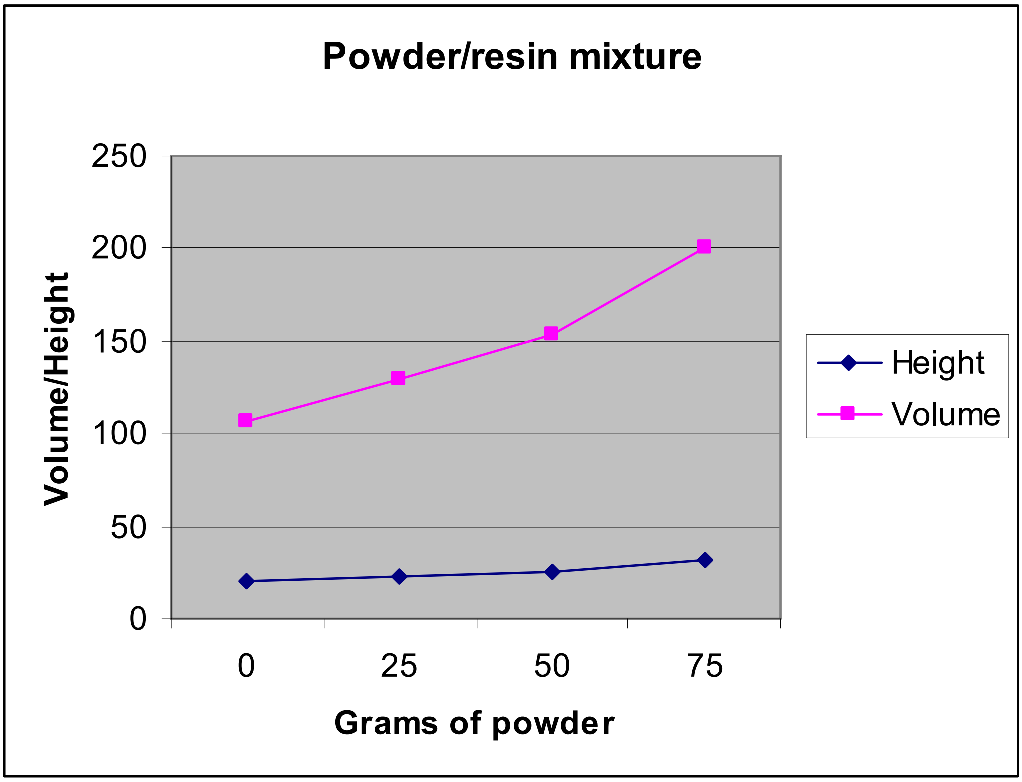

Figure 4.14: Powder/resin mixture volume and height

The cast test pieces were tested under compression load to determine if the powder decreased the strength of the resin. The 0 g, 25 g, 50 g and 75 g samples were compressed with a hydraulic press up to 100 kN of pressure. The test pieces showed no distortion or cracking. The compressive strength of F 19 resin is 48 MPa [42]. The highest calculated stress which occurred in the test pieces, using formula 4.1, was 13 MPa.

$$\sigma = \frac{F}{A} \qquad [4.1]$$

The stress is equal to the force divided by the area. Three 100 x 100 x 100 mm blocks were designed and sintered on the EOS P380 LS machine in polyamide powder. The blocks can be seen in Figure 4.15. The blocks were hollowed out and had different wall thicknesses. The thicknesses were: 2 mm (on the right), 4 mm (in the middle) and 6 mm (on the left).

Figure 4.15: 100 x 100 x 100 mm Blocks

The back of the sintered boxes were filled with 75% (by mass) powder mixed with resin. For every 100 g of resin, 75 g of powder was added. The 75% mixture had the most desirable properties in the study. It was easily mixed in a container and poured easily into the boxes. By using the 75% mixture, the cost of filling will decrease. This was done without placing the box in a vacuum casting machine to get rid of the air in the powder/resin mixture. Further studies to find the “perfect” mixture of resin and powder could be done, but for this study a 75% mixture was deemed sufficient. Due to the meniscus effect when the filler is poured into the boxes, it was necessary to machine the filler surface. This ensured that the forces were evenly distributed and would not be concentrated at a certain point. The filled boxes were compressed to find if they could withstand the pressure needed for moulding composite parts. The parts were placed in a press and tested with one ton compressive force to see if they would break or buckle but did not show any signs of stress or failure.

A problem that was observed with the filling of the blocks was that the pressure of the resin in the 2 mm wall thickness block distorted the sides of the box. The pressure that the resin caused, due to gravity and curing of the thermoset resin, resulted in the sides of the box to bulging. This problem ruled out the use of 2 mm wall thickness boxes. The 4 mm wall thickness can be used for small production runs. However, the block with 4 mm wall thickness sides also deformed under the pressure of the resin in the block. The 6 mm wall thickness block worked very well and suited the part produced. The 6 mm wall thickness block was the easiest block to handle because of its rigidity - the sides did not distort when the box was handled. A further study could be done to determine the “best” wall thickness.

4.2.2 Theoretical application of findings in experiment 2 to the mould used in experiment 1

The difference in the moulds can be seen in Table 4.7 where the design of the mould used in the first experiment was changed to have a wall thickness of 6 mm.

Table 4.7: The comparison between the original design and new design after experiment 2

	Original Part Fig. 4.1	**Changed Part Fig. 4.8**	**Difference**	**% Decrease**
Volume (mm^3)	4 995 960	1 553 210	3 058 933	66.3
Building time (H:M:S)	14:37:43	07:33:56	07:03:47	48.28
Cost (R)	21 534.60	10 921.20	10 613.40	49.29

The F 19 resin used in experiment 2 costs R 68.05 per litre. Thus the amount of volume saved in the sintering of the part had to be filled with resin. Altogether, 3.059 litres of resin would have been used, but using the 75% powder/resin mixture, only 1.637 litres resin were used. When 1.637 litre of resin are mixed with 0.75 kg of powder per kg resin (75% powder/resin), 3.059 litres are obtained. The old powder is waste that would have been discarded. It is possible to use aluminium filler powder if old polyamide powder is not available. The aluminium powder mould would cost R 37.62 per kg. This means that R 111.28 worth of resin was used. The whole mould would cost R 11 032.48 including the filling, resulting in a total cost saving of

48.76%. The final shell mould of the part in experiment 1 can be seen in Figure 4.16.

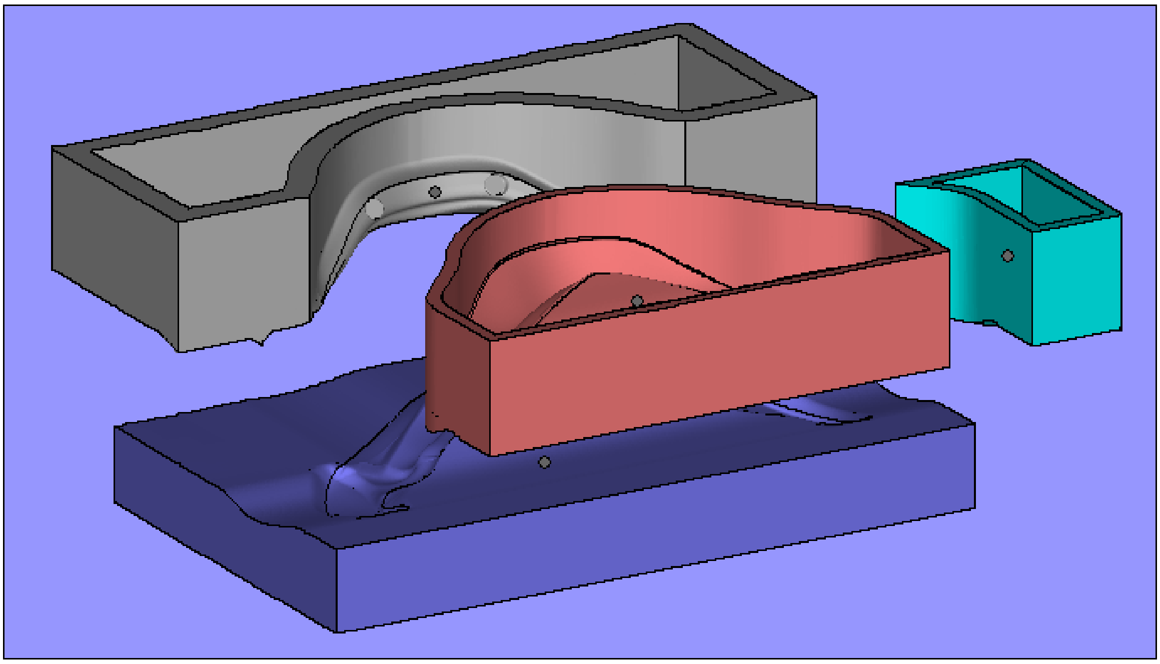

Figure 4.16: Mould with 6 mm shell to be filled with resin

A great deal of time and money can be saved using a thin-walled-design in parallel with a filler-based resin backfill approach in the mould production phase.

4.3 Experiment 3

With the results available from experiment 1 and 2, further experiments could be carried out on another part to establish what the final results would be.

4.3.1 Method used to conduct the experiment

A second mould design was received from the Leatt Corporation which had been machined from aluminium. The mould was designed taking into account the results from experiments 1 and 2. The final .stl file of the mould can be seen in Figure 4.17.

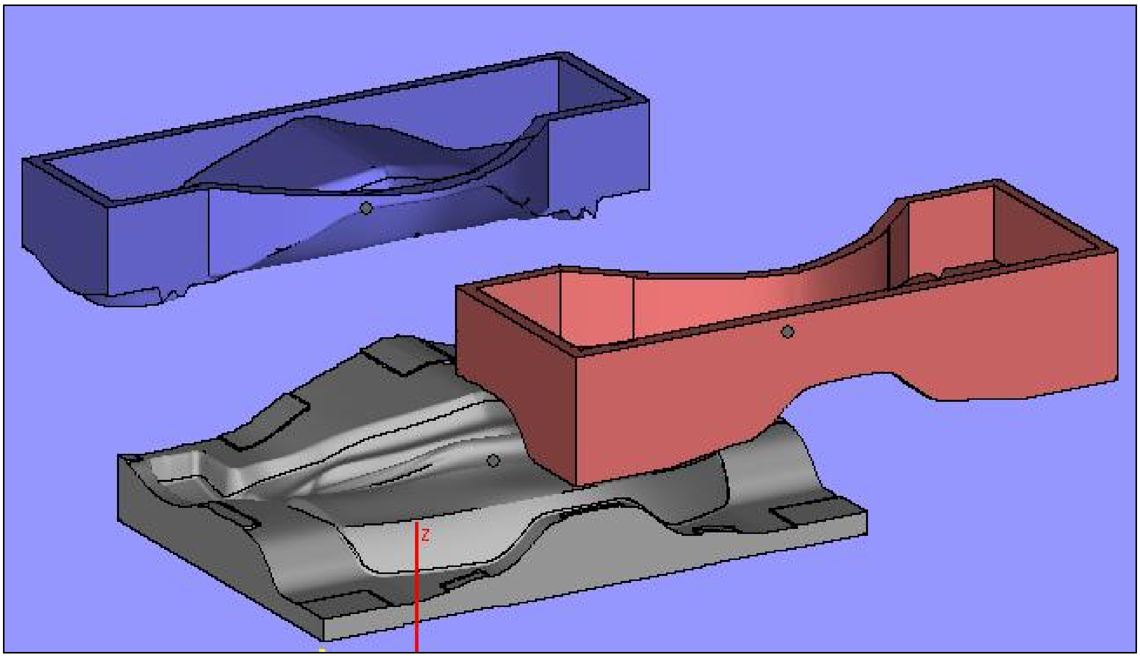

Figure 4.17: The .stl mould files for experiment 3

The new design was sintered on the EOS P380 machine in polyamide powder as shown in Figure 4.18.

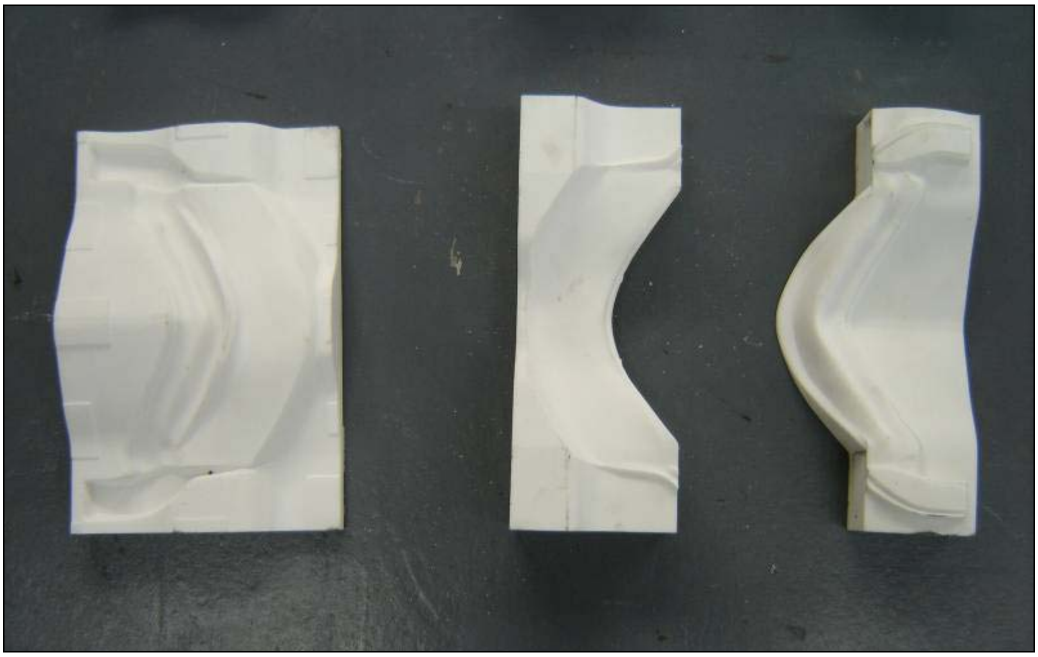

Figure 4.18: The sintered mould for experiment 3

Table 4.8: Comparison between the original mould and the new design of the second mould

	Original Part	Changed Part Fig. 4.9	Difference	% Decrease
Volume (mm3)	2 894 524	898 652	1 995 872	69
Building time (H:M:S)	11:44:42	9:29:41	02:15:01	19.59
Cost (R)	15 230.00	8 413.20	6 816.80	44.76

Table 4.8 shows the cost and time saved using the backfill method. The mould was filled with the 75% by weight powder/resin mixture. Altogether 1.996 litres of resin would have been used, but by using the 75% powder/resin mixture, only 1.068 litres were used to obtain 1.996 litres, which resulted in a resin cost of R 72.67. The cost of the mould was R 8485.87 including the cost of the resin. This is a cost saving of R 6744.13 or 44.28%.

Due to the poor top surface of the filling, the back of the mould was machined smooth on a milling machine and was couriered to Leatt Corporation in Cape Town. The machining of the back took 30 minutes at a cost of R 60.00.

CF parts were manufactured the same way as in experiment 1. The mould was pre-treated with clear lacquer to enhance the surface finish. The preform was placed in the mould and the resin was added. The mould was placed in the clamping jig, clamped with the car jacks and then placed in the oven and cured. The parts were removed from the mould and finished by trimming off the excess material.

A visual comparison between the sintered mould and the machined aluminium CNC mould can be seen in Figure 4.19. The aluminium mould is at the top and the sintered mould at the bottom of the figure.

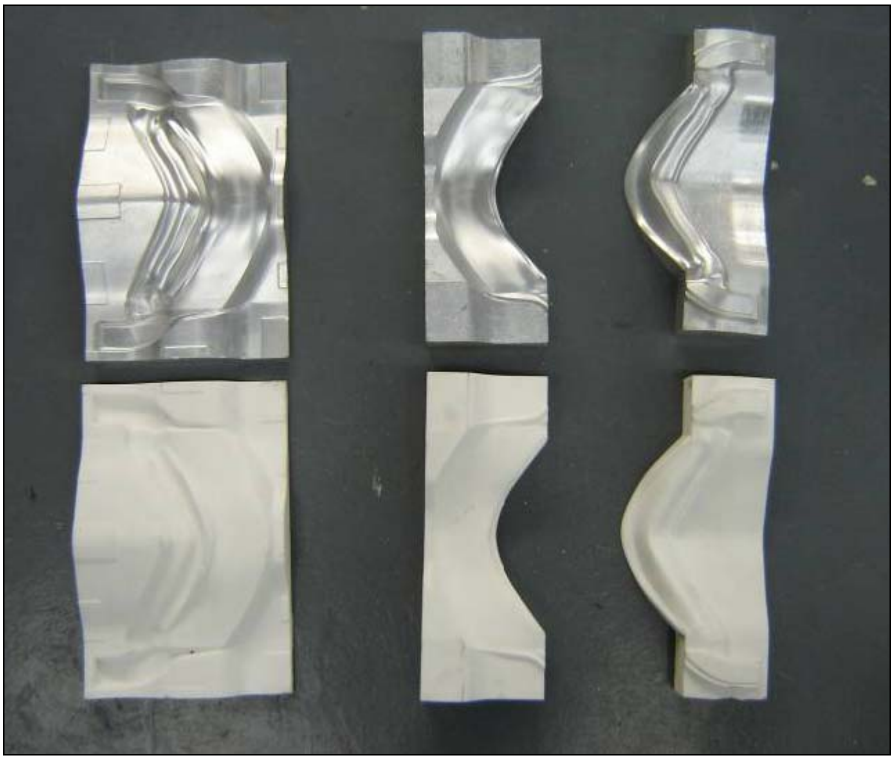

Figure 4.19: Comparison between the sintered mould and the aluminium CNC mould

The sintered mould took three days to manufacture. It was then treated with clear lacquer to improve the surface finish, which was an extra two days' work. The manufacturing of the aluminium mould took three weeks and cost R30 000. The comparison can be seen in Table 4.9.

Table 4.9: Comparison between the aluminium and polyamide moulds

Mould	**Time**	**Cost**
Aluminium	3 Weeks	R 30 000
Polyamide	5 days	R 8515.87

4.3.2 Method of measuring

The geometry of the sintered mould was captured with the Konica Minolta 3-D camera. The surface of the bottom mould part was compared with the CAD files of the part to determine how accurately the mould had been sintered. The results can be seen in Figure 4.20.

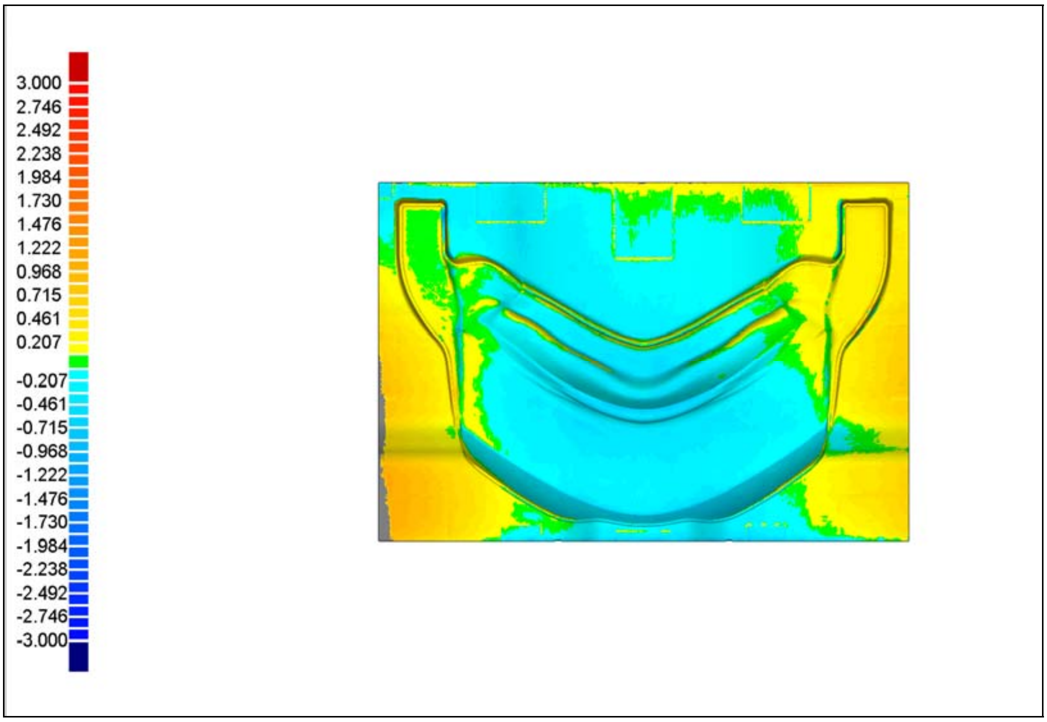

Figure 4.20: Mould 2 compared with CAD data

A graphical representation of the analysis can be seen in Figure 4.21.

