BRIDGE TOOLING THROUGH LAYERED SINTERING OF POWDER

GERRIE JACOBUS BOOYSEN

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Supervisor: Prof. DJ de Beer (D Tech. Mech. Eng)

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DECLARATION

I, GERRIE JACOBUS BOOYSEN, 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.

GJ BOOYSEN | Date

Student

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Above all, I humbly thank GOD for all His blessings and His amazing grace.

UITTREKSEL

Tegnieke wat die vervaardiging van matryse kan versnel, sal die produkontwikkelingsgemeenskap positief beïnvloed. Snelgereedskapvervaardigingskonsepte (SV), is binne die konteks van betrokke produkontwikkelingsprosesse en –teorieë geanaliseer. Konvensionele matrysvervaardigingsmetodes soos epoksie-plastiekmatryse en gemasjineerde inspuitgietvormmatryse was as vertrekpunt vir die navorsing, wat op laser sintering van poeier-materiale gefokus het, gebruik. Die nuwe generasie SV-materiale wat by die Sentrale Universiteit vir Tegnologie, Vrystaat beskikbaar is, is 'n aansienlike verbetering op die ou materiale. SV-materiale word deurentyd ontwikkel en die projek-doelwitte was om op hoogte van die nuutste ontwikkelings te bly. Die verhandeling gee 'n volledige oorsig van alle verwante tegnologieë, asook 'n in-diepte bespreking van die Selektiewe Laser Sintering (SLS) en Laser Sintering (LS) prosesse. Beperkinge op matrysgroottes, algemene matrysontwerpaspekte, polering en afwerkingstegnieke is in berekening gebring. Data is versamel om matryse wat met Snelprototipering-masjiene vervaardig is, met dié wat met konvensionele metodes vervaardig is, te vergelyk. Aspekte soos matrysleeftyd, kwaliteit, produksietyd en -koste is as parameters gebruik om verskille te bepaal en aanbevelings te maak. Analise van eksperimente en gevallestudies waar gesinterde materiale gebruik is, het bewys dat dié tegnieke lewensvatbaar vir die produksie van oorbruggings- of finale matryse is. Aanbevelings vir toekomstige gebruik t.o.v. insetgrootte en -geometrie, akkuraatheid, duursaamheid en krimpingsfaktore, om lewensvatbaarheid daarvan in SA te verseker, is gemaak.

SYNOPSIS

Faster mould production methods will undeniably impact positively on the product development community. Rapid Tooling (RT) concepts, in context with the product development process and related product development theories, were analysed. Conventional tooling techniques used such as epoxy plastic tooling and machined injection moulding techniques were used as point of departure for the research work, which focused on Laser Sintering of powder materials. The new generation RT materials that are available at the Central University of Technology, Free State, are a vast improvement on the old materials. RT materials are constantly being developed and the project aims were to stay abreast with the latest developments. The thesis gives a complete overview of all related technologies, and also an in-depth discussion of both the Selective Laser Sintering (SLS) and Laser Sintering (LS) processes. Mould size limitations, as well as general tooling design issues, polishing and finishing techniques were all taken into account. Data has been collected to compare mould inserts grown with RP machines with that of conventionally machined tools. Aspects such as tool life, part quality, lead times and cost were used as parameters to determine the differences and make recommendations. Through analysis of several experiments and industrial case studies, RT through sintered materials was proven as a capable technology, giving the option of an intermediate (bridge tooling) or even a final step of tooling. Recommendations for future use were made in terms of insert size and geometry, accuracy, durability and shrinkages, to ensure the feasibility of the RT process in SA.

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GLOSSARY

2D	Two Dimensional – Length (y), Width (x)
3D	Three Dimensional – Height (z), Width (x), Length(y)
3D Keltool	Indirect RT Fabrication process by 3D SYSTEMS
3D Printing	Three Dimensional Printing Machine
3D SYSTEMS	American manufacturer of Stereolithography and Selective Laser Sintering Systems
ABS	Acrylonitrile Butadiene Styrene
ACES	Accurate Clear Epoxy Solid
AIM	ACES Injection Mould
Alumide®	Aluminium/Nylon powder for the LS process
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CNC	Computer Numeric Controlled
CO_2 Laser	Carbon Dioxide Laser
CRPM	Centre for Rapid Prototyping and Manufacturing
CUT	Central University of Technology, Free State
Direct AIM™	Direct RT Fabrication process by 3D SYSTEMS
DirectTool™	Direct RT Fabrication process by EOS
DMLS	Direct Metal Laser Sintering
DOW Plastic	Manufacturer of injection moulding material
DTM	American manufacturer of Selective Laser Sintering Systems
EDM	Electric Discharge Machining

EOS RP Tools	EOS software that slices the .STL file into 2D layer data
EOS	Electro Optical Systems - German manufacturer of Laser Sintering Systems
EOSINT P380	Plastic-series Laser Sintering Machine from EOS
FDA	Food and Drug Administration
FDM	Fused Deposition Modeling machine
F-Theta lens	A lens inside the EOSINT P380 machine which is designed in such a way that the laser beam is focused on any area inside the build envelope
HTV	High Temperature Vulcanizing
LaserForm^{TM}A6	Third generation metal powder for the SLS process
LaserForm^{TM} ST100	First generation metal powder for the SLS process
LaserForm^{TM} ST200	Second generation metal powder for the SLS process
LOM	Laminated Object Manufacturing machine
LS	Laser Sintering process by EOS
Magics RP^{TM}	Software by Materialise in Belgium
Mechanical	An exposure parameter for the P380 machine
NM	Nanometre
PP	Polypropylene
PSW software	Control software for the P380 LS machine
RapidTool^{TM}	Direct RT Fabrication process by 3D SYSTEMS
RIM	Reaction Injection Moulding
RM	Rapid Manufacturing

RP	Rapid Prototyping
RT	Rapid Tooling
RTV	Room Temperature Vulcanizing
.STL File	Derived its name from Stereolithography
SA	South Africa
Sinterstation 2000	Selective Laser Sintering Machine from 3D SYSTEMS
SLA	Stereolithography machine
SLS	Selective Laser Sintering process by 3D SYSTEMS
Solid Edge	CAD software
Sorted	An exposure parameter for the P380 machine
STAIR STEPPING	Surface effect of layer based Prototyping Systems
TCT^{TM}	Direct RT Fabrication process by Advanced Technology
Unsorted	An exposure parameter for the P380 machine

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Chapter 1: Introduction to Rapid Tooling

Producing injection moulding tools can be slow and expensive due to the labour intensity required when using conventional tooling methods. The number of skilled toolmakers in South Africa are declining, the time-to-market of products is getting shorter and part complexity is increasing. Various Rapid Prototyping (RP) systems make it possible to make prototype models quickly, but these prototypes are still not produced in the end-use material used during the final production process. Product developers require prototypes in the end material as verification prior to commencing production. Customers also need assistance to convert their concepts or final designs to physical models at a desirable quality/price ratio. Based on the assumption that the decision was right and that the product's market potential can justify the expenses, a crucial decision has to be made to go into the final step of manufacturing the production tooling. It is clear that any process that can provide a faster mould production method as well as cut back on labour time, whilst simultaneously producing models in the end-use material, will be beneficial. The concept of Rapid Tooling (RT) offers a viable solution, giving the option of an intermediate (bridge tooling) or even a final step of tooling. To fully understand the benefit that RT can offer the product development industry, it is necessary to critically analyse the product development cycle.

1.1 PRODUCT DEVELOPMENT CYCLE

Figure 1.1 shows the product development cycle from the first idea to the final product with the RT option shown in the dashed box.