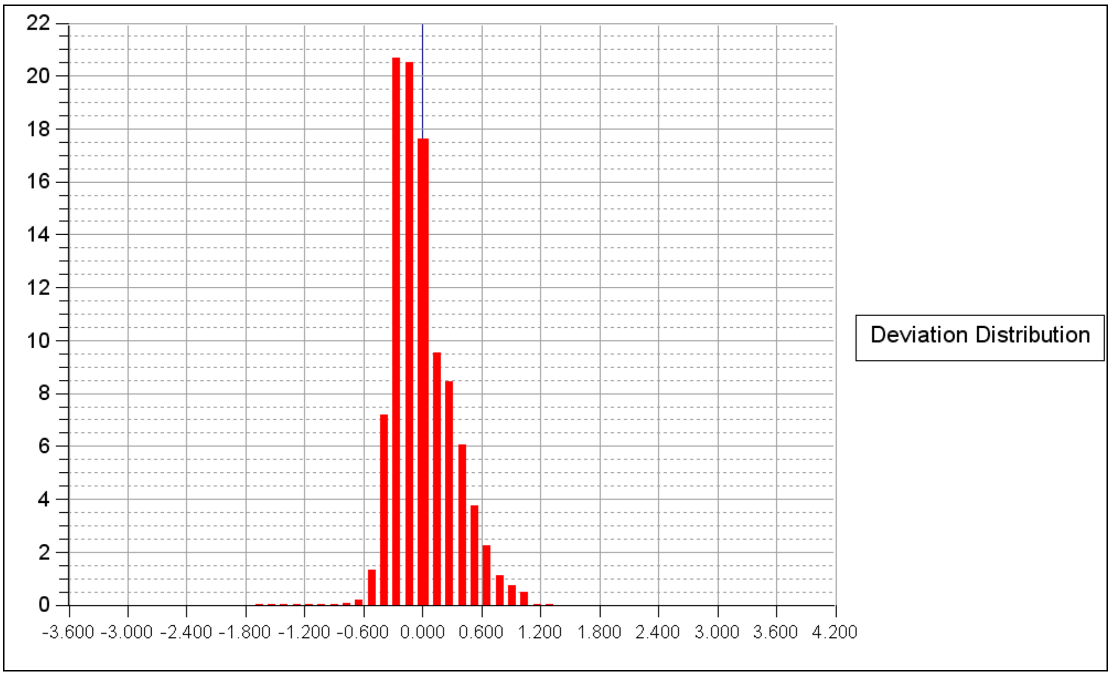

Figure 4.21: Graphical representation of the analysis done on the bottom mould compared to the CAD data

Table 4.10 shows the data that were used to compile Figure 4.21.

Table 4.10: Analysis data for the bottom mould compared to the CAD data

>=Min (mm)	<Max (mm)	# Points	%
-3	-2.873	0	0
-2.873	-2.746	0	0
-2.746	-2.619	0	0
-2.619	-2.492	0	0
-2.492	-2.365	0	0
-2.365	-2.238	0	0
-2.238	-2.111	0	0
-2.111	-1.984	0	0
-1.984	-1.857	0	0
-1.857	-1.73	0	0
-1.73	-1.603	4	0.002
-1.603	-1.476	4	0.002
-1.476	-1.349	7	0.003
-1.349	-1.222	7	0.003
-1.222	-1.095	10	0.004
-1.095	-0.968	17	0.007

Table 4.10 continues.

-0.968	-0.841	35	0.014
-0.841	-0.715	112	0.045
-0.715	-0.588	438	0.175
-0.588	-0.461	3324	1.331
-0.461	-0.334	17 909	7.17
-0.334	-0.207	51 607	20.66
-0.207	-0.08	51 241	20.513
-0.08	0.08	44 027	17.625
0.08	0.207	23 850	9.548
0.207	0.334	21 080	8.439
0.334	0.461	15 174	6.075
0.461	0.588	9339	3.739
0.588	0.715	5635	2.256
0.715	0.841	2817	1.128
0.841	0.968	1872	0.749
0.968	1.095	1171	0.469
1.095	1.222	102	0.041
1.222	1.349	9	0.004
1.349	1.476	0	0
1.476	1.603	0	0
1.603	1.73	0	0
1.73	1.857	0	0
1.857	1.984	0	0
1.984	2.111	0	0
2.111	2.238	0	0
2.238	2.365	0	0
2.365	2.492	0	0
2.492	2.619	0	0
2.619	2.746	0	0
2.746	2.873	0	0
2.873	3	0	0

The analysis was done between -3 mm and 3 mm deviation from the CAD data. As can be seen from the analysis, 58.8% of the points lie between -0.334 mm and 0.08 mm. 95.1% of the points lie between -0.6 mm – 0.6 mm. The average deviation for the oversized points was 0.291 mm. The average deviation for the undersized points was -0.209 mm. The maximum upper deviation is 1.256 mm and the maximum lower deviation is -1.726 mm. The 3-D camera is quoted as being accurate to 0.05 mm however the scanning process has some flaws e.g. when a part is scanned, the sharp edges and corners become rounded in the scan data. This can contribute to some deviation in the averages. Most of the points are smaller than the CAD data which can be due to a scaling problem when the part was sintered.

When the part is moulded, the mould is heated and expands due to thermal expansion. A scaling factor should be used when the mould is sintered to ensure accurate parts and should be calculated for the complete process.

The parts taken from the two moulds were also compared with the CAD data. The comparisons between a part from the aluminium mould and the CAD data can be seen in Figure 4.22. The part data were captured using a Renishaw Cyclone touch probe 3-D scanner and the mould data were captured using a Konica Minolta 3-D camera.

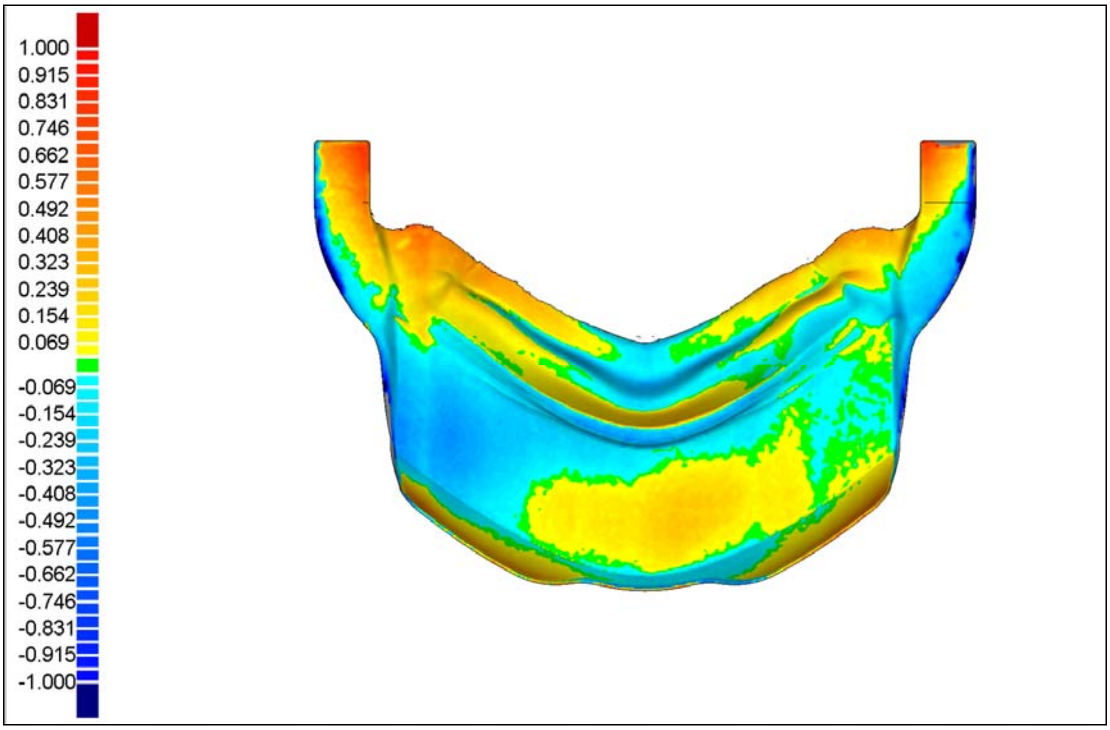

Figure 4.22: Comparison between a part from the aluminium mould and the CAD data

A graphical representation of the analysis between the part from the aluminium mould and the CAD data, shown in Figure 4.22, can be seen in Figure 4.23.

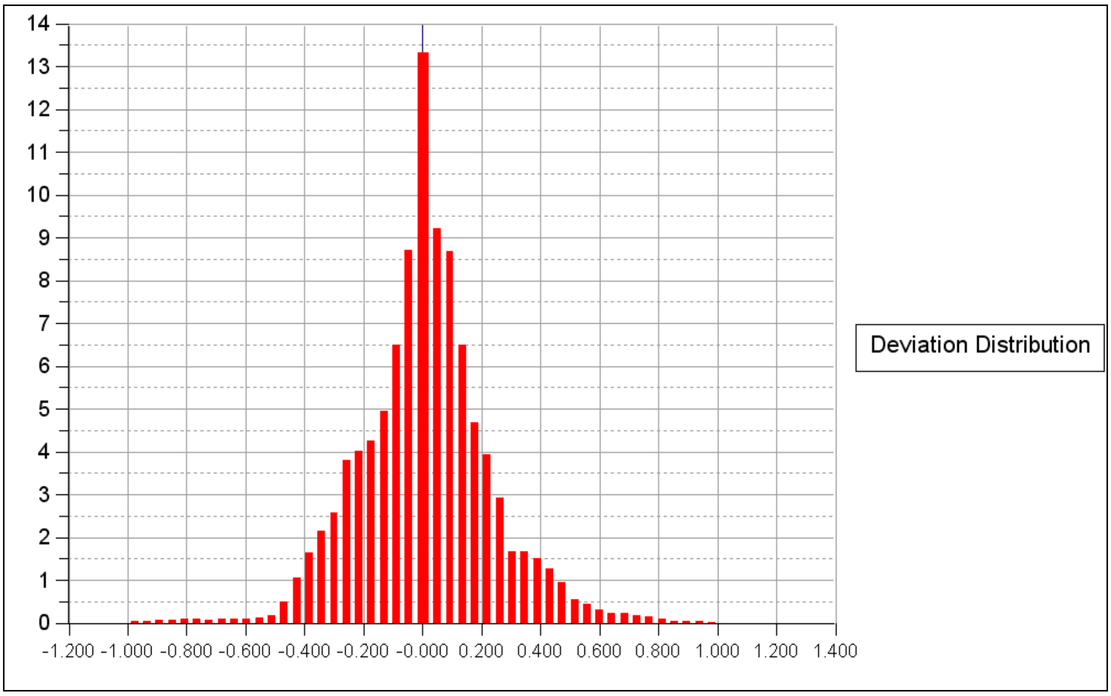

Figure 4.23: Graphical representation of analysis between the part from the aluminium mould and the CAD data

The analysis was done between 1 mm and -1 mm. The biggest positive deviation was 1.752 mm and the biggest negative deviation was -1.944 mm. The average positive deviation for the part was 0.17 mm and the average negative deviation for the part was -0.169 mm. 98% of the points lie between -0.6 mm and 0.6 mm deviation.

The comparison between a part from the sintered polyamide mould and the CAD data can be seen in Figure 4.24.

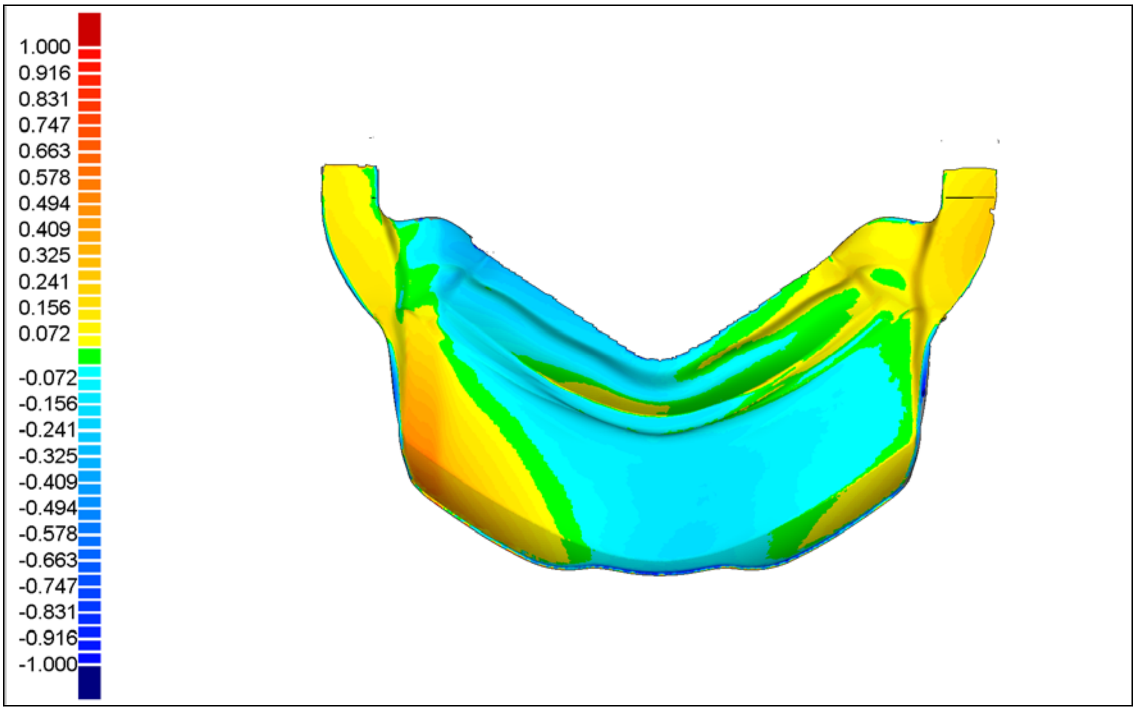

Figure 4.24: Comparison between a part from the sintered polyamide mould and the CAD data

A graphical representation of the analysis done between the part from the sintered polyamide mould and the CAD data can be seen in Figure 4.25.

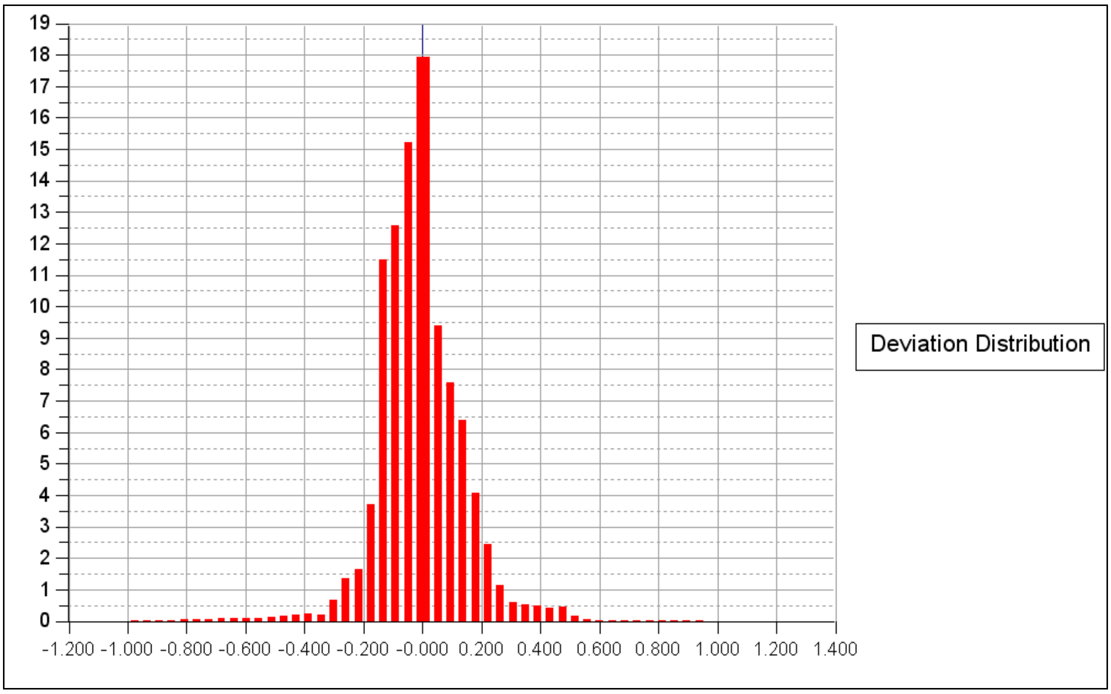

Figure 4.25: Graphical representation of analysis between the part from the polyamide mould and the CAD data

This analysis was also done between 1 mm and -1 mm. The biggest positive deviation was 1.189 mm and the biggest negative deviation was -1.797 mm. The average positive deviation for the part was 0.116 mm and the average negative deviation for the part was -0.104 mm. These are smaller values than for the part manufactured in the aluminium mould. The part manufactured in the polyamide mould was more accurate than that manufactured in the aluminium mould. 99.41% of the points lie between -0.6 mm and 0.6 mm deviation.

The comparison between the part from the polyamide mould and the polyamide mould can be seen in Figure 4.26.

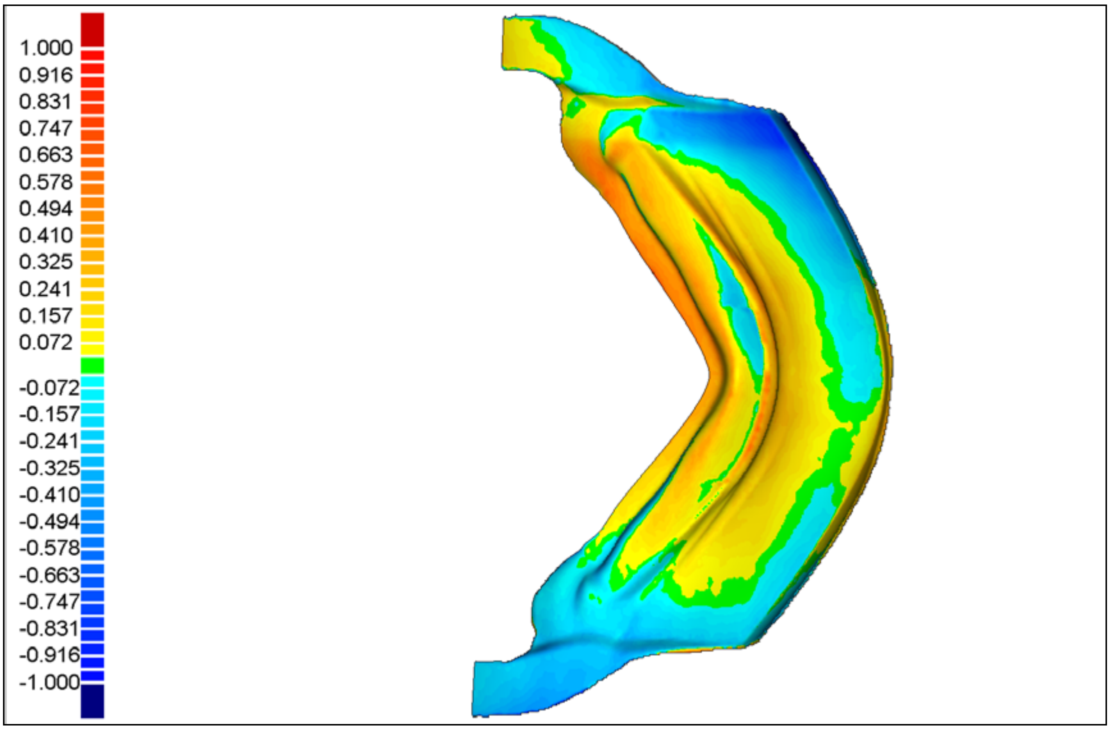

Figure 4.26: Comparison between the part produced in the polyamide mould and polyamide mould geometry

This analysis was done between 1 mm and -1 mm. The biggest positive deviation was 1.303 mm and the biggest negative deviation was -1.874 mm. The average positive deviation is 0.19 mm and the average negative deviation was -0.204 mm. 97.7% of the points lie between -0.6 mm and 0.6 mm deviation.