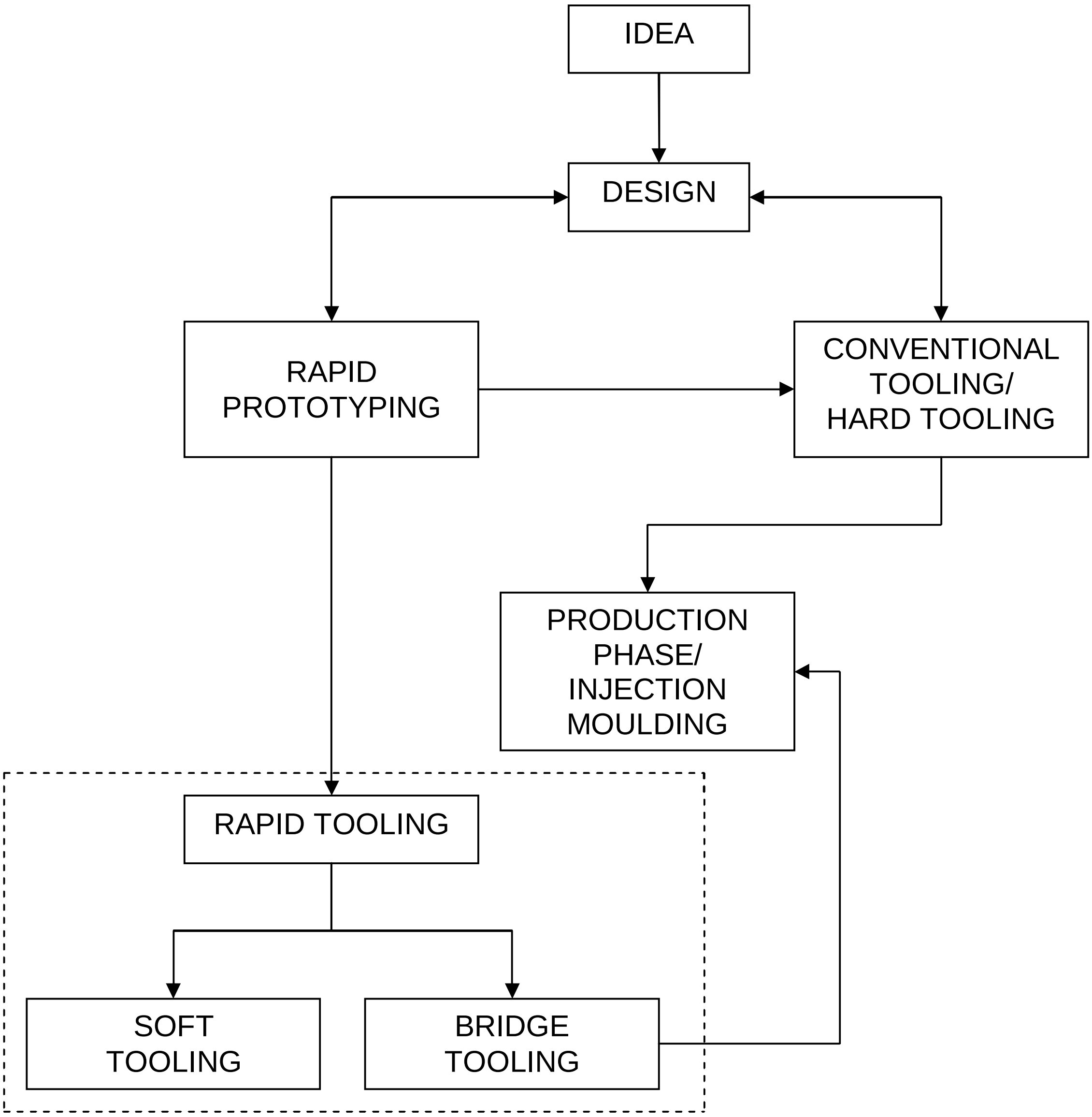


Figure 1.1 Product Development Cycle

1.1.1 Design

Any new product starts with an idea. After the concept is formulated, a three dimensional (3D) design is necessary. This is referred to as Computer Aided Design (CAD). The CAD model is essential in both the RP and the conventional tooling phase, because both technologies need the 3D design to build the product.

1.1.2 Conventional Tooling

With conventional tooling it is possible to go directly to the production phase, but the risk associated with this method is that the designers can only view their ideas as products after the first production trials. Should there be any problems in the design, it is both a costly and lengthy process to correct the mistakes by going back to the design phase and starting the whole process over again.

1.1.3 Rapid Prototyping

RP is not generally used for final (production quantity) products. Firstly, prototypes are grown from the design. The design can be finalized by quickly and easily correcting mistakes. A formal definition of RP is the physical modelling of a design using a special class of machine technology [22]. RP systems quickly produce models and prototype parts from 3D CAD model data. Using an additive approach to building shapes, RP systems join liquid, powder or sheet materials to form physical objects. Layer-by-layer, current RP machines fabricate plastic, wood-like, ceramic, and metal parts using thin, horizontal cross sections of the computer model [22 p 10]. When satisfied with the final prototype, there are two alternatives to choose from, to obtain the same end result, i.e. RT or conventional tooling. The factors that influence the choice are time-to-market, production volumes and cost. When the RP route is taken to conventional tooling, the risk that the design will not be 100% correct and all the components will not fit together, is minimized, because a physical model is available for inspection. At present, RP is saving toolmakers a significant amount of money in repair or iteration/change costs on injection moulding tools.

1.1.4 Rapid Tooling

Although various RP systems make it possible to make prototype models very quickly, these prototypes are still not produced in the end-use material used during the final production process. Product developers often require prototypes in the end material as verification prior to commencing production. The major advantage of RT is that it delivers the parts in the end material. RT is the process of employing the geometry of one object, namely the tool (which may be a mould, die, pattern, mandrel or electrode) to determine that of another - the manufactured part. RT can be divided into two groups, namely soft tooling and bridge tooling:

a) The term soft tooling refers to tooling for a short production run. The materials used to manufacture these tools include silicone rubber, epoxy resins, low melting point alloys, and aluminium. These materials are less costly and easier to work with than the different grades of steels used for hard tooling. When using soft tooling it is sometimes difficult to produce the prototype parts in the required production material, because the tool material does not allow for high pressure/temperature inside the mould.

b) “Soft tooling” generally refers to tooling made for limited production runs (less than 100 prototype parts) made in engineering plastics by injection moulding. On the other hand, it may be difficult to justify the cost of conventional tooling for limited run production of hundred to a few thousand parts. To fill the gap between soft and conventional tooling a concept known as bridge tooling has been developed. As shown in Figure 1.1 this tooling can then be used to move to the production phase for producing several hundred injection moulded parts. The focus of the research project will fall on bridge tooling.

1.1.5 Benefits of Rapid Tooling

Customers need assistance to convert their concepts or final designs to physical models at an acceptable quality/price ratio. Next, a crucial decision has to be taken whether to go into the final step of production tooling, based on the assumption that the decision was right and that the product can justify the expenses. In many cases, this is no longer necessary as RT has developed into a capable technology giving the option of an intermediate (bridge tooling) or even a final step of tooling. In South Africa (SA), typical tool lead times are between 8 – 12 weeks for non-intricate parts. For complex parts, the tool lead times may be much longer. This results in a lengthy and expensive exercise in product development. Shorter lead times can increase the rate of success of new products. By means of RT the tool can be used as a bridge tool to start production while the final production tool is manufactured, which will contribute to significantly shorter lead times. It must also be borne in mind that the market in SA is much smaller than many other international markets. If the product's lifespan is taken into account, a bridge tool or rapid tool may be the only tool needed for the manufacture of a specific product. Internationally, RT of plastic injection moulds has given many customers shorter delivery times, and reduced costs by up to 50%, with acceptable quality for short and medium run series (100 to 10 000 injections) [14 p 294]. This contributes towards reduced costs in testing the final product, shorter product time-to-market, custom- made products, faster market response and reduced risk in the introduction of the product to market.

1.1.6 The Advantages to be gained from implementing RP and RT Techniques can be divided into three areas:

a) Strategic advantages

- Time and cost savings in prototype production
- Rapid design and development changes can be made
- Reduced time-to-market
- Improved communication within and outside the company
- Increased product improvement, customization and innovation

b) Production advantages

- Integration with CAD/CAM systems
- Rapid production of test prototypes

- Problems identified and rectified before tools are made and production process starts
- Integrated production tools
- Reduction in number of test tools required

c) Decision-making advantages

- Design verification
- Verification of the manufacturing process
- Verification of plans for production
- Verification of tool design and production
- Improved communication with suppliers
- Improved communication with sales and management departments [1 p 10].

1.1.7 RT with Selective Laser Sintering Process

Selective Laser Sintering (SLS) offers a means of fabricating complex 3D parts directly from CAD data. Different materials can be used in the system. LaserForm™, a commercially available SLS material, can be used to quickly fabricate metal composite parts or moulds that have durability and thermal conductive properties similar to aluminum that can be benchmarked using standard techniques [18 p 156]. LaserForm™ (from 3D SYSTEMS), is a process that uses laser sintering and powder metal. Digital models of the core and cavity geometries can be created and transferred to a Sinterstation machine for fabrication in LaserForm™ powder. This material consists of steel particles coated with a polymer/wax binder material. The Sinterstation produces so-called “green” parts that are cured in a furnace. The furnace removes the polymer and infiltrates bronze into the mould inserts through capillary action. This process produces a fully dense tool that consists of steel and bronze. The inserts are then finished, drilled for ejector pins, and fitted to a mould base. Turnaround times are two to three days for parts and prototypes and five to ten days for complex tooling inserts, which is roughly 25%, or less, of the time required by traditional methods. Using a process that saves this much time can reduce the costs significantly [12]. An injection moulding tool that was produced by SLS technology at the University of Louisville’s Rapid Prototype Centre has run more than 160 000 parts in polypropylene with no visible wear [23 p 71].

1.1.8 RT with Alumide® for the EOSINT P-series Sintering Machines

During the EuroMold 2003 (Dec 2003), EOS GmbH released Alumide®, an aluminum-filled nylon material that allows the resulting metallic-looking, non-porous components to be machined easily and to withstand high temperatures. This offers various new possibilities for both direct manufacturing, as well as direct tooling applications. When using Alumide® material in the Laser Sintering (LS) process, typical applications are to manufacture:

- Stiff parts with a metallic appearance for applications in automotive manufacture (e.g. wind tunnel tests or parts that are not safety relevant)

- Tool inserts for injecting and moulding small production runs, illustrative models (metallic appearance)
- Educational and jig manufacture.

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 [5].

In this thesis, the bridge tooling media used for experimentation were LaserForm™ ST100 and LaserForm™ A6 from 3D SYSTEMS, as well as Alumide® from EOS GmbH.

1.2 PROBLEM STATEMENT

The new generation RT materials that are available at the Central University of Technology, Free State, are a vast improvement on the previously available material. However, limited information is available to compare them with the previous generation of materials (which were not available in SA). RT materials are constantly being developed and the project aims were to stay abreast with the latest developments.

Through this research project, data will be collected to compare mould inserts grown with RP machines with conventionally machined tools. Aspects such as tool life, part quality, lead-times and cost will be used as parameters.

The full commercialization of this process in the SA manufacturing industry means that it could be used as a daily tool to solve mould-making problems, and to decrease time-to-market of new products.

1.2.1 Hypothesis

Mould inserts grown directly on RP machines can be used as bridge tooling for injection moulding. The research project will involve factors such as building time, cost effectiveness and lead-times of the mould. Other factors to be considered are compensation for shrinkage in the building, post-cure of the mould and optimization of locally available techniques.

1.3 OBJECTIVE OF THE STUDY

It is essential for manufacturers to be the first in the marketplace with their products. This implies that three aspects are more important to the manufacturing industry than ever before:

- Product development must be shortened (time-to-market)
- Ability to deliver products rapidly in a large number of variants
- Ability to update products regularly

The term ‘RP’ immediately suggests “speedy fabrication of sample parts for demonstration, evaluation or testing.” The main aim of this research thesis is to develop quicker, cost effective injection moulding tools that can address the abovementioned issues.

1.4 METHODOLOGY

The mould inserts will be constructed using the Sinterstation 2000 from DTM (now 3D SYSTEMS) and the EOS P 380 machines. The materials that will be used are LaserForm™ ST 100 Stainless Steel, LaserForm™ A6 Toolsteel and Alumide® (a polyamide and aluminium matrix). The grown inserts will then be compared with conventionally machined inserts to determine the difference in cost, durability, time to manufacture the insert and accuracy.

To implement such a process, the research will consist of the following:

- Mould design:
    - Taking into account where the split line of the mould should be for the part to release as well as the orientation of the part in the mould.
    - Allowance for extra material for finishing/facing
    - Methodology to use bolsters/frames
- Building time: To compare the actual build time and cost of the mould with that of the conventional methods.
- Shrinkage compensation: Compensate for the shrinkage that occurs during the build and post-cure of the mould to ensure accuracy.
- Durability: To compare the number of injections that can be produced using the RT method with that of conventional tooling.

Case studies to be presented in an order that meets these requirements.

1.5 SCHEMATIC OVERVIEW OF THESIS

Figure 1.2 shows a schematic overview of the chapters that will be covered in this research project.

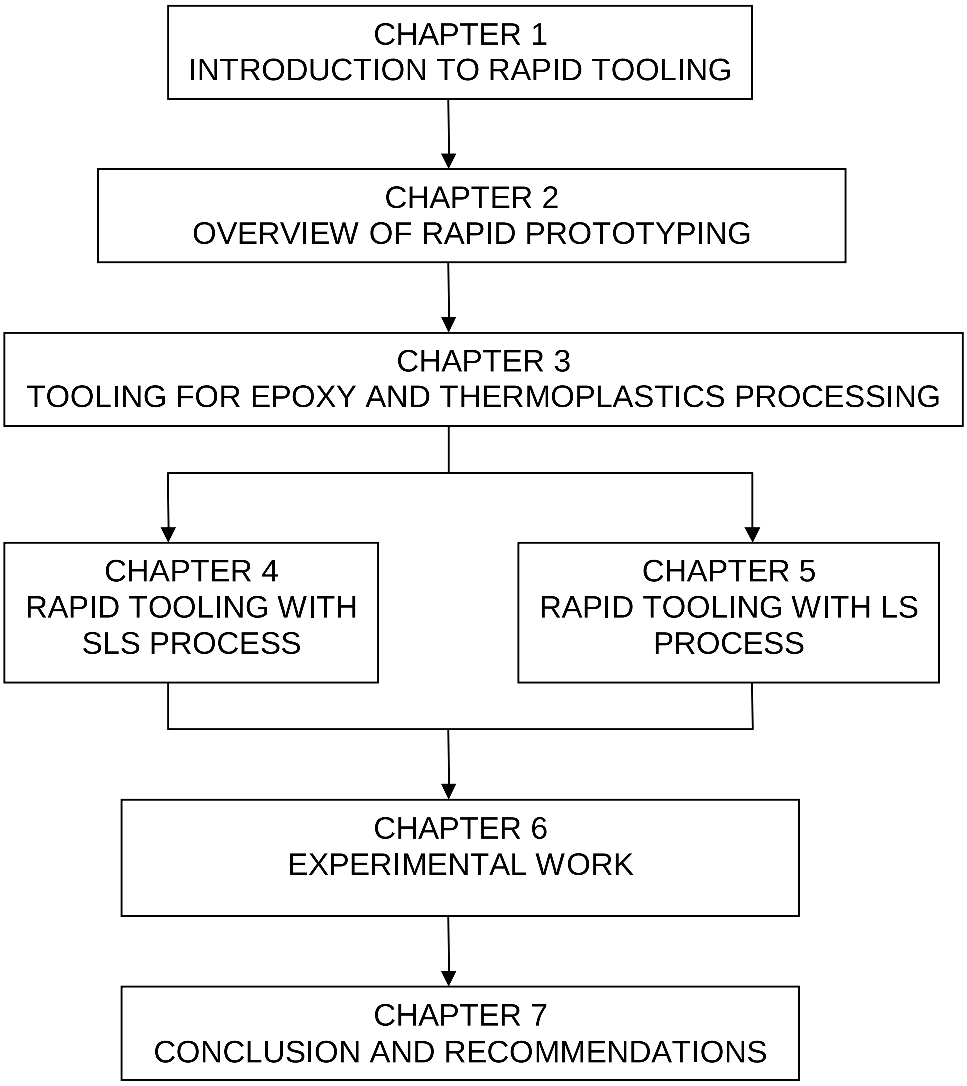


Figure 1.2 Schematic overview of the thesis

Chapter 2: Overview of Rapid Prototyping

2.1 RAPID PROTOTYPING PROCESS

The various steps in the RP product design cycle, from the design of a product to the final prototype model, are shown in Figure 2.1. Each of these steps will be discussed individually.