The graphical representation of the analysis can be seen in Figure 4.27. It had the same deviations as the previous two analyses.

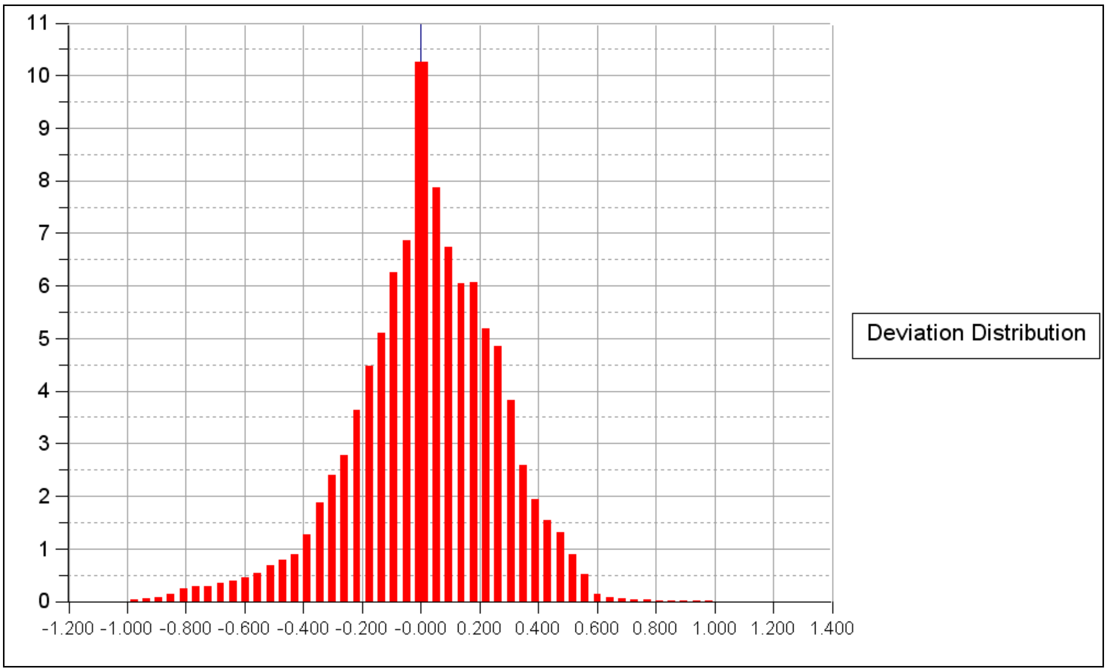

Figure 4.27: Graphical representation of the analysis between the part from the polyamide mould and the polyamide mould geometry

Unfortunately, the aluminium mould could not be sent to Bloemfontein to be scanned since production runs had to be made. A comparison between the aluminium mould and the CAD data could thus not be made nor could any comparisons be made between the aluminium mould and polyamide mould.

Table 4.11 shows the different values for the percentage points between -0.6 mm and 0.6 mm for the parts produced in the Aluminium mould, polyamide mould and the CAD data of the part.

Table 4.11: Comparison of the percentage points between -0.6 mm and 0.6 mm for the part produced in the aluminium mould, polyamide mould and CAD data

Parts	**% Points between -0.6 mm and 0.6 mm**
Aluminium mould part and CAD	98%
Polyamide mould part and CAD	99.41%
Aluminium mould part and polyamide mould part.	97.7%

4.3.3 Problems that occurred in the mould and moulding process

The first problem was that it was difficult to clamp the mould in a clamp to accurately mill the back of the mould to ensure that the mould was straight and smooth on the back. The second problem was with the surface finishing of the mould. Clear lacquer was used, but it flowed downwards and settled in the lower areas. This resulted in the mould being inaccurate and the moulded parts therefore differed from the CAD data. The mould can be sanded with a fine sand paper, or water paper to improve the accuracy and surface finish of the mould after it has been sprayed with lacquer.

4.4 Experiment 4

From all the data obtained throughout the previous experiments, a mould was designed to check if a production run could be made with a sintered mould and mould-making method. A new mould had to be designed as the Leatt

Corporation could no longer participate in the study which meant that one of their designs could not be used for this experiment.

4.4.1 Method used to conduct the experiment

A CF part was designed for manufacture using a mould that was sintered from polyamide and Alumide® on the EOS P380 LS machine. Polyamide is a pure nylon material and Alumide® is a mixture of polyamide and aluminium. A water bottle carrier for a bicycle was designed, which can be seen in Figure 4.28.

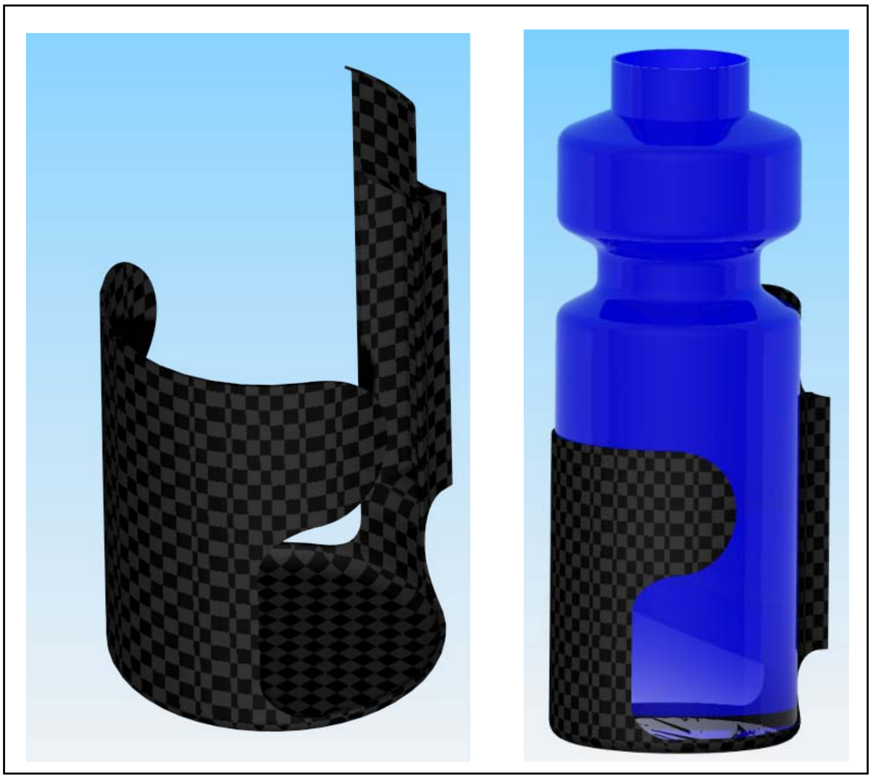

Figure 4.28: Water bottle carrier for a bicycle

This lightweight part was ideal for manufacturing from CF. Most of the water bottle carriers manufactured at present are made from aluminium; however, CF water bottle carriers are being used more regularly. The mould for the water bottle carrier was designed and evaluated. Minor adjustments to the mould were made and the mould was sintered using the knowledge obtained from the previous experiments. The sintered mould's .stl files can be seen in Figure 4.29.

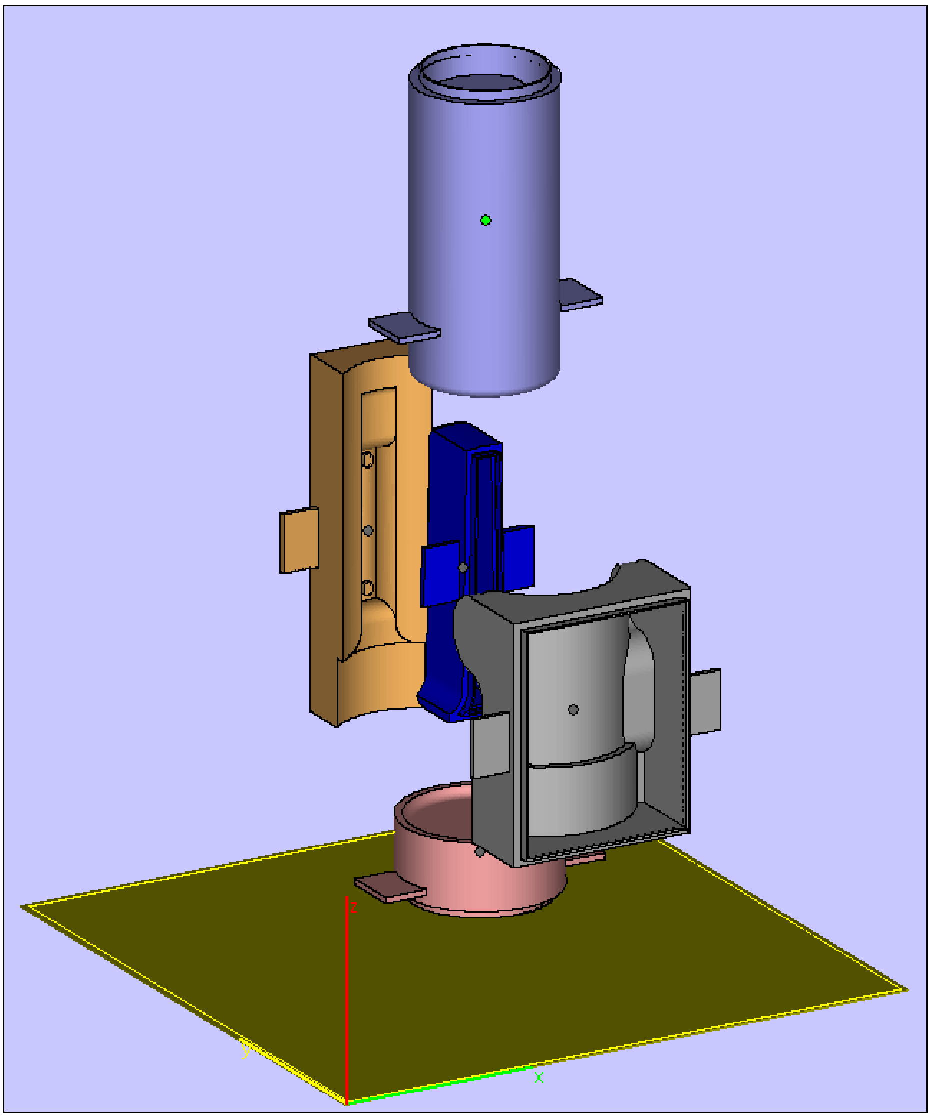

Figure 4.29: The thin-walled mould for the water bottle carrier

The mould consisted of five parts. Each part was designed with a thin wall of 6 mm to reduce the volume of the parts. Small "ears" were sintered on the mould to make it easier to place the parts flat in a vice in order to mill the filler resin flat at the back of the mould after casting. File of the initial mould can be seen in Figure 4.30.

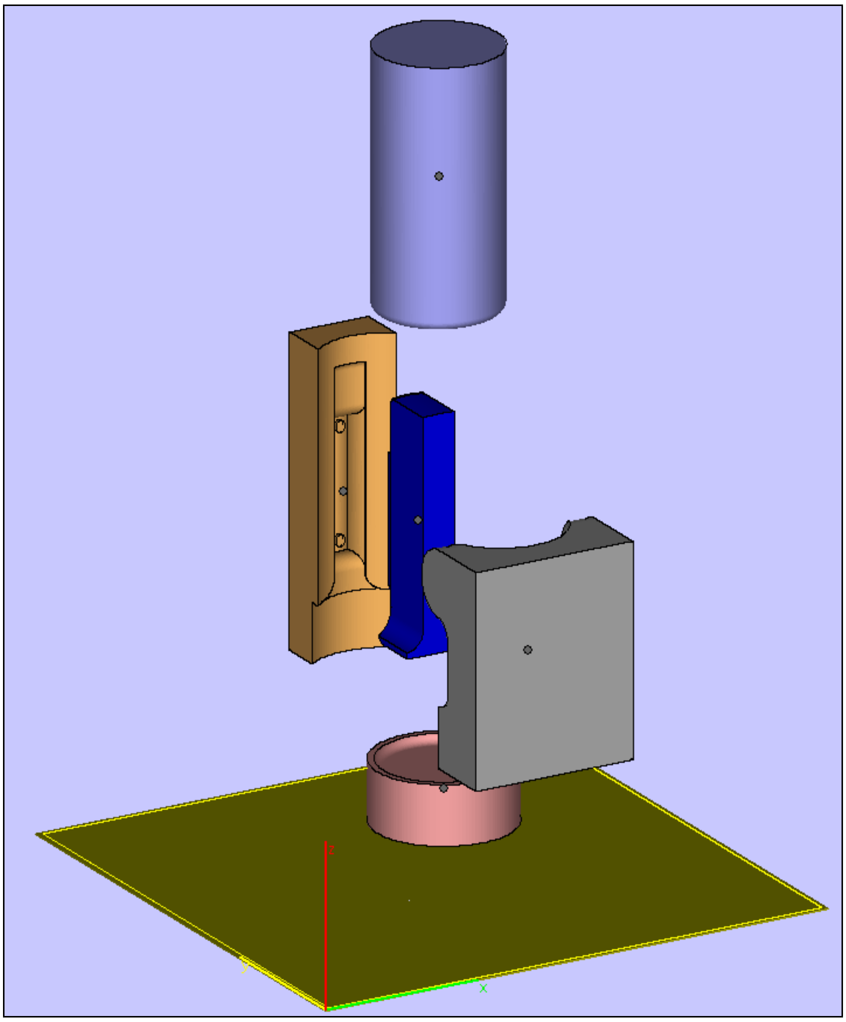

Figure 4.30: Water bottle carrier mould that was not thin-walled

Table 4.12: The difference between the solid mould and thin-walled mould for the water bottle holder sintered in polyamide

	Original Part Fig. 4.20	**Changed Part Fig. 4.19**	**Difference**	**% Decrease**
Volume (mm^3)	1 433 654	808 952	624 703	43.57
Building time (H:M:S)	10:33:02	10:29:43	00:03:19	0.5
Cost (R)	10 453.80	8 698.20	1 755.60	16.8

Altogether 0.5 litres of resin instead of 0.625 litres was used in the experiment to backfill the mould. This is as a result of the filling material being used with the resin. The cost of the resin was R 68.05 per litre and the cost of the resin used in the experiment was R 34.03. The total cost of the mould was R 8732.23. This is a total cost saving of 16.4% on the total adjusted mould compared to the initial mould. The delivery time on the mould was overnight. The mould was built through the night on the EOS P380 machine.

A second water bottle holder mould was sintered from Alumide®. This is a relatively new material that is manufactured by the Electro Optical Systems Company (EOS). This material is a mixture of polyamide and aluminium and has a better heat transfer coefficient than the PA2200 polyamide. The heat transfer coefficient of Alumide® is 0.8 W/(mK) [Appendix B] whereas the heat transfer coefficient of polyamide is 0.25 W/(mK) [Appendix C]. The moulds were vibrated in the vibrating machine and then sprayed with a clear lacquer to seal all the pores in the material and to improve the surface finish. The mould was then sanded with a P1200 grit water paper. Once the mould was dry, it was polished with Ramwax and a release agent was applied, as with the first mould, to ensure the CF did not stick to the mould.

The same cut-out pattern was used as in the polyamide water bottle mould and the same process steps were followed as in the polyamide water bottle mould experiment for the manufacturing of the Alumide® moulds.

Table 4.13: The difference between the solid and thin-walled moulds for the water bottle holder sintered in Alumide®

	Original Part Fig. 4.30	**Changed Part Fig. 4.29**	**Difference**	**% Decrease**
Volume (mm^3)	1 433 654	808 952	624 703	43.57
Building time (H:M:S)	10:33:02	10:29:43	00:03:19	0.5
Cost (R)	15 713.19	11 383.47	4 329.72	27.6

The same amount of resin was used as in the polyamide experiment with the water bottle holder mould. The cost of the thin-walled mould was R 11 417.50 which is a saving of 27.3%. It would have taken the same amount of time to produce the Alumide® moulds as it would have taken to produce the polyamide moulds.

The cost to make the mould from aluminium would be R 17 011.20. The aluminium will cost R 2156.56. The machining cost would be R 14 854.64. The quote for the aluminium was obtained from Rodca Distributors with a delivery time on the aluminium of two days. It would take approximately 18 hours to cut the aluminium for the whole mould. This includes programming the machine, to clock it and to machine the aluminium but does not include the polishing and finishing of the mould which would take approximately another eight hours. The total time to manufacture the mould would be approximately 26 hours. These times are all estimated values as the mould was not manufactured. The times and quotation were obtained from the CRPM. The exact manufacturing time for the aluminium mould is unknown. However, it was estimated that the mould can be manufactured in three to four days with a working day of eight hours. The delivery time on the aluminium mould would be approximately six working days if the delivery time of the aluminium is taken into account.

The estimated time saved in using the polyamide mould or the Alumide® mould instead of the aluminium mould was five days. This is a saving of 83.3%. The money saved by using a polyamide mould instead of a conventional aluminium mould is R 8313 which is a saving of 48.86%.

The greatest advantage of the sintering process is when two or more moulds are required. The cost per mould is reduced as the number of moulds increase per build. It would cost R 10 357.47 to produce two polyamide thin-walled moulds in one build at the same time. The unit price per aluminium mould basically remains the same. The running cost of the CNC machine and time to produce the parts will remain the same, but since two moulds are required, all costing factors have to be doubled. The two moulds can be manufactured at the same time in an LS machine. The unit cost per mould, if two moulds are manufactured at the same time in the EOS P380 machine, is

R 5178.74. There is little difference between the costs to produce one or two moulds. There is a saving of R 3553.49 per unit if two moulds are produced instead of sintering one mould at a time. This is a saving of 40.7% per unit. To produce two thin-walled Alumide® moulds at the same time would cost R 17 472.78. This is a unit cost of R 8736.39. If this is compared to the sintering of one mould, the difference in cost is R 2681.11 per unit, which is a saving of 23.5%, compared to sintering a single mould.

A schematic representation of the unit cost per mould and the number of moulds sintered in one build is shown in Figure 4.31.

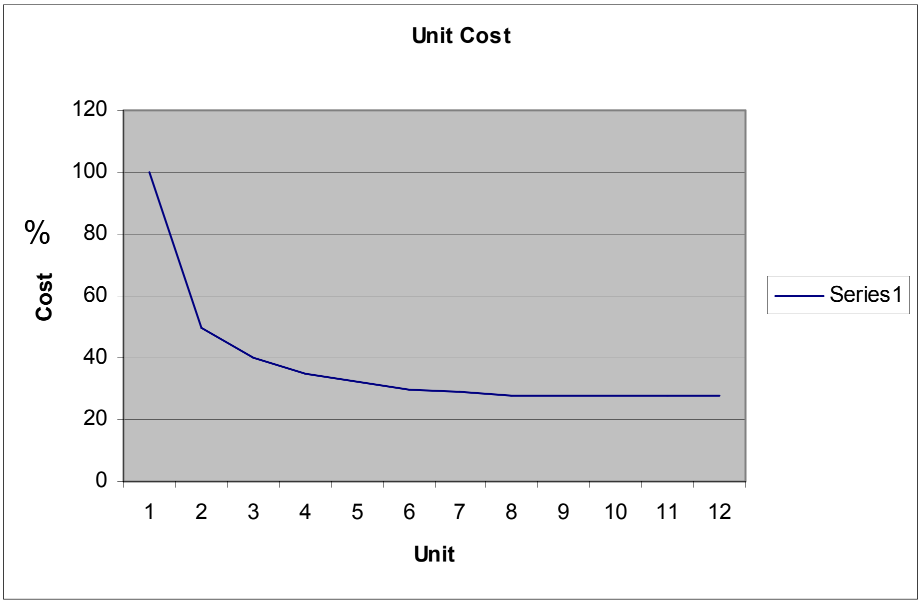

Figure 4.31: The schematic representation of unit cost to quantity of moulds per build

As can be seen in Figure 4.31, the unit cost will reduce drastically at first. From that point the unit cost will stabilise per build.

The polyamide mould before it was sprayed with clear lacquer can be seen in Figure 4.32.

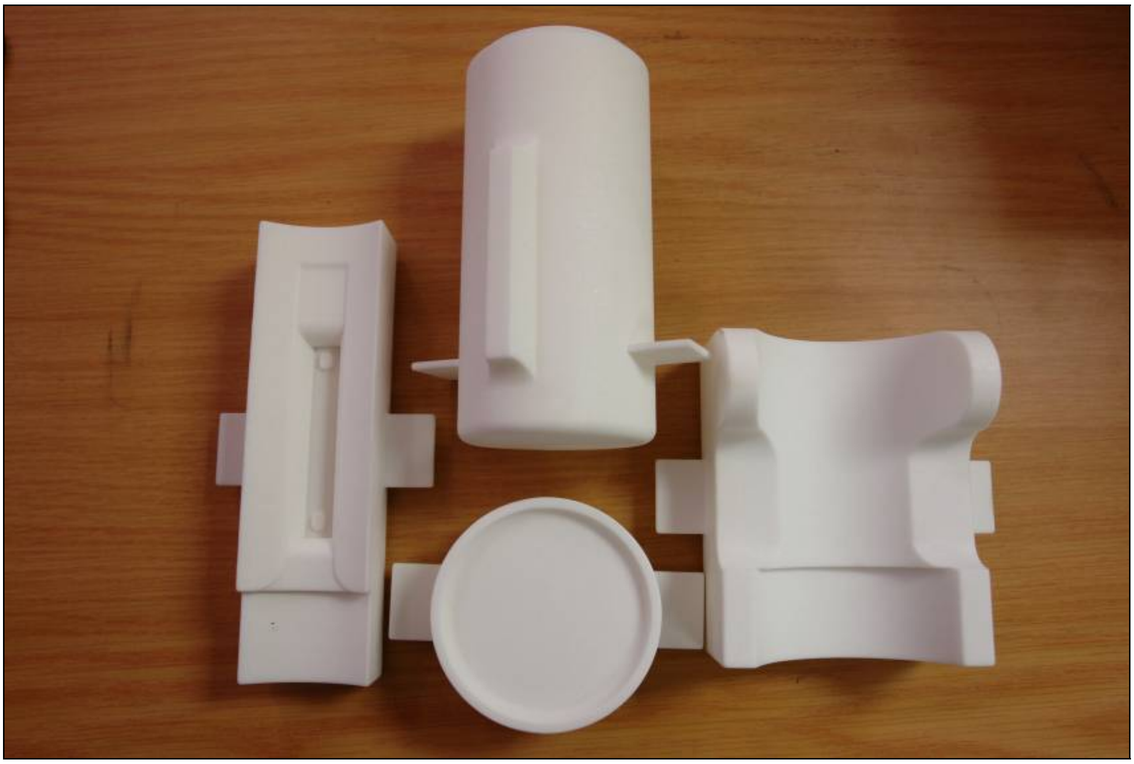

Figure 4.32: The polyamide mould before surface treatment

The Alumide® mould before it was sprayed with clear lacquer can be seen in Figure 4.33.

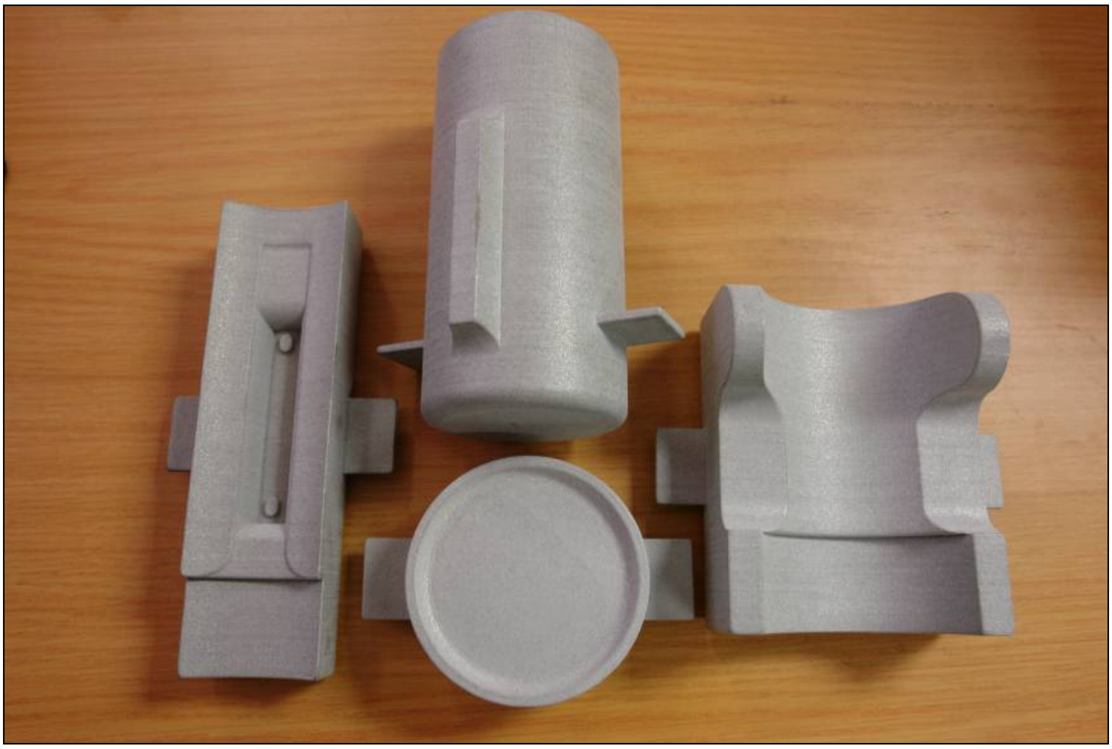

Figure 4.33: The Alumide® mould before surface treatment

The mould was vibrated for four hours. In the vibrating process the parts are placed in a machine filled with abrasive stones. The machine vibrates at a high frequency which causes the stones to polish the surface of the parts, giving a better surface finish. The vibrating machine can be seen in Figure 4.34.

Figure 4.34: Vibrating machine

The stones used in the vibrating machine can be seen in Figure 4.35.

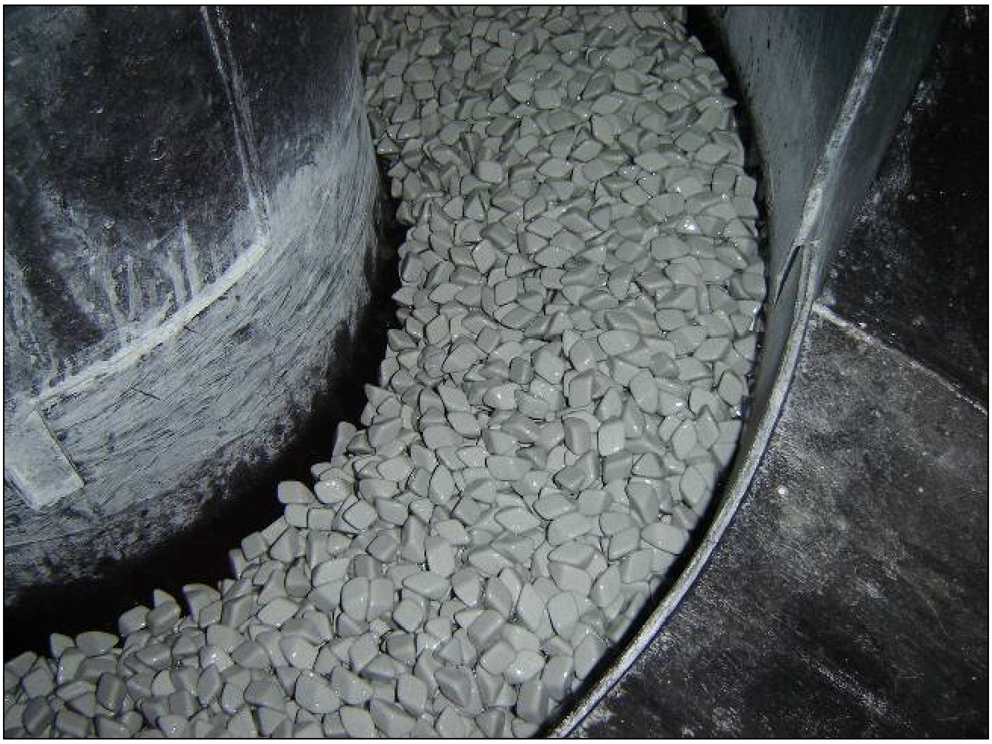

Figure 4.35: The abrasive stones in the vibrating machine

The ears that were added on the parts to make it easier to machine the filled backs of the parts can be seen in Figure 4.36. These ears make it easier to align the parts in a vice to machine the resin that is used to fill the back of the part. The ears were machined off after the resin filled back of the part was machined. A 5 mm extrusion can also be seen on the back of the parts in Figure 4.36.

Figure 4.36: The 5 mm extrusion on the back of the part and the ears to assist with machining

The extrusion assisted with the backfill of the parts. The powder/resin mixture was filled to the top of this extrusion, and the resin and extrusion were machined off afterwards. This ensures that the parts have a smooth back. The mould that was backfilled can be seen in Figures 4.37 and 4.38. After the parts were sprayed with clear lacquer, the parts were sanded with P1200 grid water paper to ensure a smooth surface finish. Before the moulding could begin, a coating of release agent was applied to ensure that the CF parts would release from the mould. The release agent that was used is a product called Safelease #30. It is a water-based polytetrafluoroethylene (PTFE) release agent. PTFE is better known by its DuPont brand name, Teflon. The mould was covered with the release agent each time before the CF was placed in the mould.

Figure 4.37: The polyamide mould with filled back

Figure 4.38: The Alumide® mould with filled back

4.4.2 Experiment

In this experiment, 200 g/m^2 prepreg CF was used. This was bought from Advanced Materials Technology (Pty) Ltd. (AMT). This is a high strength application material which is filled with a thermosetting plastic resin and is cured at 140°C. The resin takes three hours to cure at this temperature. The technical data on the resin can be seen in Addendum A. The mould was manufactured from polyamide, which can be heated to a maximum temperature of 163°C. The Alumide® can be heated to a maximum temperature of 165°C. Another problem that occurred during the moulding stages was the softening of the moulds. The Vicat softening temperature B/50 of the polyamide is 163°C [44]. The Vicat softening temperature or softening point is where a 1 mm^2 cross-section needle can penetrate 1 mm into a Polymer with a force of 9.81 N or 49.05 N. The test using a 9.81 N force is called the A test and the test with a 49.05 N force is called the B test [44].

Although the mould was not heated to 163°C, the polyamide PA2200 material and the Alumide® material did soften as the mould was heated. This might cause problems in high pressure applications.

The oven that was used in the experiments can be seen in Figure 4.39.

Figure 4.39: The oven used in the experiments

A problem that was identified during experiments 4 and 5 was the thermal conductivity of the polyamide and Alumide®. The heat took longer to reach the CF than it would have taken in an aluminium mould. The thermal conductivity of the PA2200 powder parts that were used in the experiment is 0.25 W/(mK). The thermal conductivity of aluminium is 237 W/(mK) [43]. The thermal conductivity of Alumide® parts is 0.8 W/(mK). This would result in the aluminium transferring the heat faster to the CF. However; it does not cause a delay in the cycle time. The cycle time for the aluminium, polyamide and Alumide® moulds is three hours at 140°C.

A moulded part from the first set of moulds can be seen in Figure 4.40.

Figure 4.40: Water bottle holder from the sintered moulds

4.4.3 Conclusion

The case study has shown that it is possible to use the LS process to produce CF moulds. The moulds could be manufactured faster and more cost-effectively than the aluminium mould. Due to the geometry of the part it was difficult to determine how accurate the process is. The material properties of the Alumide® and PA2200 polyamide differ from that of aluminium. This can cause inaccuracy in the component manufacturing process due to the heating of the moulds.

4.5 Experiment 5

A second set of moulds was sintered in polyamide and Alumide® to test the durability of the moulds. The moulds can be seen in figures 4.41 – 4.43. Figure 4.41 is a top view of the moulds, Figure 4.42 is a back view of the moulds before the back filling process and Figure 4.43 is the moulds after the back filling process. In figures 4.41 – 4.43 the polyamide mould is on the left and the Alumide® mould is on the right.

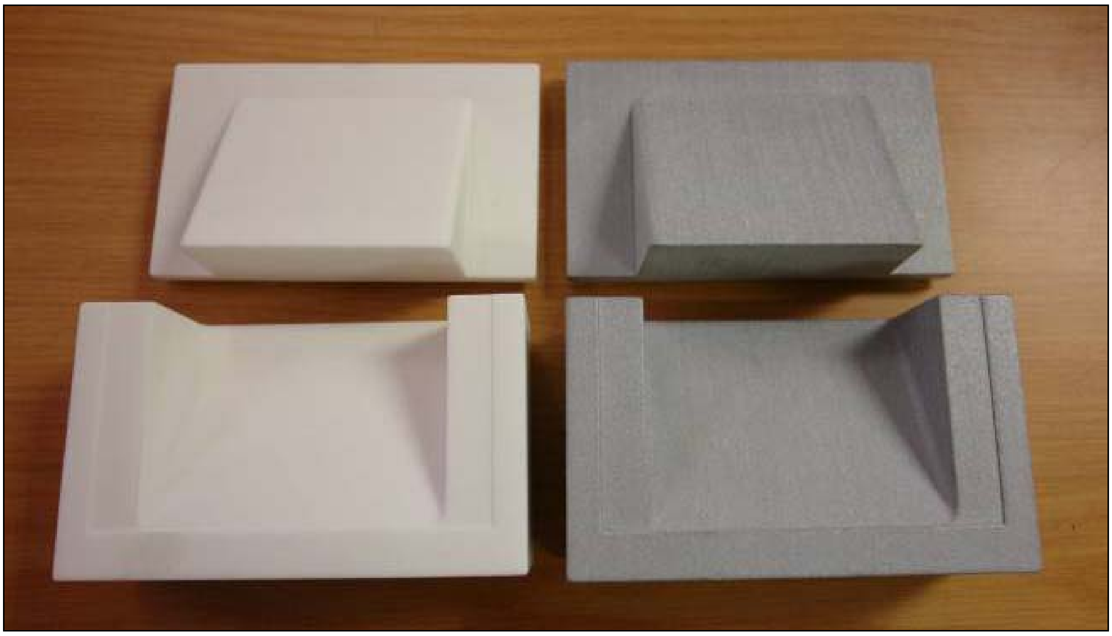

Figure 4.41: A top view of the second mould that was sintered in polyamide and Alumide®

Figure 4.42: A bottom view of the second mould sintered in polyamide and Alumide®

Figure 4.43: The filled second mould sintered in polyamide and Alumide®

These moulds were produced to determine if the geometry of a part will influence the number of CF components produced with a mould. This will determine whether a simpler geometry mould will produce more parts and deteriorate less, than a mould for a more complex part.

A moulded part from the second set of moulds can be seen in Figure 4.44.

Figure 4.44: A part from the moulds in experiment 5

4.5.1 Results from experiments 4 and 5

Sixty parts were manufactured from the moulds in experiments 4 and 5. Although the Alumide® moulds transfer the heat better, all the moulds performed the same in terms of part quality. All four moulds showed the same signs of deterioration. The resin started to build up in sharp corners in the moulds. Another problem identified was where the moulds sealed on a layer of CF. Due to the continual high pressure region created in these areas, the sharp edges started to become round. The build-up in the sharp corners can be seen in Figure 4.45 and the rounding of sharp edges can be seen in Figure 4.46.

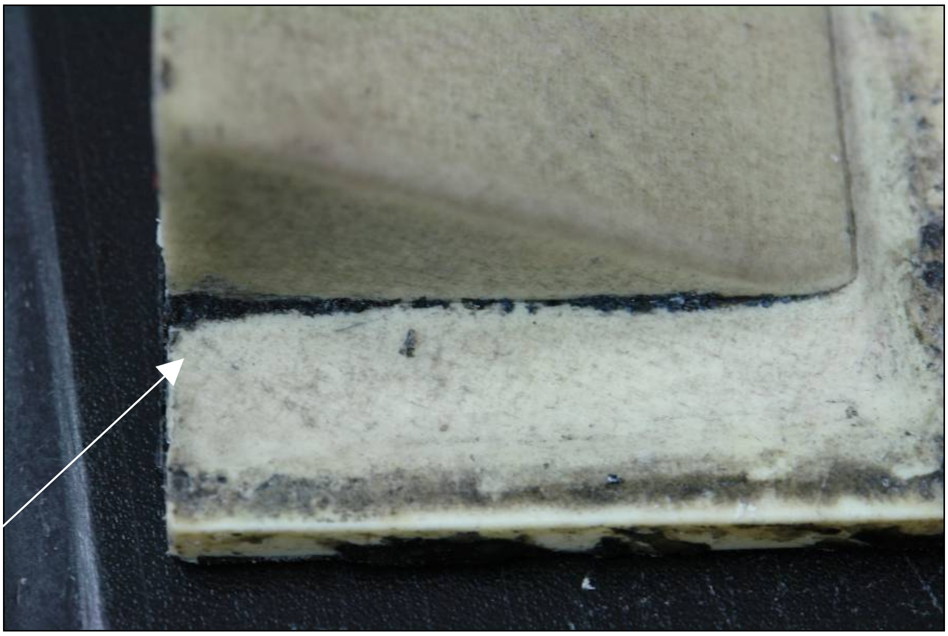

Figure 4.45: Build up of resin in sharp corners

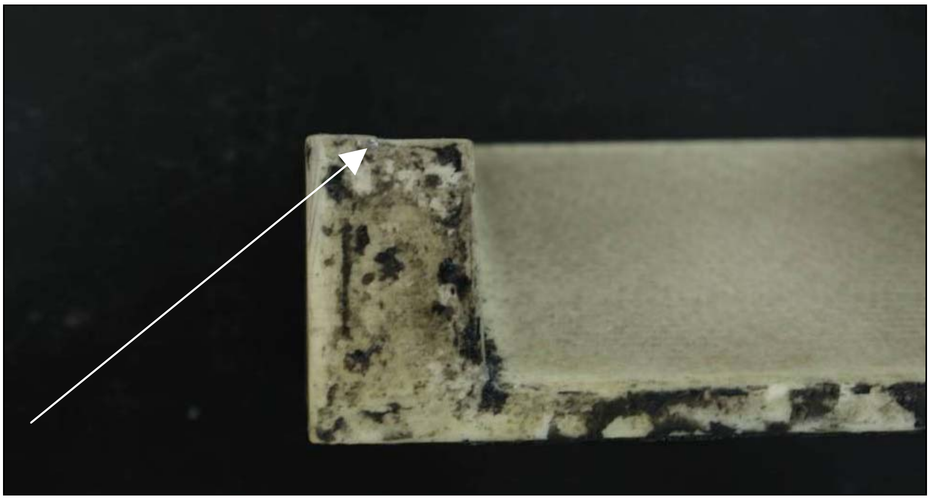

Figure 4.46: Rounding of sharp edges due to the high pressure caused by clamping

The polyamide and Alumide® moulds performed well if only prototype moulding is required. These moulds could be used if a limited production run is needed for CF moulding. The moulds produced 60 parts with the same quality throughout.

In Figure 4.47, a dimensional analysis of the first part produced in the Alumide® mould for experiment 5 can be seen. The part was easy to scan with the Konica-Minolta non-contact 3-D scanner and could easily be compared with the CAD data.