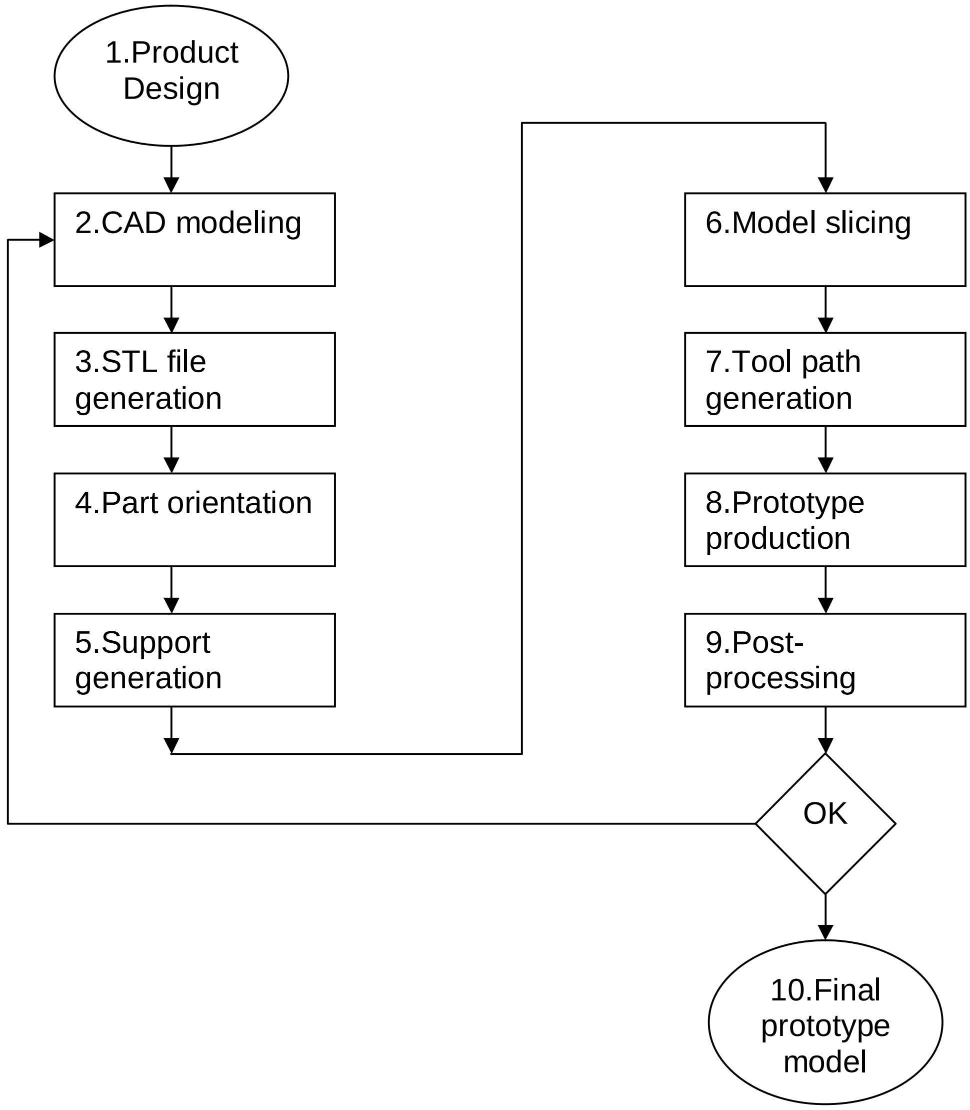


Figure 2.1 Steps in the RP process [21 p137]

After the cycle has been completed and the final prototype is produced, it is possible that some alterations to the product are necessary. In order to make these alterations, one will have to return to step 2 (CAD modelling) and change the design as required. This can be done as many times as is necessary to obtain the desired product.

2.1.1 3D CAD Modelling

RP can produce prototype models of any geometry provided a computer description of the object is available. Most of the current RP systems need an input file in the .STL format to be able to grow the object. A good .STL file is necessary because the RP machine's part output is only as good as the input file; it reproduces the good as well as the bad surfaces of a design. All features inside the design must be unified through a boolean function, which can either be done directly in CAD or by means of the Magics RP^{TM} software, to ensure a watertight design. A solid model can also be constructed by using surface detail and joining these surfaces together to be able to build these parts on a RP system. These surfaces can be obtained by using reverse engineering techniques, but will still need some processing. The following aspects must be considered to transform a CAD surface model into a solid model:

- extend the CAD surfaces
- find intersections between surfaces
- apply chamfering and fillets to surfaces

  [21 p140]

2.1.2 CAD File Transfer: The .STL File

To turn a CAD representation into a physical part, a secondary file (called a .STL file, deriving its name from Stereolithography) needs to be exported from the CAD file and loaded into the RP machine. The .STL format is used by all RP technologies to “read” the CAD data.

This .STL file is used to generate the supports, if necessary, that are required for the part building phase. The file is then sliced up into cross sectional layers and these layers are imported into the RP machine which in turn will build the layers to form the designed part. The .STL files are not exact copies, but approximations, because the surface of the CAD model is generated by ordering a series of triangular facets over the surface, as can be seen from Figures 2.2 and 2.3 [20 p 10]. Figure 2.4 shows the accuracy of the .STL file as a function of the size, the facets and the resulting deviation from the part surface [11 p 58].

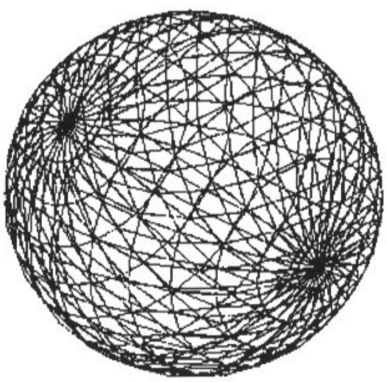


Figure 2.2 Faceted approximation of a sphere

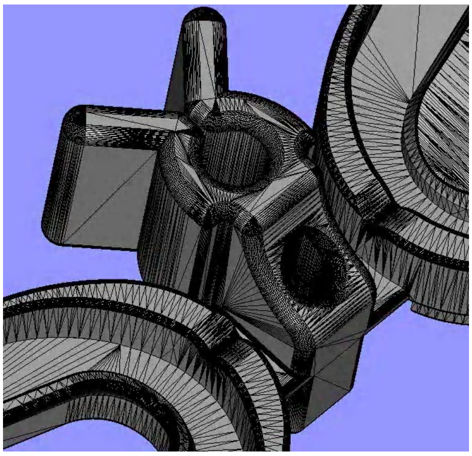


Figure 2.3 Faceted approximation of a part

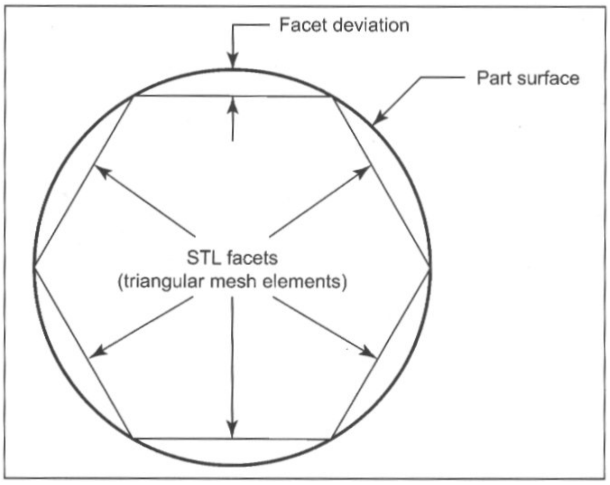


Figure 2.4 The accuracy of the .STL file [11 p 58]

2.1.3 Part Orientation

Part orientation plays a vital role in the surface finish of a part, because of the layer-wise part construction by a RP machine. To achieve the best surface finish, the critical surfaces must be orientated to face the laser/printer head. Producing a fine circular profile necessitates that the orientation of the circular profile has to face the laser/printer head. Should the part be orientated to create the circle by stacking of the layers, a stair-step profile will result, as shown in Figure 2.5.

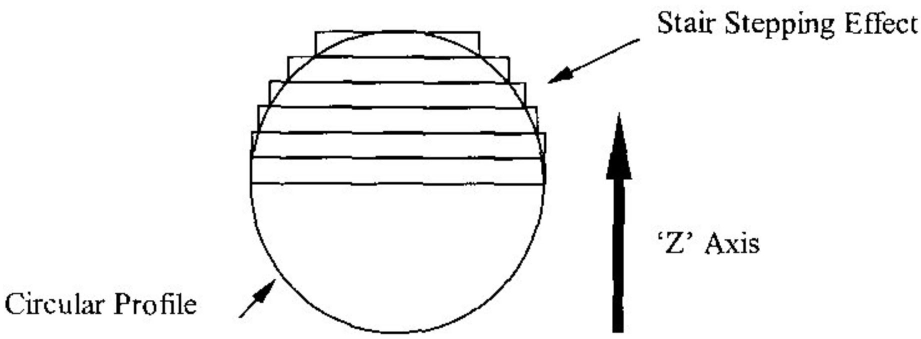


Figure 2.5 An exaggerated example of how stair-stepping affects a circular profile [20 p SM/11]

2.1.4 Support Generation

After the orientation, support structures are generated for the part. Depending on the RP process used, it sometimes happens that there are insufficient automated support generated structures and further support structures are needed on down-facing areas. The support generation is done on the .STL file before slicing the part.

There are several reasons why supports are necessary:

- To support areas that are disconnected from the main body of the part being built, but are joined to the model after subsequent layers have been built, as seen in Figure 2.6.

- Over-hanging or cantilevered areas need to be supported, as seen in Figure 2.7.
- The part needs to be anchored to the platform during the build [21 p158].