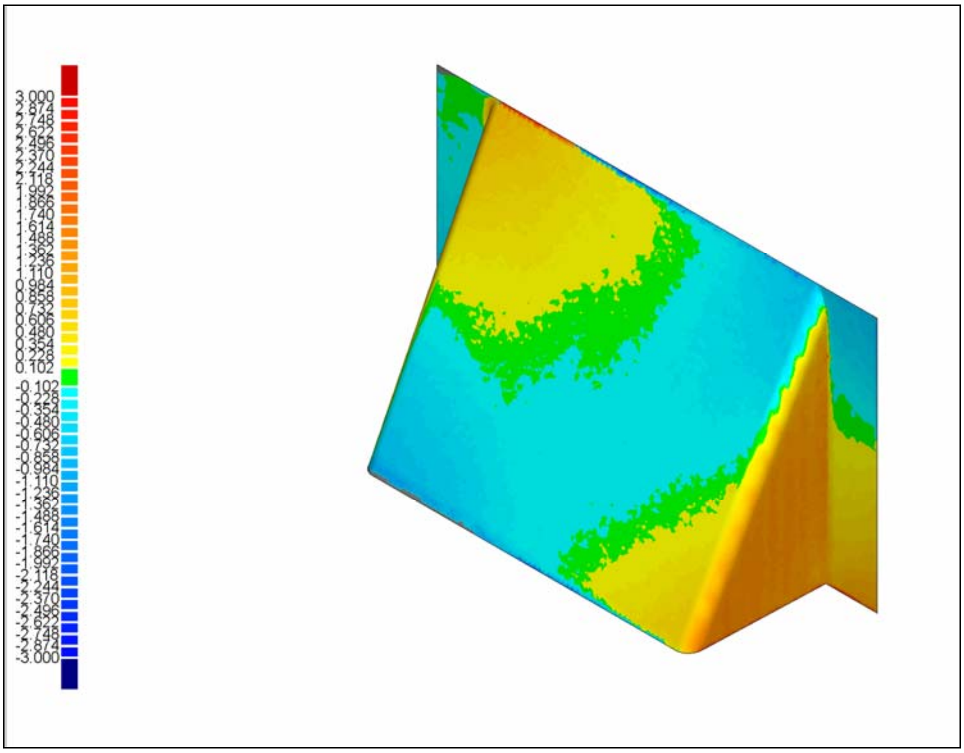

Figure 4.47: Dimensional analysis results for the first part in the Alumide® mould for experiment 5

A key to the colours in the figure can be seen in the bar on the left of the figure.

In Table 4.14, the maximum distance in mm for a data range is given in column one, the minimum distance in mm for the given data range is given in column two. The number of points for the distance data range is given in column three. The percentage of the total amount of points in the distance data range is given in column four.

Table 4.14: Number and percentage point at each deviation for the first part produced in the Alumide® mould

>=Min (mm)	<Max (mm)	# Points	%
-3	-2.874	0	0
-2.874	-2.748	0	0
-2.748	-2.622	3	0.002
-2.622	-2.496	1	0.001
-2.496	-2.37	8	0.005
-2.37	-2.244	2	0.001
-2.244	-2.118	26	0.015
-2.118	-1.992	74	0.043
-1.992	-1.866	86	0.049
-1.866	-1.74	97	0.056
-1.74	-1.614	101	0.058
-1.614	-1.488	100	0.057
-1.488	-1.362	101	0.058
-1.362	-1.236	107	0.061
-1.236	-1.11	97	0.056
-1.11	-0.984	195	0.112
-0.984	-0.858	521	0.299
-0.858	-0.732	1159	0.666
-0.732	-0.606	2486	1.429
-0.606	-0.48	5604	3.221
-0.48	-0.354	8627	4.958
-0.354	-0.228	12 764	7.335
-0.228	-0.102	30 180	17.344
-0.102	0.102	46 037	26.457
0.102	0.228	15 307	8.797
0.228	0.354	10 013	5.754
0.354	0.48	7357	4.228
0.48	0.606	5045	2.899
0.606	0.732	3819	2.195

Table 4.14 continues.

0.732	0.858	3376	1.94
0.858	0.984	2876	1.653
0.984	1.11	3182	1.829
1.11	1.236	3512	2.018
1.236	1.362	5978	3.435
1.362	1.488	3435	1.974
1.488	1.614	708	0.407
1.614	1.74	299	0.172
1.74	1.866	129	0.074
1.866	1.992	108	0.062
1.992	2.118	107	0.061
2.118	2.244	79	0.045
2.244	2.37	68	0.039
2.37	2.496	50	0.029
2.496	2.622	45	0.026
2.622	2.748	37	0.021
2.748	2.874	31	0.018
2.874	3	23	0.013

A graphical representation of Table 4.14 can be seen in Figure 4.48.

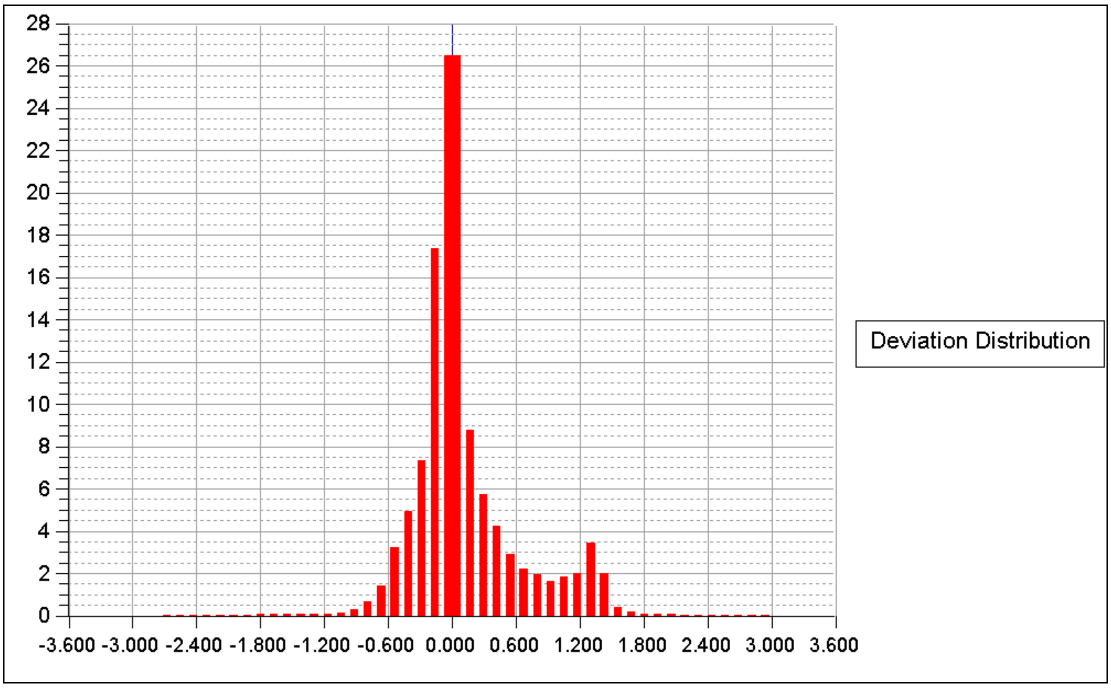

Figure 4.48: Graphical representation of the dimensional analysis results for the first part moulded in the Alumide® mould as shown in Table 4.14

In Figure 4.49 the dimensional analysis for the first part moulded in the polyamide mould can be seen.

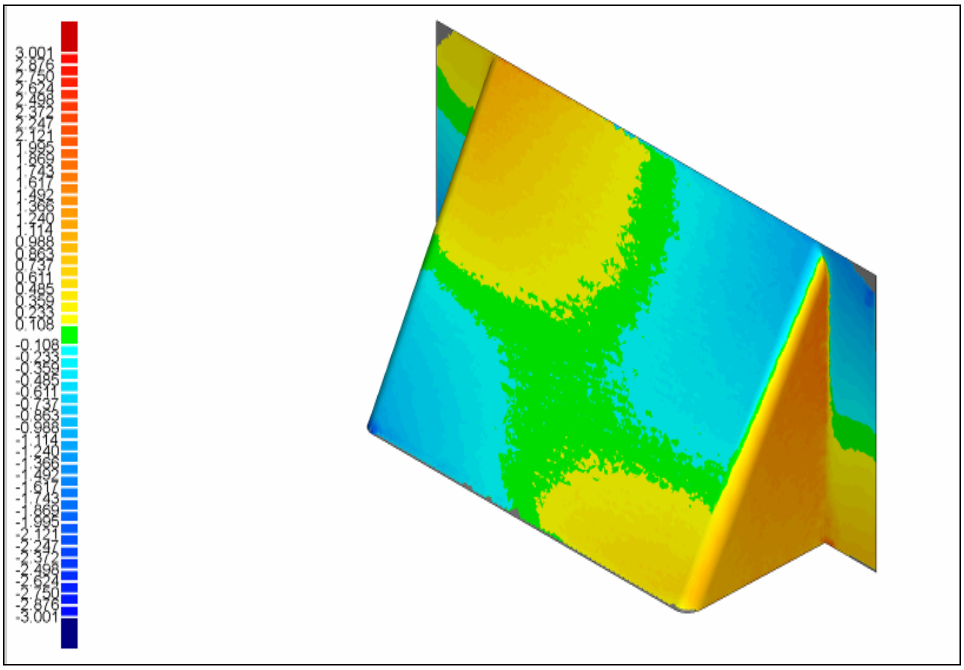

Figure 4.49: Dimensional analysis results for the first part in the polyamide mould for experiment 5

Table 4.15 is a representation of the data for the first part produced in the polyamide mould similar to Table 4.14.

Table 4.15: Number and percentage point at each deviation for the first part produced in the polyamide mould

>=Min (mm)	<Max (mm)	# Points	%
-3.001	-2.876	2	0.001
-2.876	-2.75	6	0.004
-2.75	-2.624	4	0.002
-2.624	-2.498	3	0.002
-2.498	-2.372	4	0.002
-2.372	-2.247	20	0.012
-2.121	-1.995	80	0.048
-1.995	-1.869	130	0.078
-1.869	-1.743	182	0.109
-1.743	-1.617	261	0.156
-1.617	-1.492	320	0.192
-1.492	-1.366	365	0.219
-1.366	-1.24	530	0.317

Table 4.15 continues.

-1.24	-1.114	781	0.468
-1.114	-0.988	986	0.591
-0.988	-0.863	1454	0.871
-0.863	-0.737	2605	1.56
-0.737	-0.611	4153	2.487
-0.611	-0.485	6034	3.614
-0.485	-0.359	7912	4.739
-0.359	-0.233	11 107	6.652
-0.233	-0.108	16 672	9.985
-0.108	0.108	48 021	28.76
0.108	0.233	19 237	11.521
0.233	0.359	11 778	7.054
0.359	0.485	7472	4.475
0.485	0.611	4513	2.703
0.611	0.737	3835	2.297
0.737	0.863	3375	2.021
0.863	0.988	3973	2.379
0.988	1.114	3387	2.028
1.114	1.24	2605	1.56
1.24	1.366	1966	1.177
1.366	1.492	1583	0.948
1.492	1.617	1150	0.689
1.617	1.743	390	0.234
1.743	1.869	36	0.022
1.869	1.995	5	0.003
1.995	2.121	0	0
2.121	2.247	0	0
2.247	2.372	0	0
2.372	2.498	0	0
2.498	2.624	0	0
2.624	2.75	0	0
2.75	2.876	0	0
2.876	3.001	0	0

Figure 4.50 is a graphical representation of Table 4.15.

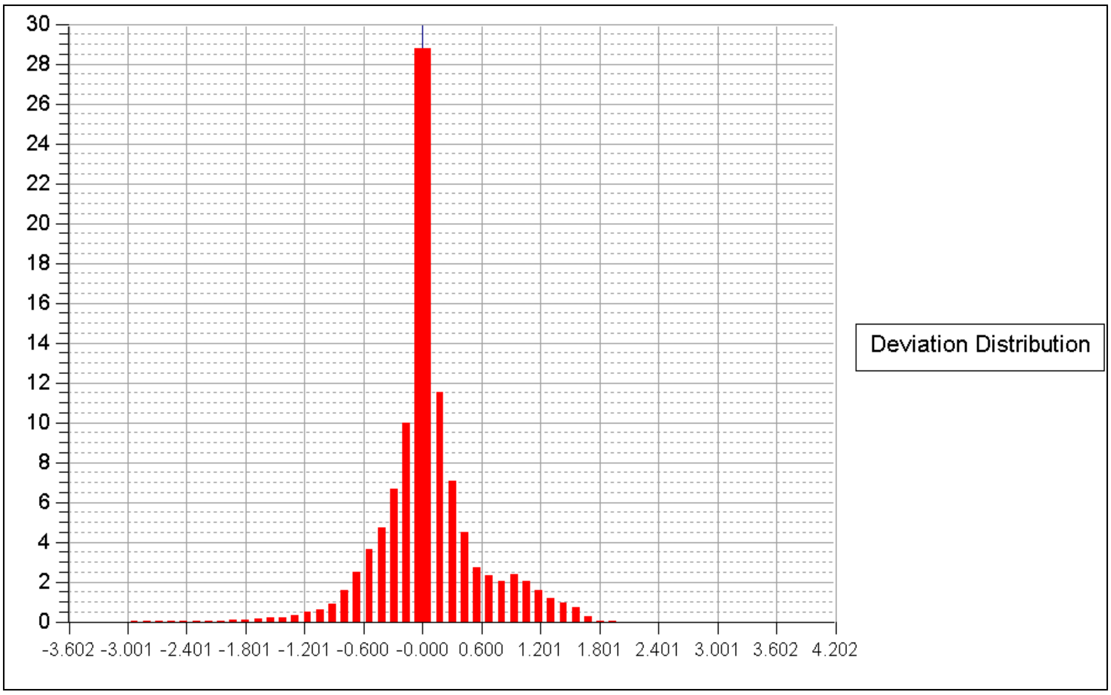

Figure 4.50: Graphical representation of the dimensional analysis results for the first part moulded in the polyamide mould as shown in Table 4.15

The graphical representation of the dimensional analysis carried out for parts 10, 20, 30, 40, 50 and 60 from the Alumide® mould can be seen in figures 4.51 – 4.56.

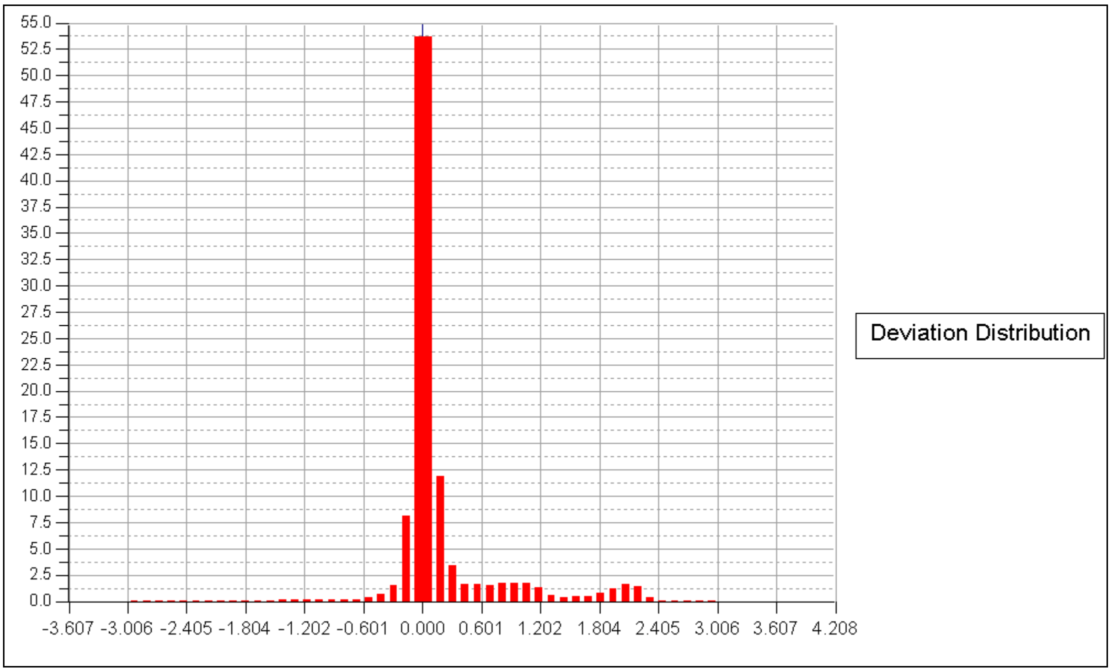

Figure 4.51: Graphical representation of the dimensional analysis results for part 10 moulded in the Alumide® mould

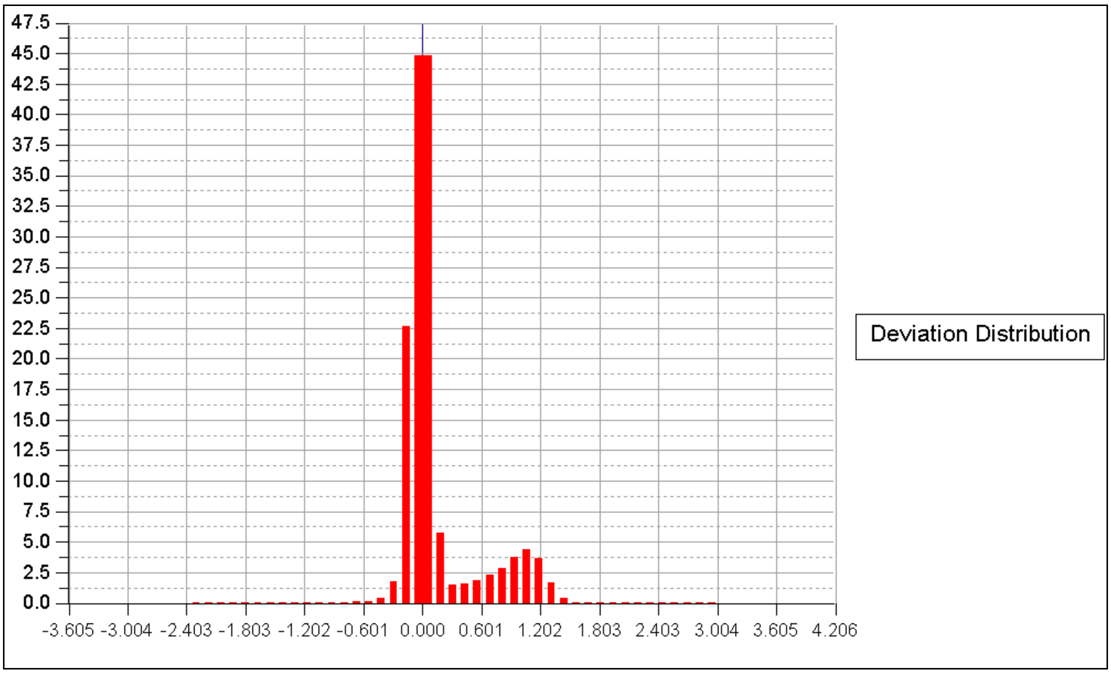

Figure 4.52: Graphical representation of the dimensional analysis results for part 20 moulded in the Alumide® mould

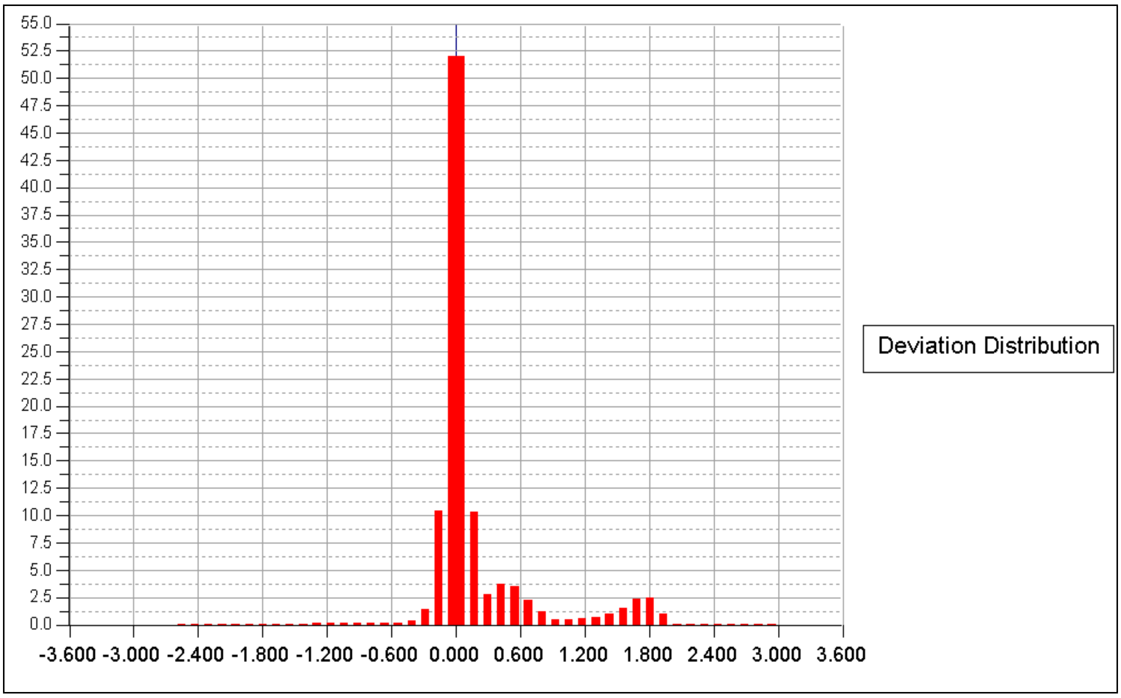

Figure 4.53: Graphical representation of the dimensional analysis results for part 30 moulded in the Alumide® mould

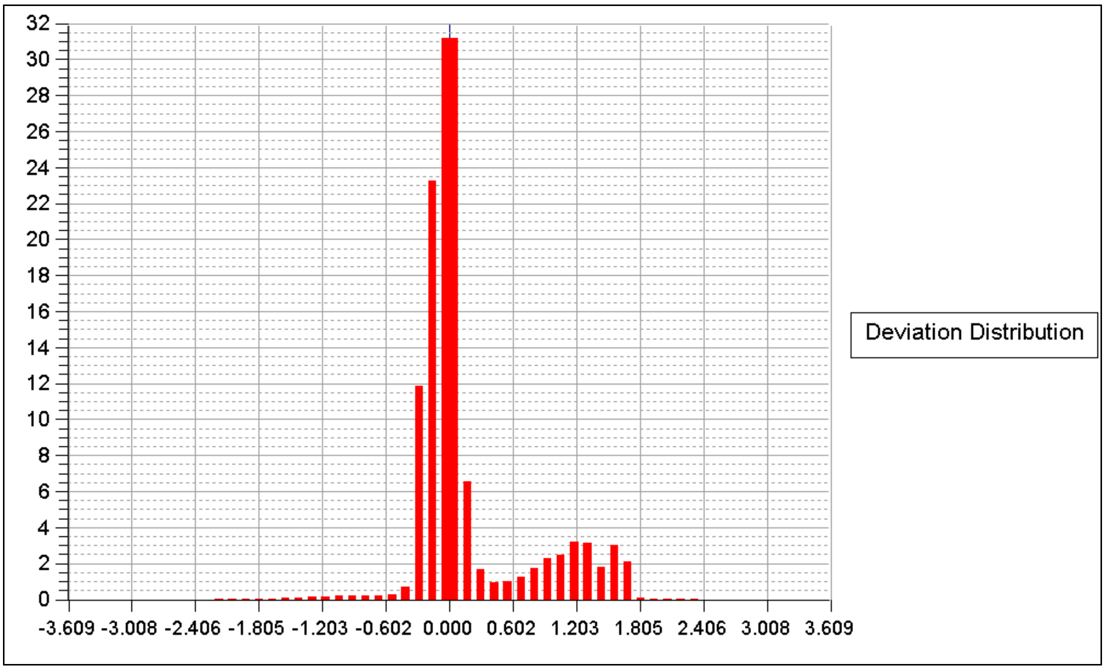

Figure 4.54: Graphical representation of the dimensional analysis results for part 40 moulded in the Alumide® mould

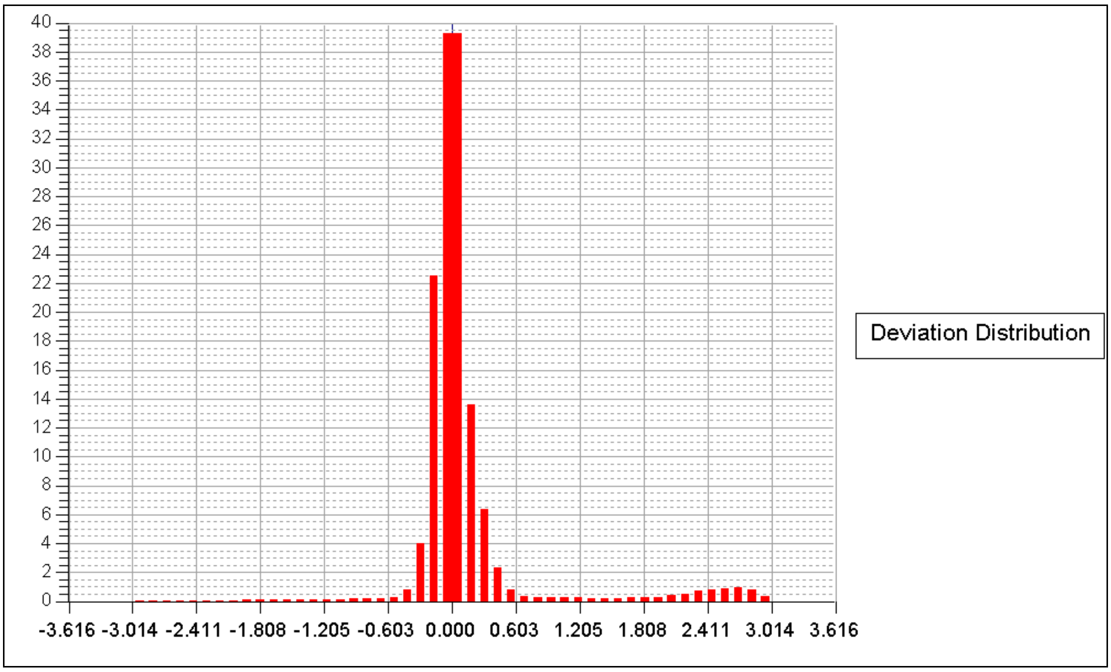

Figure 4.55: Graphical representation of the dimensional analysis results for part 50 moulded in the Alumide® mould

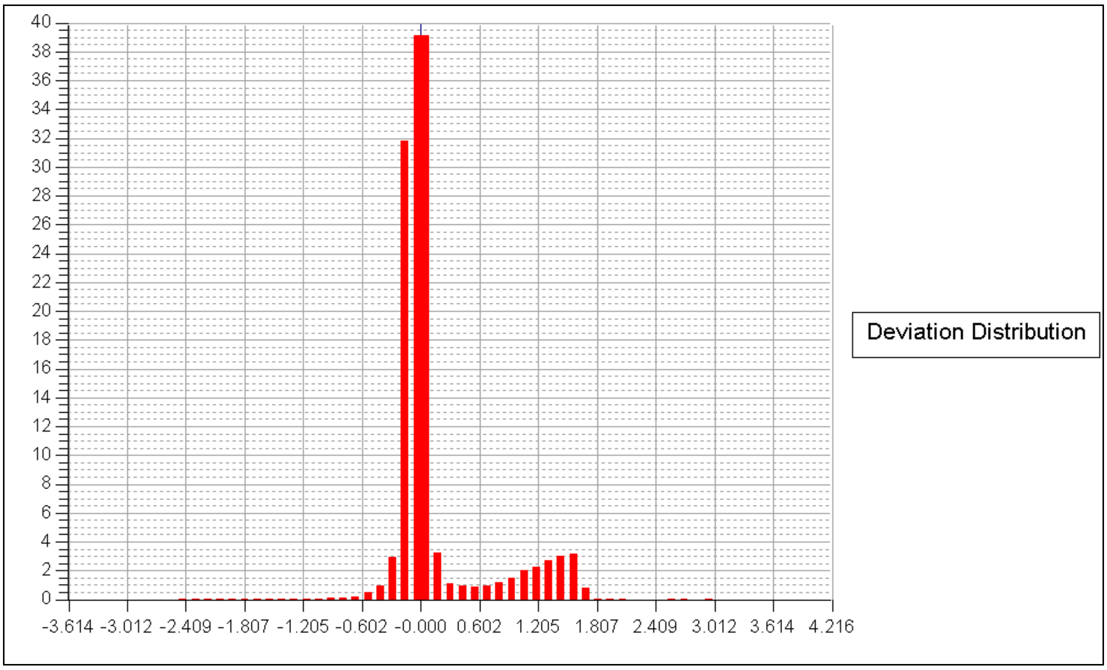

Figure 4.56: Graphical representation of the dimensional analysis results for part 60 moulded in the Alumide® mould

Figures 4.57 – 4.62 are representations of the dimensional analyses of parts 10, 20, 30, 40, 50 and 60 from the polyamide mould.

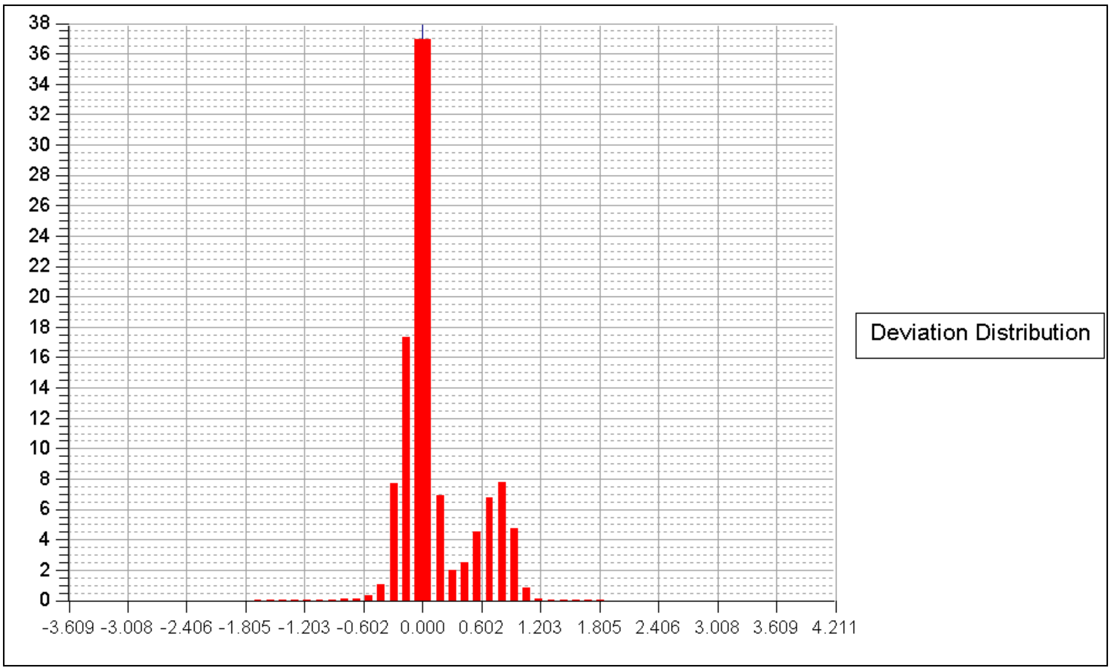

Figure 4.57: Graphical representation of the dimensional analysis results for part 10 moulded in the polyamide mould

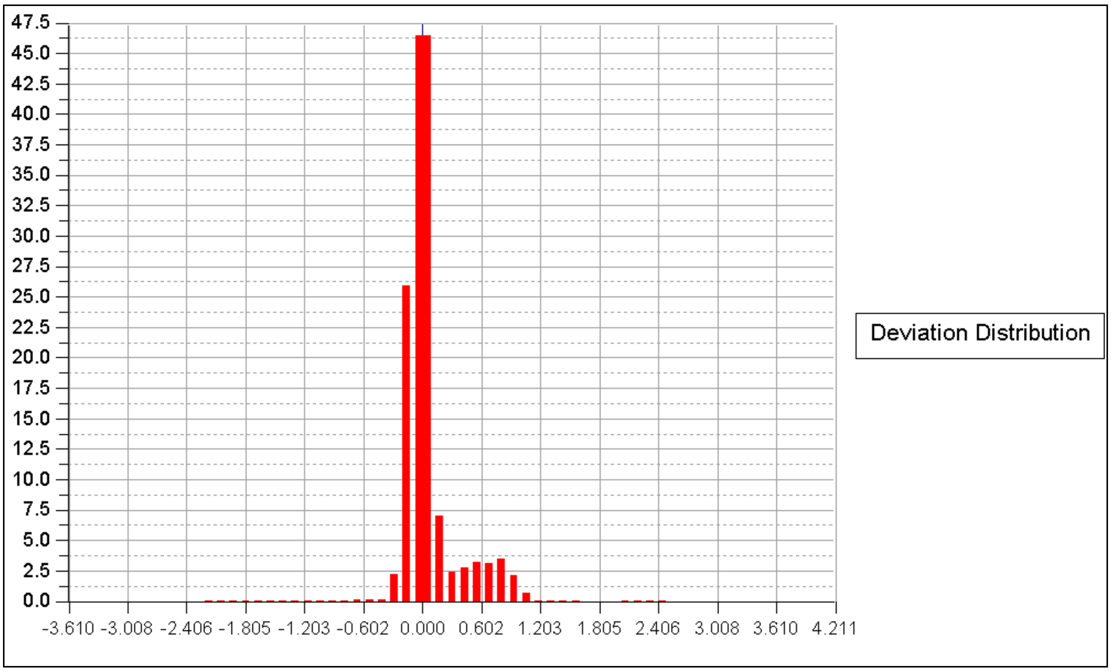

Figure 4.58: Graphical representation of the dimensional analysis results for part 20 moulded in the polyamide mould

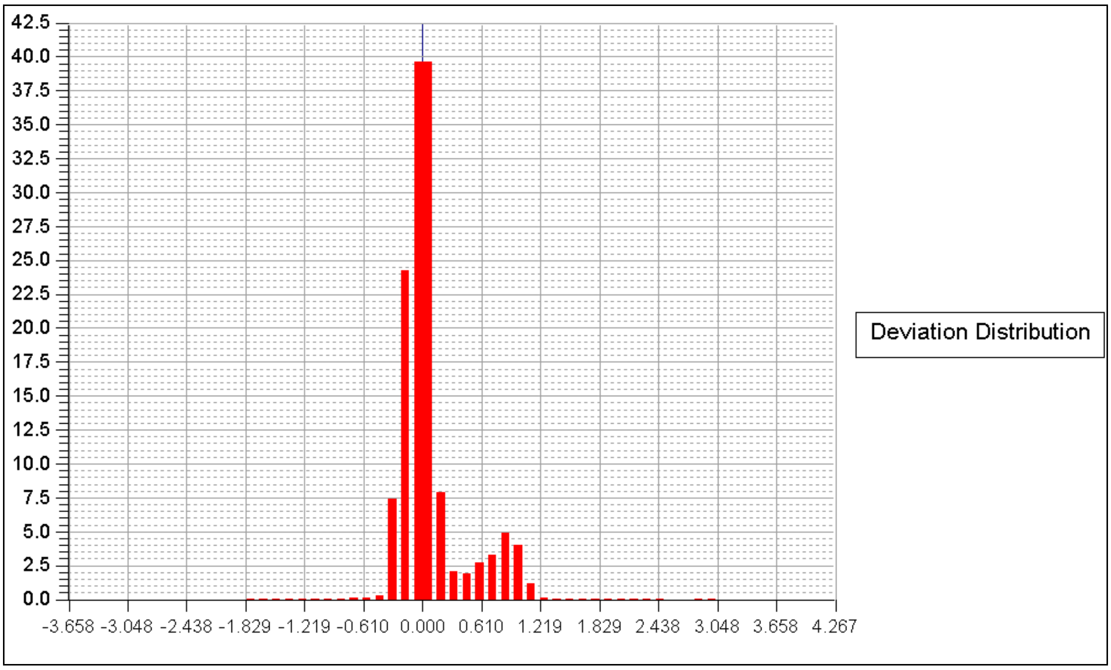

Figure 4.59: Graphical representation of the dimensional analysis results for part 30 moulded in the polyamide mould

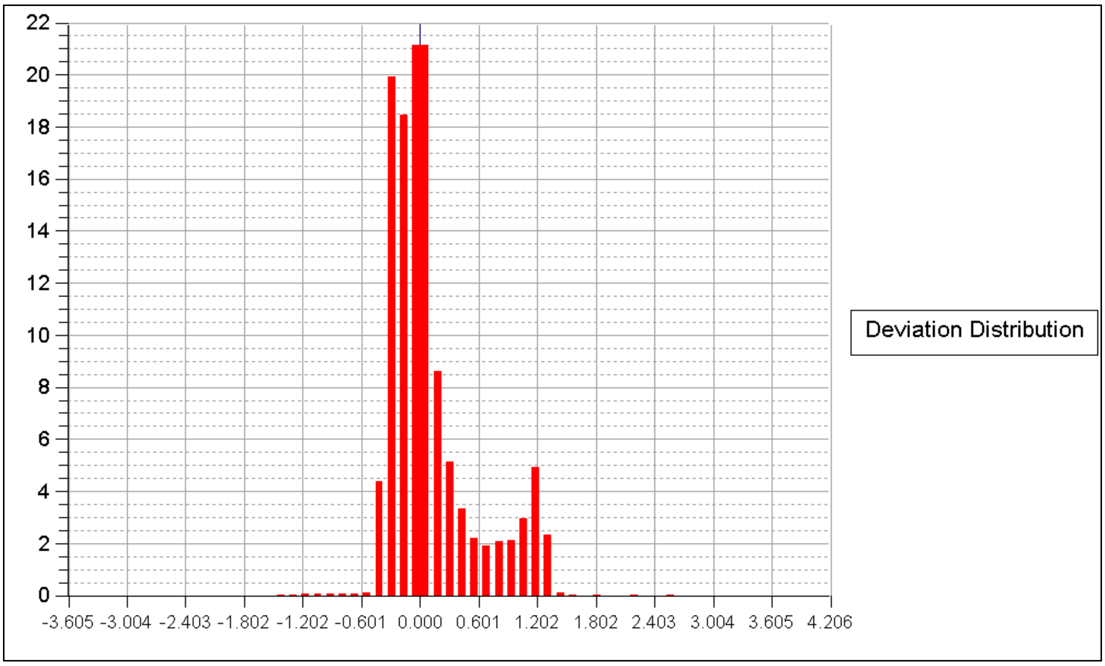

Figure 4.60: Graphical representation of the dimensional analysis results for part 40 moulded in the polyamide mould

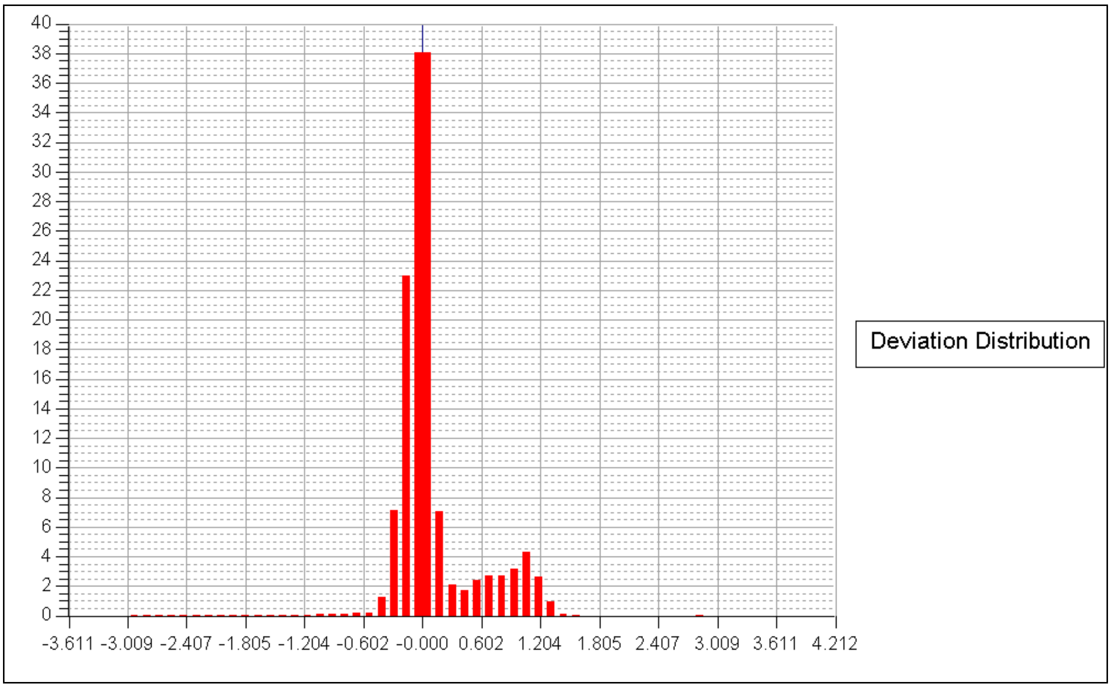

Figure 4.61: Graphical representation of the dimensional analysis results for part 50 moulded in the polyamide mould