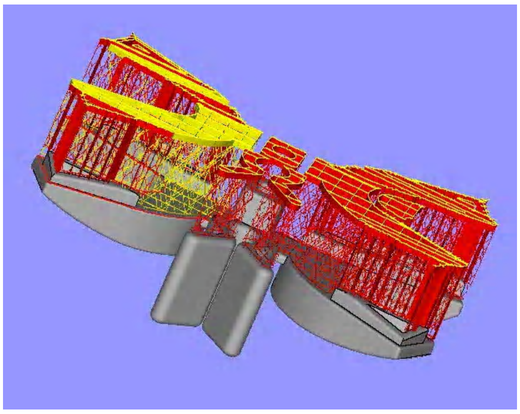


Figure 2.6 Example of support structures on disconnected areas

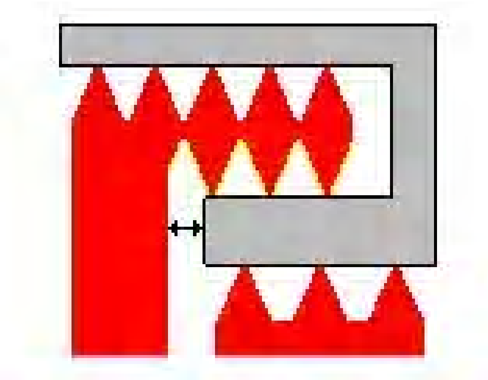


Figure 2.7 Illustration of support structures for overhanging areas [16]

2.1.5 Model Slicing and Tool Path Generation

In contrast to material removal manufacturing technologies like CNC milling, RP technologies are based on layered/additive technologies. The .STL file, with its support structures, must be sliced layer-by-layer. This sliced layer represents surface contours of the cross-section of the designed part at a specific Z height. The cross-section is traced by giving X and Y movement to the laser/printer head. The X, Y movement is known as a tool path and by adding material in the Z axis direction, a 3D part is built. There are many different strategies (contour and fill) that the laser/printer head can follow to improve the surface finish of a part.

2.1.6 Model Production on an RP Machine

The produced tool path is sent to an RP machine to build the prototype model layer-by-layer, including support (if necessary). When using RP, the working surface is always the top of the previous solidified layer. The significance of this is that RP can replicate designs that are unimaginable in any other prototype manufacturing process. This means that by using RP, a sphere can be constructed within another sphere in just one operation, as seen in Figure 2.8. The un-solidified material must be removed from the space between the two spheres to avoid bonding between the spheres.

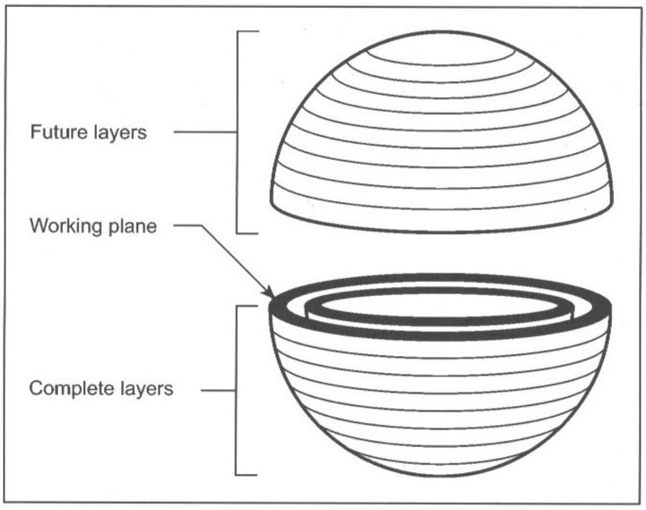


Figure 2.8 Spheres built up layer-by-layer [11 p 29]

2.1.7 Post-Processing

Post-processing is necessary for some of the RP processes, for example:

- post-curing in the case of stereolithography
- infiltration and furnace sintering in the case of certain SLS materials
- removal of the support structures and surface polishing in most of the other RP processes.

2.2 RP TECHNOLOGIES AVAILABLE IN SOUTH AFRICA

The methods of operation of the five main types of RP processes available locally are discussed below:

- **Curing process,** where a photo-sensitive polymer is exposed to a light source in order to harden the polymer, e.g. Stereolithography.
- **Sheet process,** where thin sheets of a material are cut to shape and stacked on top of each other, e.g. Laminated Object Manufacturing (LOM).
- **Dispensing process,** where a material is melted and then deposited either as a hot filament e.g. Fused Deposition Modeling (FDM) or as individual hot droplets such as Inkjets and Three Dimensional Printing (3D Printing) of wax/polymer.
- **Sintering process,** where a powdered material is sintered together using a heat source, typically a laser beam, e.g. SLS and LS.
- **3D Printing process,** where a binder is printed on powder material, e.g. Z-Corp machines.

[20 RP/6]

2.2.1 Selective Laser Sintering (by 3D SYSTEMS)

In the SLS process, a laser is traced over the surface of tightly compacted powder (A), as can be seen from Figure 2.9. A roller (B) is used to spread the powder evenly over the surface of the build cylinder (C). The powder is supplied by the powder delivery piston that rises more than the layer thickness to make sure that there is no short feeding on the build cylinder. The fabrication piston (D) simultaneously moves down one layer thickness to accommodate the layer being constructed [3].

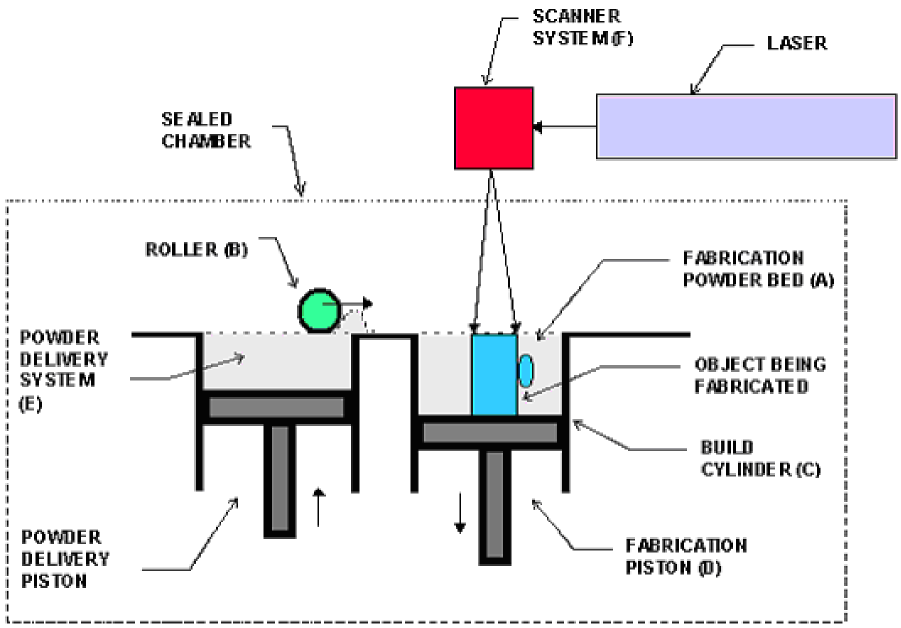


Figure 2.9 Schematic view of a SLS machine by 3D SYSTEMS [3]

Heating elements are used to maintain a constant temperature, just below the melting point of the plastic powder, on the surface of the build cylinder. The heat from the laser, guided by the scanner system (F), needs only to elevate the temperature slightly to cause sintering, which will speed up the process significantly. Throughout this process, a nitrogen atmosphere is also maintained in the fabrication chamber to prevent oxidation in the hot powder.

After completion of the build, the build piston rises to elevate the part out of the machine. This can only happen when the part cake has cooled down below 60˚C, which can take up to two days on larger parts. Excess powder around the parts is brushed away whereafter manual finishing can start. No supports are necessary for this process because overhangs and undercuts are supported by the powder bed. Much progress has been made by sintering machine manufactures over the years in improving surface finish and porosity. This process has also been extended to provide direct fabrication of metal parts and tools [3].

2.2.2 Laser Sintering (by EOS)

The LS process starts with an exposure of the cross-section of the part to be built, as indicated in Figure 2.10. The building platform is lowered by one layer's thickness to give the part a 3D axis. After the building platform is lowered, the dispensing unit dispenses fresh powder in the recoater. The recoater applies a fresh layer of powder over the existing exposure and then the process is repeated [7].