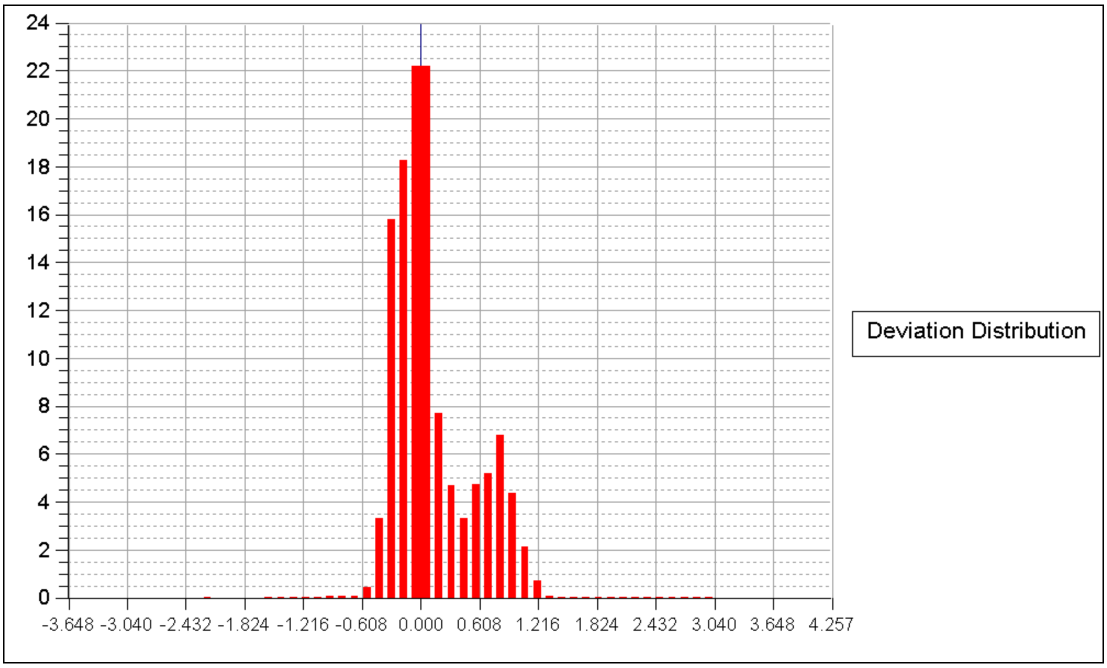

Figure 4.62: Graphical representation of the dimensional analysis results for part 60 moulded in the polyamide mould

Figure 4.63 is a representation of the average percentage of points for each deviation distance for the parts produced in the Alumide® mould.

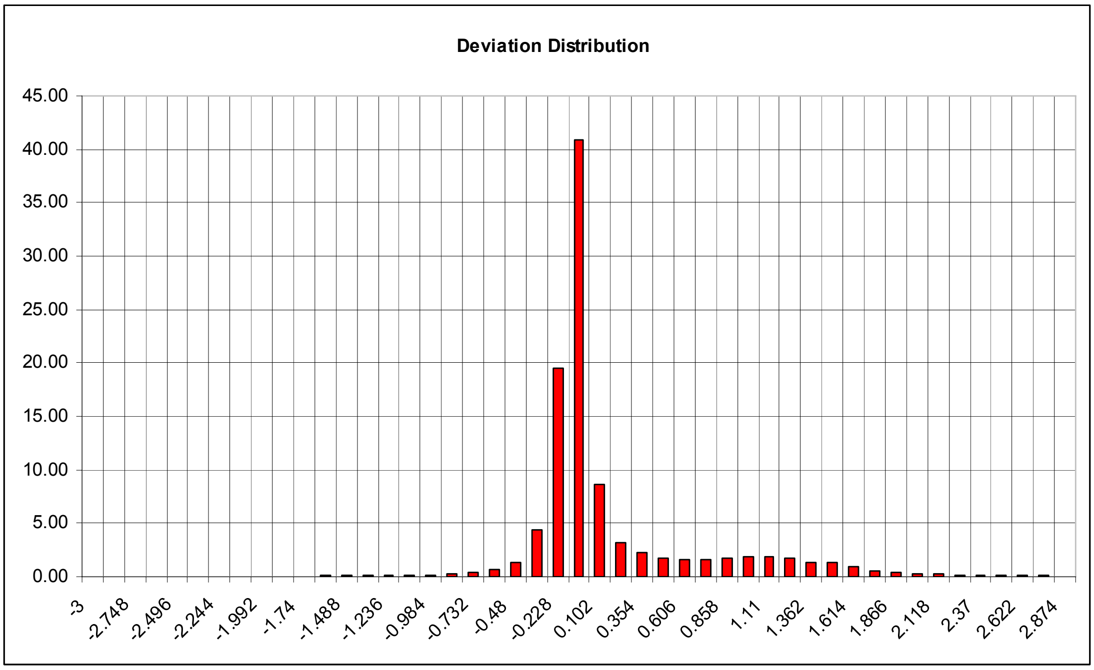

Figure 4.63: The average percentage points per deviation for the parts produced in the Alumide® mould

Figure 4.64 is a representation of the average deviation for the parts produced in the polyamide moulds.

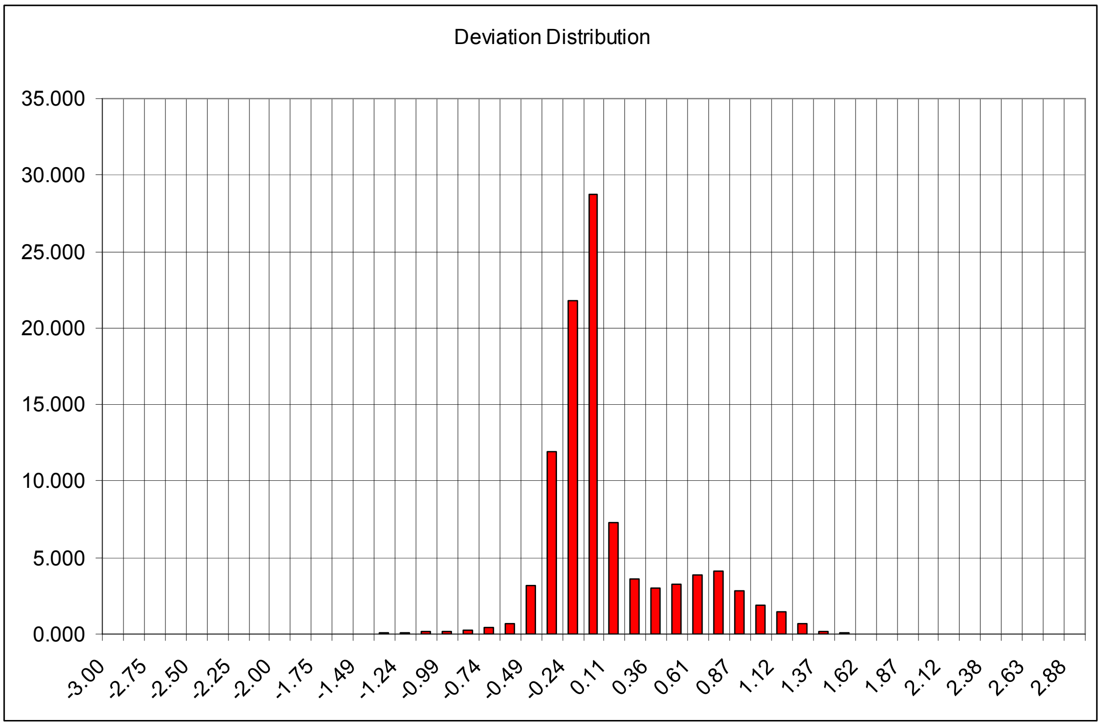

Figure 4.64: The average percentage points per deviation for the parts produced in the polyamide mould

Figure 4.65 represents the percentage of points for each of the parts produced in the Alumide® mould that are greater than 0 mm. This is just an indication that all the parts produced in the Alumide® moulds are mostly larger than the CAD data. This can be due to the fact that the moulds are heated to 140°C to cure the resin. The mould expands when it is heated and results in the parts being larger than the CAD data.

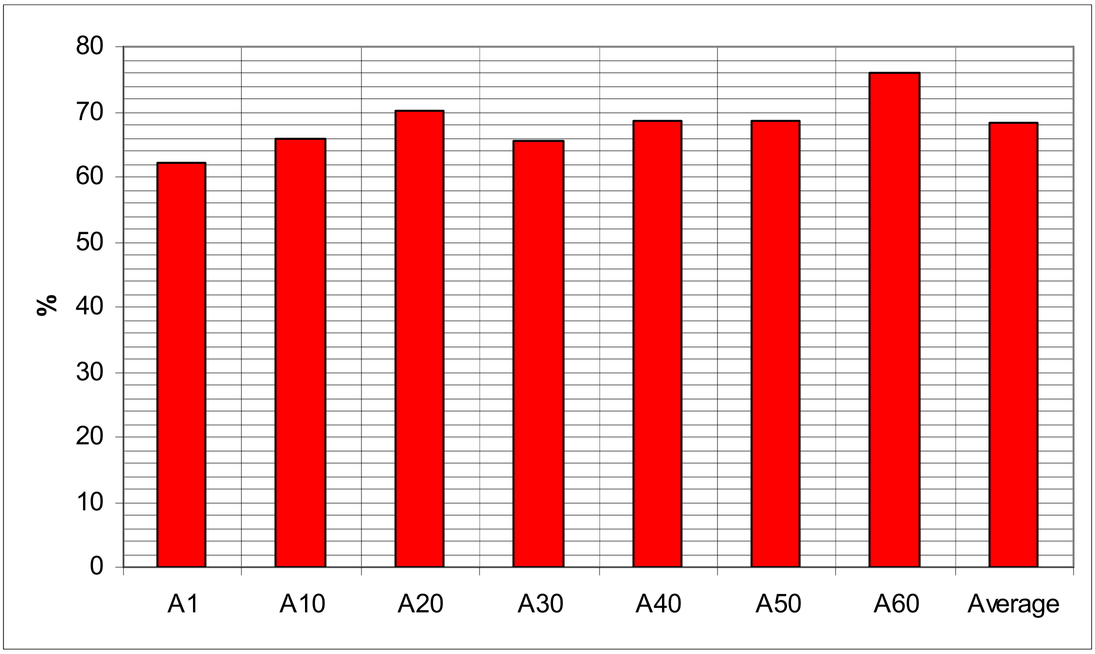

Figure 4.65: Representation of percentage points between 0 mm and 3 mm for the parts produced in the Alumide® mould

A1 represents part number 1 in the Alumide® mould, A10 for part number 10, A20 for part 20 and so forth. Figure 4.66 represents the percentage of points for each of the parts produced in the polyamide mould that lie between 0 mm and 3 mm. As with the parts produced in the Alumide® mould, the parts produced in the polyamide mould are mostly larger than the CAD data. This is also due to the fact that the mould is heated to cure the resin.

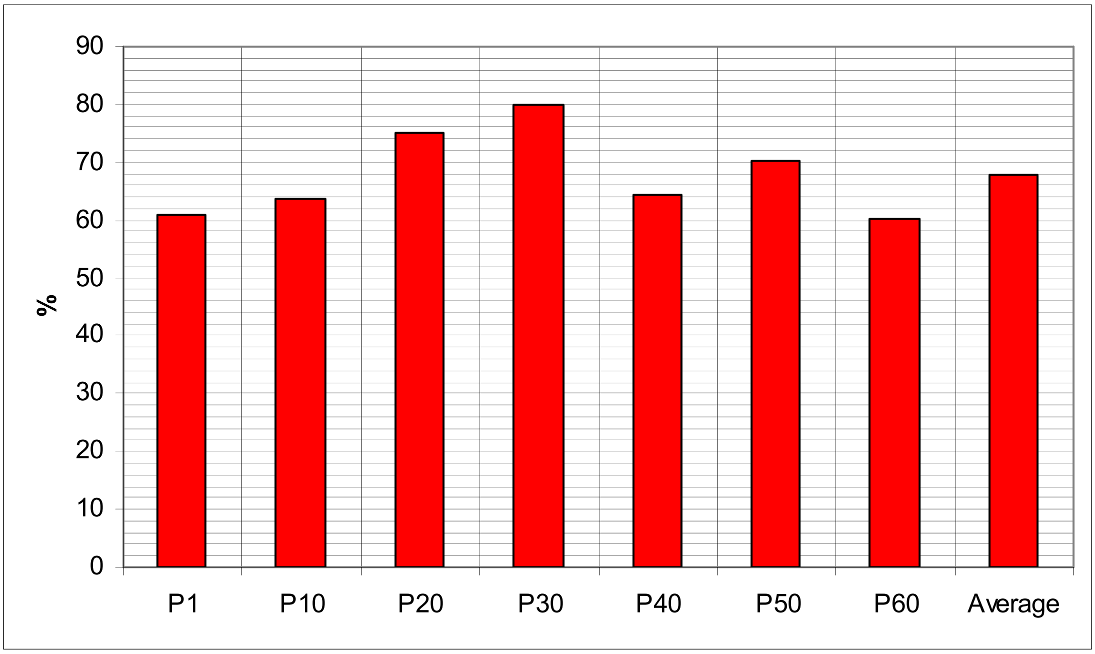

Figure 4.66: Representation of percentage points between 0 mm and 3 mm for the parts produced in the polyamide mould

P1 represents part number 1 in the polyamide mould; P10 is for part number 10, P20 for part 20 and so forth. The average for the points larger than the CAD for the parts produced in the Alumide® mould is 68.20%. The average for the points larger than the CAD data for the parts produced in the polyamide mould is 67.79%. The parts produced in the Alumide® mould are slightly larger than the parts produced in the polyamide mould. This can be due to a difference in thermal expansion coefficients for Alumide® and polyamide. The thermal expansion coefficients are not available for Alumide® and polyamide due to a slight difference in the material properties per batch.

The average measured strength of the material moulded in the two moulds was 526.15 MPa (Appendix D). According to the material data sheet (Appendix A); the maximum tensile stress of a single layer of the material is

680 – 780 MPa. The difference between the measured and the theoretical values can be because of the sandwich effect or imperfections in the moulded material. The sandwich effect occurs where the layers thicken the material, but actually weaken it. The force between the layers of the material is transmitted through the resin and not the fibres. A three dimensional weave of 1 mm thick will be stronger than layers of two dimensional woven material that is 1 mm thick altogether. In the three dimensional woven materials the load is transmitted through the materials with fibres and in the layers of two dimensional woven materials the load is transmitted through the material with the resin. A three dimensional weave can be seen in Figure 2.10.

The fact that the moulds cannot be compressed more than the polymer material allows influences the overall strength of the part. The pressure in the mould determines the fibre/resin volume. The harder the mould can be pressed, the higher the fibre/resin volume will be.

There were however problems with the process such as that the sharp corners filled with resin and the sharp edges were rounded by the pressure. The release of the parts was satisfactory for all the moulds and none of the parts were stuck in the moulds. Therefore, the releasing properties of the material were good, with both the Alumide® and polyamide moulds showing the same results. The only advantage the Alumide® has over the polyamide is a better heat transfer coefficient.

CHAPTER 5

RESULTS AND ANALYSIS OF RESULTS

The experiments were carried out to determine whether it is possible to use LS parts from the EOS P380 machine for CF moulding. Alumide® and PA2200 polyamide powder parts were used in the experiments. The moulds were designed to be used for prototype moulding or as small production moulds.

5.1. The mould design

The findings from the experiments prove that the moulds can be used for small production runs (± 100 parts) or for prototype moulding. The mould design should however be adapted to the process. The moulds can be designed in such a way that up to 45% of the LS manufacturing cost of the parts, compared to solid mould designs can be saved. By designing parts with thin-walls and using resin and excess powder as backfill, a great deal of building time and material can be saved resulting in a cost saving. If excess polyamide powder is not available aluminium filler powder can be used. The aluminium powder cost R 37.62 per kg. Time can be saved by producing the moulds with the LS process. A time saving of over 80% is possible for small parts compared with the time it would take to produce the moulds with aluminium. An even bigger time saving is possible for large complex parts, which will significantly reduce costs.

The cost of a part produced using the LS process is independent of the complexity of the part. The only cost factor for parts built with the LS process is the volume of powder used and the height of the part. The height and the volume of the part determine the time it will take to build the part. The building time is the biggest factor in determining cost of the part.

In experiment 4, there was a cost difference of 32.88% between the Alumide® mould and the CNC produced mould. There was a cost difference of 48.67% between the PA2200 polyamide mould and the CNC produced mould. The more complex the parts become, the bigger the difference in cost will be.

A significant advantage of the LS process is when more than one mould is produced. The cost per part actually decreases as more parts are produced per build. This is a great advantage if a large number of parts have to be produced and more than one mould is needed. In conventional mould manufacturing processes, the cost per part remains the same. The time taken to manufacture the parts also stays the same for conventional processes. In the LS process, more than one mould can be manufactured at the same time. The time it will take to produce a number of parts can vary with a minimal time variation as long as the parts fit on the same layer of the building platform. The building time is the largest factor in the costing of LS parts. This also depends on the size of the parts. Small parts can be manufactured in large numbers without adding much to the cost, whereas with large parts, the cost saving per part will decrease the larger the parts become. The LS parts are restricted by the size of the parts the machine is able to sinter. The

EOS P 380 machine has a building volume of 340 x 340 x 620 mm. There are machines with a bigger building volume such as the EOS P 730 machine which has a building volume of 700 x 380 x 580 mm.

The more complex the part to be manufactured on a CNC machine, the more it will cost to produce and the longer it will take to manufacture. The costing on a CNC machine is determined by the size of the material used and the time it will take to machine the block to the desired shape. The time it takes to produce a part on the CNC escalates with the increase in complexity. For complex parts a 4 – 5 axis CNC machine is needed. These machines are even more expensive to run than a 3-axis machine. The machining volume that a CNC machine can cut is however larger than the volume a LS machine can sinter.

5.2. Operation and handling of the mould

It was possible to produce 60 parts from the moulds in experiment 4 and 5. The mould was not tested to destruction. After the initial wear on the mould no further wear was observed. Only 60 parts were manufactured as the necessary results were obtained. There was resin build-up in the sharp corners and the sharp edges were also deformed due to the pressure. This wear however did not escalate. Nor did it worsen as more parts were manufactured.

No problems were experienced with the moulding process if the moulds were well prepared beforehand. The moulds were treated with a clear lacquer which filled all the pores in the material and ensured a good moulding surface. The clear lacquer however should be applied carefully. It can happen that it builds up in lower part of the mould. The moulds were also coated with a release agent each time before a part was moulded, which kept the surface of the mould in good condition. The release agent improved the surface finish of the moulds and acted as filler for any imperfections on the moulding surface. The LS parts are quite porous, and therefore, a filler is required to prevent the parts from sticking to the surface or alternatively, a coating surface like plating can be investigated.

5.3. Clamping of the parts

The first moulds were clamped with car jacks, but the moulds in experiment 4 and 5 were clamped with steel clamps that were bolted. Plates were cut to ensure a large surface between the clamp and the mould. The moulds become quite soft at high temperatures and therefore, a surface that pressed on the whole back side of the mould was needed to prevent the clamps from damaging the moulds.

5.4 Finishing of the CF parts

The moulds were not strong enough to finish off the edges, so had to be trimmed afterwards. This was done with a small bench grinder. Small parts were done quickly but larger complex parts could take much longer. This process is also required if the moulds are manufactured from aluminium. However, if the clamping force is sufficient, this process can be faster for parts manufactured from an aluminium mould.