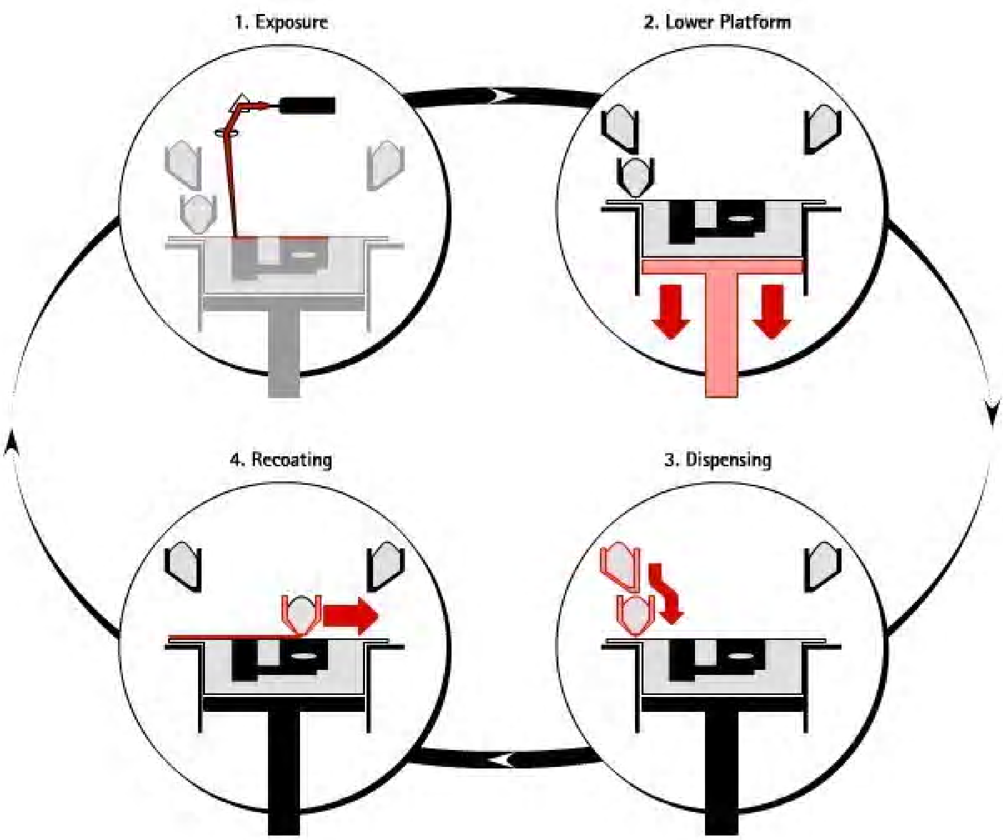


Figure 2.10 Schematic view of a LS machine by EOS [7]

EOS has developed three different technologies to supply three applications namely:

- EOSINT P series - for plastic sintering
- EOSINT S series - for sand sintering
- EOSINT M series – for metal sintering

2.2.3 Conclusion

When choosing an RP technology, one must be aware of the advantages and disadvantages of each of the technologies and what technology will be the most suitable for a specific application.

For example, when making presentations to management or customers, the Stereolithography models will be the models of choice, with their good surface finish, accuracy, and replication of detail. If, however, the model is to be subjected to any degree of handling, the superior strength of the SLS/LS models will be more suitable.

The above-mentioned processes are typically only used to produce a small quantity of parts. Rapid Manufacturing (RM), a new paradigm in RP technology, makes it possible to produce larger quantities of prototypes that can be used for small run productions.

Chapter 3: Tooling for Epoxy and Thermoplastics Processing

3.1 EPOXY PLASTIC TOOLING

3.1.1 Soft Tooling Processes available in SA

Processes that are suitable for batches of one to 20 parts are usually known as ‘soft tooling’ techniques [6 p 197]. The following techniques/technologies are available in SA:

- Silicone Rubber Tooling
- Spin Casting
- Silicone Vacuum Casting
- Castable Resin Moulds
- Sprayed Metal Tooling
- Reaction Injection Moulding (RIM)

a) Silicone Rubber Tooling

Room temperature vulcanizing (RTV) silicone rubber moulds are one of the most popular tooling applications for RP parts. These moulds are used to make polyurethane or epoxy castings either through gravity casting, vacuum casting or RIM. The process starts with a master pattern produced in an RP machine which is hand finished to achieve the desired surface quality. After a predetermined split-line is formed, RTV silicone rubber is poured over the master pattern to form the mould. Casting is done with a two-part thermoset material [22 p 42].

b) Spin Casting

In this process, moulds are made from high temperature vulcanizing (HTV) rubber. The mould is constructed from clay-type rubber discs in which the prototypes are arranged radially in the disc-shaped tool. The tool can produce castings in polyurethane, wax or zinc-based alloys.

The tool is rotated to ensure that the centrifugal force pressurises the cavity, in order to fill cavities during casting. This is an excellent process for casting small products, e.g. corporate gifts, jewellery or belt/shoe buckles that will ultimately be manufactured in large quantities using die-casting [13 p 277].

c) Silicone Vacuum Casting

The silicone vacuum moulding process starts off by using a prototype generated in an RP machine. This prototype is used to create a silicon mould as described in silicon rubber tooling (refer to 3.1.1. a). After curing, the silicon mould is opened and the prototype removed. The mould can produce plastic parts in polyurethane resin under a vacuum. This process can also be used for wax patterns, which can be used to produce investment castings [15 p 118].

d) Castable Resin Moulds

Castable resin moulds are constructed by mounting a master/prototype in a mould box with the parting line marked out in plasticine. The one half of the mould is formed by pouring resin over the master and the process is repeated for the other half. Diverse tooling resins with different filler materials (e.g. aluminium powder/pellets) can be used to achieve dissimilar mechanical and thermal properties.

e) Sprayed Metal Tooling

In this process, molten metal is sprayed onto a master which is constructed of resin, wood, plaster or metal, creating a metal shell. The metal shell is backfilled with an epoxy to form an insert, which can be used for processes such as vacuum forming, injection moulding, compression moulding and blow moulding.

f) Reaction Injection Moulding (RIM)

The RIM process uses a resin injection system with two pressurized chambers. The silicone tool is filled at atmospheric pressure, by inserting an injection nozzle into the mould, whereafter the two pressurized chambers pump the material until the excess resin is driven up through the riser holes. When filled, the silicone tool is placed in a post-curing oven to fully solidify the two-part resin before the cavity is split open and the process repeated [20 RT8].

3.1.2 Shortcomings of the Soft Tooling Processes

- These processes are only suitable for limited run production [18 p 157].
- Despite the wide range of materials that can be used for casting, the choice in soft tooling materials is still limited and is only a simulation of the production material. For mechanical tests and limited run production, it is crucial that prototypes are cast using the same material and manufacturing process as the production part [6 p 197].
- Accuracy is a problem in some soft tooling processes [18 p 157].
- In complex parts (e.g. with undercuts), the durability of the moulds is a problem [18 p 157].
- Soft tooling casting material is expensive.

3.2 INJECTION MOULDING

In order to remain competitive in product development, the focus is often on fabricating injection moulds faster and at lower cost. RT, which meets these requirements, is often used to test the market reaction to a product before committing to a production tool.

RT moulds are used to make thermoplastic parts, as they will be produced in the production mould. The injection moulding process starts with raw material in the form of pellets. The raw material is fed into the hopper and if necessary, can be pre-dried before moving it into the barrel. A mould is then clamped inside the mould opening. A screw is used to move the material from the hopper to the mould. Heaters around the barrel melt the material before it moves through the sprue into the mould. Each polymer has a specific melting point and this set point is fed into the control unit of the injection moulding machine. A cooling cycle takes place after the injection of the material into the cavity, in order to solidify the molten material before the mould can be opened. After ejecting the part, the process is repeated again. Figure 3.1 shows a schematic diagram of an injection moulding process.

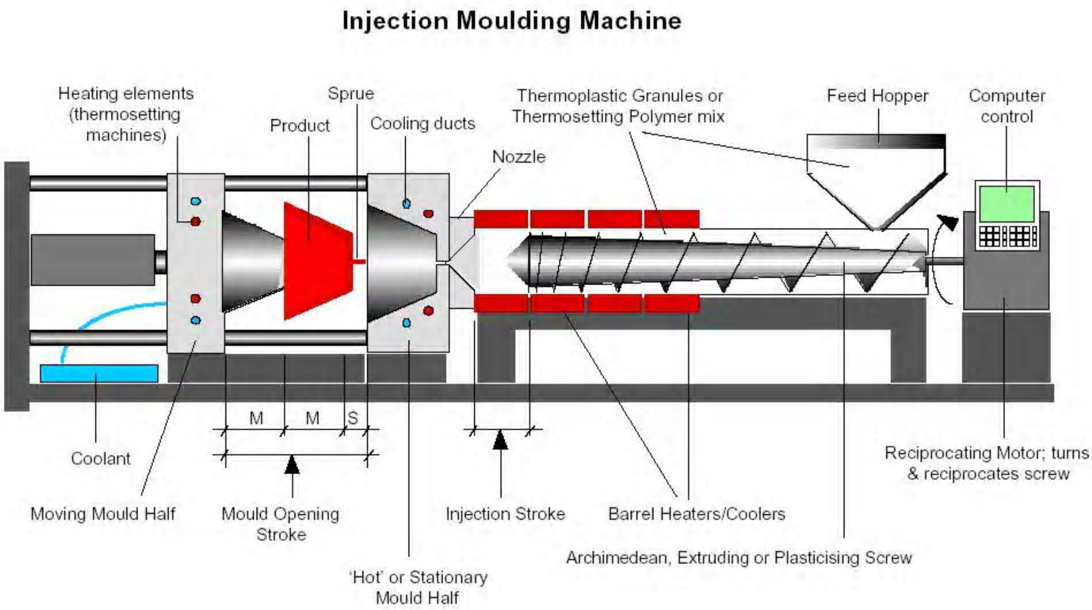


Figure 3.1 Diagram of the injection moulding process/machine [3]

3.2.1 Conventional Tooling

Injection moulds are made by various processes such as EDM (Electric Discharge Machining), CNC milling, wire cutting and combinations thereof. However to construct a mould using these processes can be a time/labour intensive exercise. As shown in Figure 3.2, steel cavities appear to be more expensive than those made in other materials. In spite of this, steel cavities are normally the preferred option, due to the longer service life of the mould.

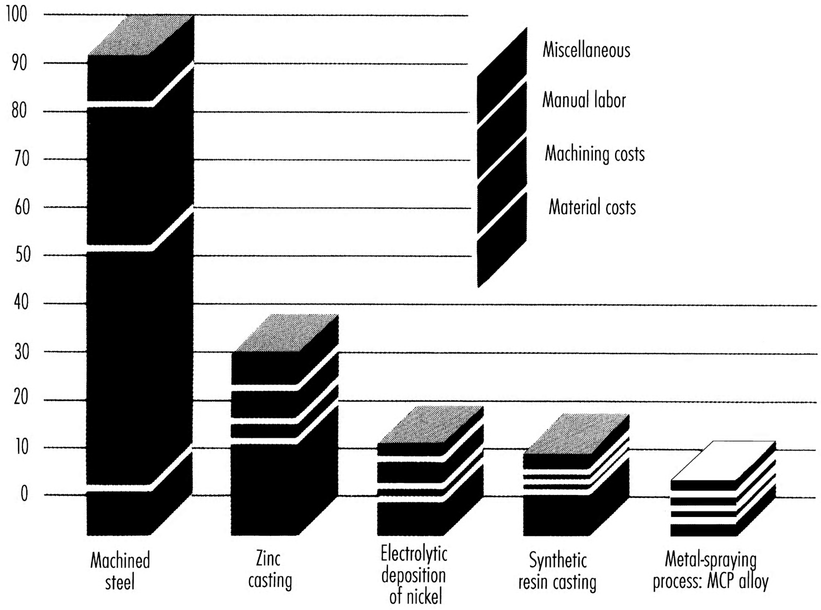


Figure 3.2 Relative costs for cavities made from various materials [17]

It is clear that in order for the tool-making industry to keep up with the shorter time-to-market of new products, only up-to-date equipment, such as CNC controlled wire cutters and five axes CNC controlled milling machines, are used in modern tool rooms. In spite of this equipment, some new products need an even faster turnaround time and conventional tooling cannot live up to this expectation.

3.2.2 Comparison of CNC lead-times to RP

The total lead-time from data receipt to part delivery can be divided into three stages, namely pre-processing, construction time and post-processing. When evaluating RP within these parameters, it is found that most of the process is performed with no supervision which means that RP is not labour intensive. Only pre-processing and post-processing needs human intervention. Therefore, RP systems can produce prototypes for 24 hours of the day, throughout weekends, which gives RP a tremendous advantage, when compared to CNC operations that require staffing as seen from the Table 3.1

Table 3.1 Utilization of machine hours per year for a RP system compared to a CNC system [11 p156]

Theoretically, RP systems could produce prototypes	Realistically, RP systems could produce prototypes	Three axis CNC systems working a three-shift operation
8760 hours a year	7000 hours per year	6025 hours (excluding weekends and holidays)

Table 3.2 shows lead-times of some tooling processes as well as the expected tool life associated with each process.

Table 3.2 Lead-times associated per process [4]

Tooling Route	**Lead-Times**	**Tool Life**
Vacuum Casting	2 days - 2 weeks	2 - 20 off
Thin RIM	2 days - 2 weeks	2 - 50 off
RIM	2 days - 3 weeks	2 - 100 off
Spin Casting	5 days - 2 weeks	2 - 500 off
Cast Ceramic Tools	2 – 5 days	2 - 1000 off
Cast Epoxy Tooling	2 – 5 days	2 - 10 000 off
Spray Metal Zinc	2 – 4 weeks	2 - 200 off
Spray Metal Steel	3 – 6 weeks	2 - 10 000 off
SL Tooling	1 – 2 weeks	2 - 500 off
Laser Sintered Tooling	1 – 3 weeks	2 - 20 off
Cast Zinc Tooling	1 – 2 weeks	2 - 1000 off
Cast Steel Tooling	2 – 4 weeks	2 - 10 000 off
Investment Cast Tooling	2 – 4 weeks	2 - 10 000+ off
Keltool	2 – 4 weeks	2 - 10 000+ off
Electro-formed Tooling	4 – 8 weeks	2 - 10 000+ off

3.2.3 The use of RT for Injection Moulding

Producing injection moulding tools can be slow and expensive and labour intensive when using subtractive CNC or spark eroding methods. The number of skilled toolmakers are declining, the time-to-market of products is getting shorter and part complexity is increasing which means that a larger number of tools have to be created by a declining number of toolmakers. From the abovementioned it is clear that any process that can provide faster mould production as well as cutting back on labour time will be a favourable solution. RT offers a possible solution to cut back tooling production time [3]. RT can also offer an improvement in mould performance due to the incorporation of conformal cooling. The ability to fabricate complex conformal cooling channels so as to provide better thermal performance, may even help to decrease the cycle times, which again lowers the unit cost of the product. RP injection moulding fabrication methods should be considered for projects in which:

- the reduction of time-to-market is important,
- short to medium volume production runs are needed,
- parts may be difficult to machine or need a lot of EDM work because of their geometry [3].

3.2.4 RT's Limitations

The limitations of RT include:

- less accurate moulds are produced when compared to CNC processes,
- RT moulds are less durable than tool steel CNC produced moulds,
- RT moulds may have part size and geometry limitations,
- may not be easy to correct or modify changes to RT produced moulds [3].

Different types of RT technologies are not necessarily restricted to the same limitations in each technology.

3.2.5 Selecting a Process

The selection of a process to manufacture a final RT mould, starting from a CAD file, depends on a number of factors including:

- the application,
- volume of the parts to be produced,
- final material and accuracy requirements,
- part size,
- surface finish or texture needed,
- part detail/complexity, and
- wall thickness [3].

In the manufacturing of a mould, it is sometimes advisable to combine conventional mould making techniques with RT techniques to reach the most economical and appropriate manufacturing solution.

From Figure 3.3 it is clear that at various stages a particular process is most suitable. The figure also indicates when it is cost effective to produce a part in production material and when to produce in simulant material.