The parts produced had a matt surface finish and not a polished finish. In an aluminium mould it is possible to obtain a polished finish directly from the mould. To achieve a polished look directly from a LS mould, the CF must be sandwiched between two plastic layers. The layers can be removed after the moulding process, which ensures a polished look on the parts.

CHAPTER 6

CONCLUSION

This study proved that it is possible to directly manufacture moulds for CF compression moulding through RM with a laser sintering machine. The moulds can be used for prototype moulding, but allows the prototype moulding process and the production moulding process to be the same process. It can also be used for small production runs where only ± a 100 parts are required which can be used for final production or market research purposes for small parts. The mould size is however restricted by the size that the LS machine can sinter.

The parts produced in the moulds can be used for low performance parts. However, the parts are not suited for high performance parts used in aerospace and high-end automotive components. The parts manufactured for high performance industries must have a very good surface finish and accuracy.

Low performance parts are used as cosmetic components such as car dashboards and the interiors of aeroplanes, to name a few examples. This is a large industry worldwide with more components being manufactured from CF due to the weight saved by using this material. Some aerospace manufacturers predict that the extensive use of composite materials can save maintenance time and expenses and can cut the fuel burn per passenger by 20%. Some aeroplanes have a 50% composite material content and not just high performance parts are being manufactured from composite materials. A number of aluminium parts are also being replaced by CF parts. Some of these parts can be manufactured by using RM.

A mould can be manufactured far quicker by using the RM process to manufacture moulds to prototype a part than with conventional methods. The mould can also be used to prototype the process used to manufacture the final component and can be produced up to 80% cheaper than an aluminium mould. The saving depends on the size and complexity of the part that is required. The CF prototyping market is very large and under- developed. Most of the prototypes are produced by the hand lay-up process which is time consuming and not accurate. The parts show different characteristics compared with the final production part due to the following:

- Fibre/resin volume of the hand lay-up process differs from the final compression production process
- The pressure at which the part is produced
- The resin used in the hand lay-up process differs from the resin used for the compression moulding process

Using a compression process as prototyping method, the parts will be similar or the same as the final production compression process.

More research however needs to be done in this field. Other moulding processes should be investigated which can make use of rapid manufactured moulds. Only compression moulding was investigated in this study, but there are other moulding methods that can use this technology such as resin transfer moulding (RTM), vacuum assisted resin transfer moulding (VARTM), hand lay-up and spray moulding. All of these moulding processes have their own challenges and difficulties.

Further research in the compression moulding field can also be done. A precise scaling factor is needed to produce accurate parts. A thermal expansion coefficient is needed for the sintered materials. This will help to produce more accurate parts. Different surface finishes can be studied as well as new methods of finishing the surface so that the pores are sealed and the surface finish of the parts are acceptable for more high-end parts. The back filling of the parts can also be further studied.

As the process of RM for CF moulding is used more frequently, new challenges will arise, and new research projects will arise from these challenges.

References

1. Kaw, A.K.; Mechanics of Composite Materials; CRC Press, Boca Baton, 1997
2. Lenau, T.; Design Insight, Carbon Fibre; Available from: <http://www.designinsite.dk/htmsider/m0632.htm>; [Accessed 17 May 2006]
3. Bikebiz; Annual Production of Carbon Fibre; Available from: <http://www.bikebiz.co.uk/daily-news/article.php?id=5532>; [Accessed 17 May 2006]
4. Gibson, R.F.; Principles of Composite Materials Mechanics; McGraw-Hill, Inc., New York, 1994
5. Henne, M.; Modelling of Thermal Aspects in Liquid Composites for Industrial Applications; Eidgenössischen Technischen Hochschule, Zürich, 2003
6. Wikipedia; Carbon Fibre; Available from: <http://en.wikipedia.org/wiki/Carbon_fibre>; [Accessed 17 May 2006]
7. Fitzer, E.; Köchling, K.H.; Boehm, H.P.; Marsh, H.; Recommended Terminology For The Description Of Carbon As A Solid; Pure & Applied Chemistry; Vol. 67, No.3, pp. 473-506, 1995
8. Hyer, M.W.; Stress Analysis of Fibre-Reinforced Composite Materials; McGraw-Hill, Inc., New York, 1998
9. Total Fishing; Carbon Fibre; Available from: <http://www.total-fishing.com/News.asp?Action=View&ID=EFBB030ED5B44DC8A57ED588B1278D76>; [Accessed 8 May 2006]

10. Cairns, D.S.; Rossell, S.M.; Fluid Flow Modelling of Resin Transfer Moulding for Composite Material Wind Turbine Blades Structures; Department of Chemical Engineering Montana State University-Bozeman, 2004

11. Lenau, T.; Design Insight, Process Hand Lay-up; Available from: <http://www.designinsite.dk/htmsider/p0102.htm>; [Accessed 21 January 2005]

12. Gurit; SP Systems, SP Guide to Composites; Available from: <http://www.spsystems.com/solutions/general_pdfs/SPGuide_to_Composite.pdf>; [Accessed 12 November 2004]

13. Saint-Gobain / Vetrotex; Available from: <http://www.sgva.com/fabrication_processes/rna_handlay.html>; [Accessed 21 January 2005]

14. Heiden, P.A.; Michigan Tech University, Resin Transfer Moulding; Available from: <http://islnotes.cps.msu.edu/trp/liquid/rtm/index.html>; [Accessed 1 August 2005]

15. van Pelt, D.; Saad, F.; Low8, Manufacturing Methods; Available from: <http://www.low8.com/ale/index.php?cid=72>; [Accessed 6 April 2006]

16. Western Technigraphics LTD; Technologies, Spray Lay-up Process; Available from: <http://www.wtec.org/Loyola/polymers/c1_s4.htm>; [Accessed 6 April 2006]

17. Way Composites – Overview; Applied Composites; Available from: <http://appliedcompositescorp.birkey.com/imgs/compression_molding.gif>; [Accessed 16 November 2006]

18. Wikipedia; Carbon Fibre-reinforced Polymer; Available from: <http://en.wikipedia.org/wiki/Graphite_reinforced_plastic>; [Accessed 17 May 2006]

19. Bullard; Helmet book, Compression Moulding; Available from: <http://www.bullard.com/Fire_Rescue/helmet_book/section_1.shtml>; [Accessed 6 April 2006]

20. Wikipedia; Compression Moulding; Available from: <http:www.answers.com/topic/compression-molding>; [Accessed 18 May 2006]

21. Contact Angle and Surface Energies; Avialeble from: <http://www.ucs.ull.edu/~yxs7228/New%20Folder/SP3.pdf>; [Accessed 30 May 2006]

22. Non-destructive Testing Resource Centre; Surface Energy (Surface Wetting Capability); Available from: <http://www.ndt-ed.org/educationResources/CommunityCollege/PenetrantTest/PTMaterials/surfaceenergy.htm>; [Accessed 01 August 2006]

23. Hansen, F.K.; The Measurement of Surface Energy of Polymer by Means of Contact Angle of Liquids on Solid Surface; Department of Chemistry, University of Oslo, 2004

24. Zisman, W.A.; ACS Advanced Chemical Series 43; 1964

25. Ramé, E.; How Does Liquid Wet a Solid? Hydrodynamics of Dynamic Contact Angle, 1999

26. Mulligan, D.R.; Sims, G.D.; Characterisation of Fibres Surfaces by Wetting Techniques; Crown, 1999

27. Srivastava, N.; Davenport, R.D.; Burns, A.B.; 2003. A Microfabricated Viscocometre, 7th International Conference on Miniaturized Chemical and Biochemical Analysis Systems; October 5-9, 2003, pp. 563-566

28. Roechling Glastic Composites; Laminates White Paper; Available from: <http://www.glastic.com/laminates_wp.htm>; [Accessed 18 April 2006]

29. Kenneth, L.F.; Starr, T.F.; Thermoset Resin.; Rapra Publishing, 2003

30. Dyer CMM Services; Hardware, <http://dyercmm.com/hardware.html>; [Accessed 20 November 2006]

31. Konica Minolta; 3D Digitizing – New Konica Minolta 3D Digitizer; Available from: <http://konicaminolta.com/products/instruments/vivid/vivid910.html>; [Accessed 20 November 2006]

32. Leatt Brace; Available from: <http://www.racingneckbrace.com/r1.jpg>; [Accessed 25 November 2006]

33. eFunda; Rapid Prototyping: SLS; Available from: <http://www.efunda.com/processes/rapid_prototyping/sls.cfm>; [Accessed 6 December 2004]

34. Cottrill, D.M.; A Thermal Study of the Selective Laser Sintering Process; University of Wisconsin, 2004

35. Wagner, T.; Höfer, T.; Knies, S.; Eyerer, P.; Laser Sintering of High Temperature Resistant Polymers with Carbon Black Additives; Inter. Polymer Processing XIX, Hanser Publishers, Munich, 2004

36. Shockley, B.; Selective Laser Sintering; AE 510 Research Paper, 2002

37. Kumar, S.; Selective Laser Sintering: A Qualitative and Objective Approach; JOM, 2003; pp. 43

38. The University of Kansas; School of Engineering, Selective Laser Sintering; Available from: <http://www.engr.ku.edu/~rhale/ae510/websites_f02/SLS/website/process.html>; [Accessed 6 December 2004]

39. Materialise UK; Selective Laser Sintering: New Dimensions; <http://materialise.com>; [Accessed 23 May 2006]

40. Mot-tech Rapid Prototyping; The SLS Process, Selective Laser Sintering; Available from: <http://www.mor-tech.com/rprototypingslsm.htm>; [Accessed 6 December 2004]

41. Axson; Product Data, Fastcast Polyurethane; Available from: <http://www.axson.com>; [Accessed 19 June 2006]

42. Matthews, F.L.; Rawlings, R.D.; Composite Materials: Engineering and Science; Chapmam & Hall, London, 1995

43. Wikipedia; Aluminium; Available from: <http://en.wikipedia.org/wiki/Aluminium>; [Accessed 29 August 2007]

44. Wikipedia; Vicat softening point; Available from: <http://en.wikipedia.org/wiki/Vicat_softening_point>;
[Accessed 7 September 2007]

APPENDIX A

TECHNICAL DATA SHEET: PREPREG EPOXY SYSTEM IMP505

TECHNICAL DATA SHEET

Prepreg epoxy system
IMP 505

Description

IMP 505 is from 120°C to 150°C curing toughened epoxy matrix with good strength retention at elevated temperature, good processability, excellent surface finish and good impact resistance suitable for use in performance car and sporting leisure applications.

Benefit and Features

- toughened epoxy
- good impact resistance
- good strength retention
- long shelf life and out life at room temperature
- autoclave, vacuum and press mould processing
- good tack and drape characteristics
- versatile cure temperature (from 120 °C at 150 °C)
- very good Tg °C

Resin Matrix Properties

Colour		Transparent
Density	(gr/cm3)	1,18
Gel Time at 130 °C	minutes	120
Tg (DS C) °C	°C	110 - 170
Flexural Strength (ISO 178)	MPa	148 - 170
Modulus (ISO 178)	MPa	3500 - 4000
Tensile Strength (ISO 527)	MPa	680 - 780
Water Absorption (ISO 62-60 min 100°C)	%	2.0 - 3.0
Modulus (ISO 527)	%	0.52 - 0.58
Elongation (ISO 527)	MPa	3500 - 4000

Prepreg storage Life

These prepregs should be stored as received in a cool dry place or in a refrigerator. At room temperature, storage life is:

- 12 Months at –18 C°
- 4-6 Weeks at room temperature (23 C°)

After removal from refrigerator storage, prepreg should be allowed to reach room temperature before opening the polythene bag, thus preventing condensation.

Precautions for use

G.Angeloni s.r.l. recommends that customers observe established precautions for handling resin and the fine fibrous materials. Operators working with this product should wear clean, impervious gloves to reduce the possibility of skin contact and to prevent contamination of the material. Safety Data Sheet is available for this product.

APPENDIX B

MATERIAL DATA SHEET: ALUMIDE®

Material data sheet

Alumide®

1 General

A typical application for Alumide® is the manufacture of stiff parts of metallic appearance for applications in automotive manufacture (e.g. wind tunnel tests or parts that are not safety-relevant), for tool inserts for injecting and moulding small production runs, for illustrative models (metallic appearance), for education and jig manufacture, among other aspects.

Surfaces of parts made of Alumide® can be finished by grinding, polishing or coating. An additional advantage is that low tool-wear machining is possible, e.g., milling, drilling or turning.

Alumide® is suitable for processing on the following systems:

- EOSINT P 730, P 700
- EOSINT P 390, P 385, P 380i, P 380, with or without powder conveying system
  EOSINT P 360 with upgrade S&P, P 350/2 + upgrade 99 + upgrade S&P
- FORMIGA P 100

2 Technical data

General material properties

Average grain size	ISO 13320-1	60	µm
	Laser diffraction	2.36	mil
Bulk density	EN ISO 61	0.67	g/cm³
Density of laser-sintered part	EOS-method	1.36	g/cm³
		85	lb/ft³

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Internet: www.eos.info

Material data sheet

Mechanical properties

Tensile modulus	EN ISO 527	3800	MPa
	ASTM D638	551	ksi
Tensile strength	EN ISO 527	48	MPa
	ASTM D638	6962	psi
Elongation at break	EN ISO 527	4	%
	ASTM D638	4	%
Flexural modulus	EN ISO 178	3600	MPa
	ASTM D790	522	ksi
Flexural strength	EN ISO 178	72	MPa
	ASTM D790	10443	psi
Charpy - Impact strength	EN ISO 179	29	kJ/m^2
Charpy - Notched impact strength	EN ISO 179	4.6	kJ/m^2
Shore D - hardness	ISO 868	76	-
	ASTM D2240	76	-

Thermal properties

Melting point	EN ISO 11357-1	172 – 180	°C
Heat deflection temperatur	ASTM D648 (0.45 MPa)	351	°F
Vicat softening temperature B/50	EN ISO 306	169	°C
	ASTM D1525	336	°F
Heat conductivity (170 ° C)	Hot wire method	0.5 – 0.8	W(mK)-1

Electrical properties

Surface resistance [10 V]	IEC 93	3 x 1012	Ω
	ASTM D257-93	3 x 1012	Ω
Specific surface resistance	IEC 93	5 x 1014	Ω
	ASTM D257-93	5 x 1014	Ω
Volume resistance [10 V]	IEC 93	6 x 1012	Ω
	ASTM D257-93	6 x 1012	Ω
Specific volume resistance	IEC 93	3 x 1014	Ω . cm
	ASTM D257-93	3 x 1014	Ω . cm
Dielectric breakdown strength	EN 60243-1	0.1	kV/mm
Dielectric constant (1 kHz)	DIN 53483	13 ± 1.5 (100 Hz)	-
		10 ± 0.5 (1 MHz)	-
Dielectric loss factor (1 kHz)	DIN 53483	0.018 ± 0.002	-

Due the aluminium particle content, it was not possible to produce a breakdown on the test specimens in the conventional meaning (e.g. ceramic). Breakdown was due to the formation of leakage paths at voltages < 200 V~.

The resistance measurements were made on laser-sintered test specimens on which the surface had only been treated by blasting with glass beads and was thus relatively rough. Different values can thus be expected with ground or polished surfaces.

The electrical properties are heavily dependent on temperature and moisture content. The values listed characterise the sample part with the following conditioning: storage at 23°C and 50% relative humidity up to saturation. The information given above relates to the characterisation of the electrical behaviour of the material (test bodies) and not to that of a finished part.

The mechanical properties depend on the x-, y-, z-position of the test parts and on the exposure parameters used.

APPENDIX C

MATERIAL DATA SHEET: POLYAMIDE PA2200

Material data sheet

PA 2200

1 General

Typical applications of the material are fully functional parts with high end finish right from the process, which easily withstand high mechanical and thermal load.

PA 2200 is suitable for processing on the following systems:

- EOSINT P 730, P 700
- EOSINT P 390, P 385, P 380i, P 380, with or without powder conveying system
  EOSINT P 360 with upgrade S&P, P 350/2 with upgrade 99 and upgrade S&P
- FORMIGA P 100

2 Technical data

General material properties

Average grain size	ISO 13320-11	56	µm
	Laser diffraction	2.20	mil
Bulk density	EN ISO 60	0.45	g/cm³
Density of laser-sintered part	EOS method	0.93	g/cm³
		58	lb/ft³

Mechanical properties

Tensile modulus	EN ISO 527	1700	MPa
	ASTM D638	247	ksi
Tensile strength	EN ISO 527	48	MPa
	ASTM D638	6962	psi

Elongation at break	EN ISO 527	24	%
Elongation at break	ASTM D638	24	%
Flexural modulus	EN ISO 178	1500	MPa
	ASTM D790	217	ksi
Flexural strength	EN ISO 178	58	MPa
	ASTM D790	8412	psi
Charpy - Impact strength	EN ISO 179	53	kJ/m^2
Charpy - Notched impact strength	EN ISO 179	4.8	kJ/m^2
Izod – Impact strength	EN ISO 180	32.8	kJ/m^2
Izod – Notched impact strength	EN ISO 180	4.4	kJ/m^2
Ball indentation hardness	EN ISO 2039	78	N/mm^2
Shore D - hardness	ISO 868	75	-
	ASTM D2240	75	-

The mechanical properties depend on the x-, y-, z-position and on the exposure parameters used.

Thermal properties

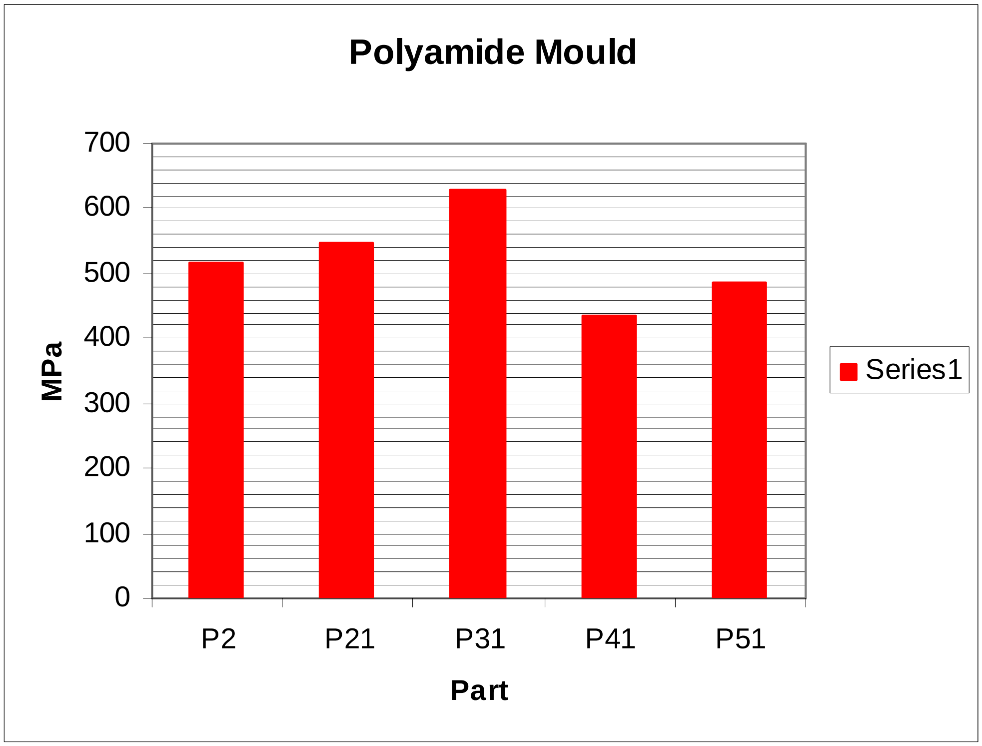
Melting point	EN ISO 11357-1	172 - 180	°C
Vicat softening temperature B/50	EN ISO 306	163	°C
	ASTM D1525	325	°F
Vicat softening temperature A/50	EN ISO 306	181	°C
	ASTM D1525	358	°F

The data are based on our latest knowledge and are subject to changes without notice. They do not guarantee properties for a particular part and in a particular application.

APPENDIX D

TENSILE STRENGTH TEST RESULTS

Tensile strength test results for the PA2200 polyamide parts.



Tensile strength test results for the PA2200 polyamide parts.