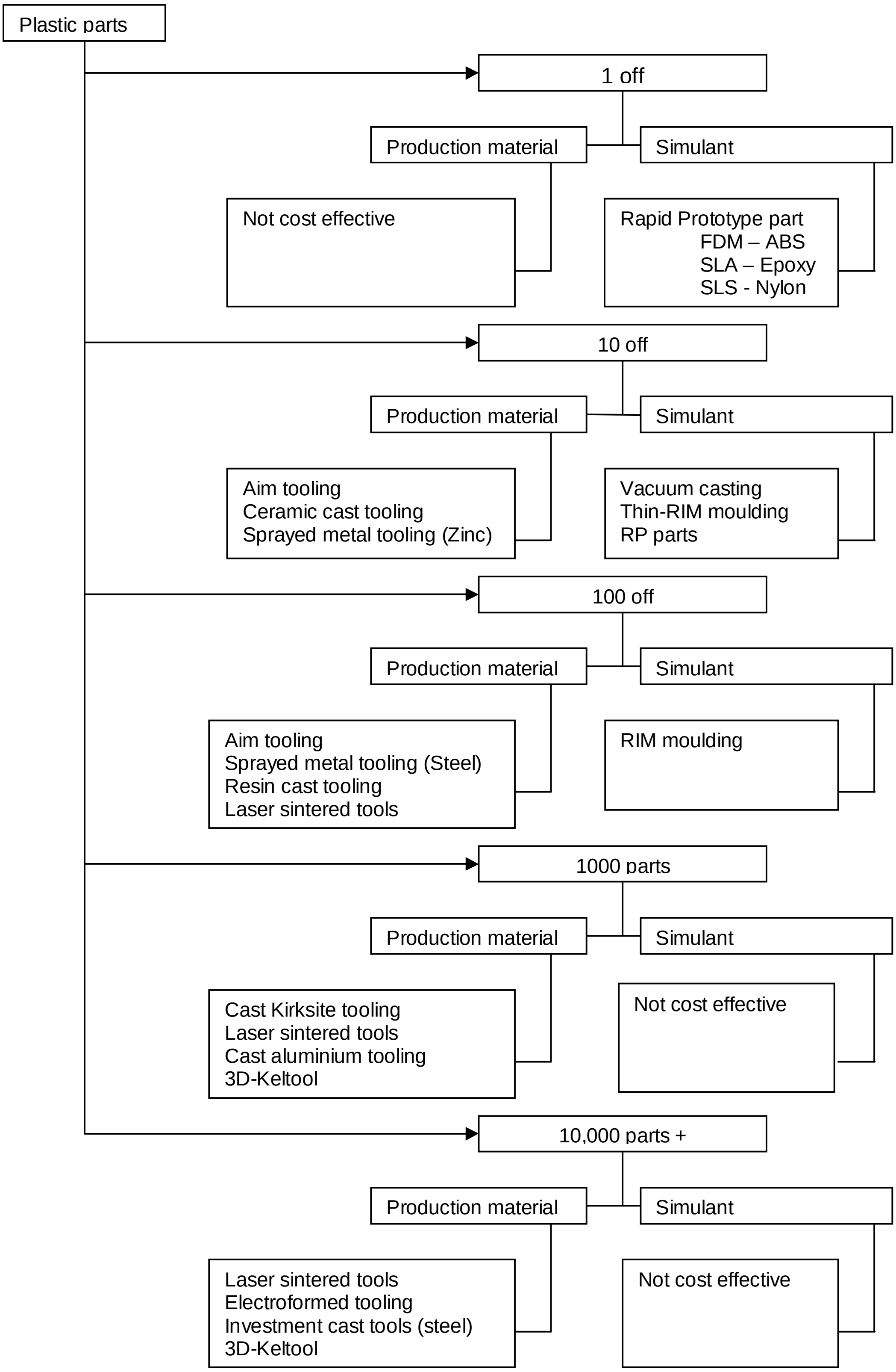


Figure 3.3 Matrix of plastic part production [20 p RT/5]

3.3 RAPID TOOLING

RT can be divided into two categories, namely: i) indirect or secondary processes, where RP prototypes can be used as master patterns for the fabrication of a mould or ii) direct fabrication processes, where the moulds/inserts can be manufactured directly on a RP machine.

3.3.1 Indirect/secondary Process RP Fabrication of Injection Moulds

The indirect/secondary process involves a RP prototype master that is used as a pattern to cast/produce a mould. In the end, the RP part will form the cavity, using processes like investment casting, epoxy casting as well as sand casting to manufacture the mould.

a) Aluminium and Zinc Kirksite Tooling

In order to produce higher production volumes and more aggressive polymers using injection moulding, it is critical that the tool material is made of a harder material than that used in soft tooling. Molten metals, such as aluminium or zinc based alloys, can be used as tool materials in the casting process.

The process starts off with a pattern/prototype. The pattern must be constructed with a material capable of withstanding the casting temperatures of aluminium and zinc, which is approximately 450˚C. Silicone is cast around the prototype to produce a cavity whereafter ceramic is cast into the silicon cavity to reproduce the prototype geometry in a harder material. The dried ceramic model is placed inside a moulding frame, whereafter the molten aluminium/zinc is cast over the model. One half of the mould is produced first and then the process is repeated for the other half. This process is more suited for parts with less complexity, because the ceramic model can easily be damaged during the casting process [20 p RT/12].

b) Investment Cast Tooling

The process starts by using a RP generated model of the mould to be constructed, as a sacrificial pattern. The pattern is dipped into ceramic slurry to produce a ceramic shell and the dipping process is repeated to achieve the desired wall thickness of the ceramic shell. The ceramic shell is transported into an oven where the pattern is melted out, leaving only the investment casting shell. After drying, the ceramic shell is heated to prevent cracking during the casting process, when the molten tool material alloy is poured into the gating system of the shell. The shell is split open after the solidification/cooling process to remove the metal mould [15 p 117].

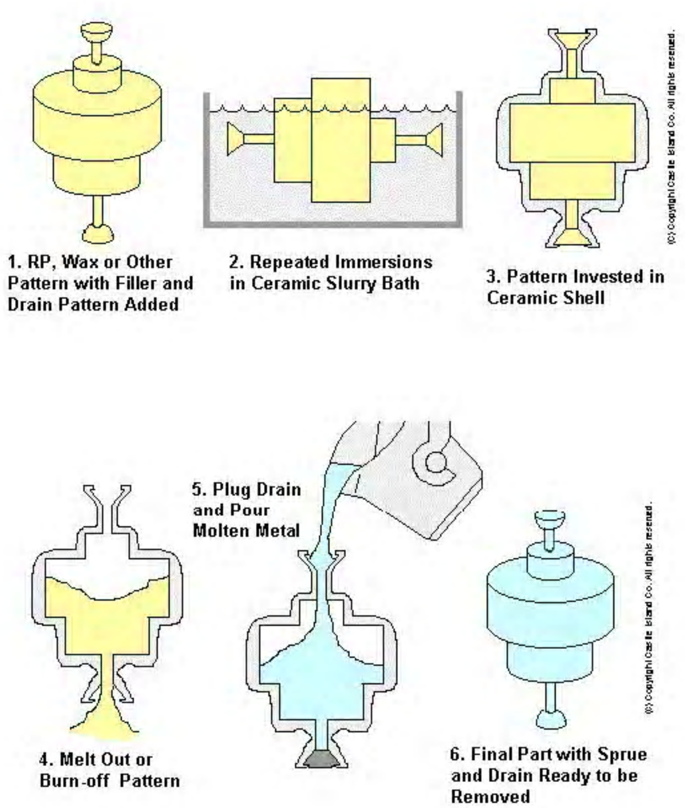


Figure 3.4 Schematic representation of the Investment Casting Process [3]

Investment casting tools can be used for both injection mould cavities and die casting tools. However, it is important to note that it is difficult to maintain high accuracy due to the unpredictable shrinkage of the casting process.

c) 3D Keltool

The 3D Keltool process starts with a Stereolithography model of the final part, which is hand finished to the desired surface quality by sanding and polishing. Silicone rubber is poured over the model, which is placed into a moulding frame, to make an interim silicone mould. The interim silicone mould is once again placed in a moulding frame and the silicone is poured over the interim mould. This process is necessary to obtain a copy of the Stereolithography model in silicone rubber.

A mixture of metal particles, e.g. tool steel and a binder material, is poured over the silicone rubber model. After curing the metal particles and binder, the silicone model is removed and the metal mould is transported into an oven to fuse the particles together and melt out the binder material. Finally, the fused part is infiltrated with copper to produce a fully dense tool [1 p 68].

d) Electro-formed Tooling

Electro-formed tooling is a process that forms a tool by electroplating onto an RP pattern. In order to electroplate onto the RP model, a conductive surface is required. The conductive surface is achieved by applying silver paint or gold sputtering to the surface. The part with the conductive surface can be electroplated by the deposition of copper or nickel ions. This process is continued until the desired wall thickness of the tool surface is reached. The tool surface is backfilled by an epoxy resin to strengthen the tool face. The same process is necessary to produce the other half of the cavity. The main disadvantage of electro-formed tooling is the long lead times needed to produce the tooling surfaces, which can take days for a thin skin coating and weeks for a 5 mm thick tool surface. However, the process is suitable for building large tools where lead times are not a factor [20 p RT/13].

e) Epoxy Tooling

Epoxy tooling starts with a RP model as a master, which is hand finished to the desired surface finish. A casting box is placed around the prototype whereafter an aluminium-filled epoxy is cast over one half of the prototype. The process is repeated for the manufacture of the other half of the cavity.

f) Laser-Sintered Sand Casting Moulds and Cores

By using LS and specially designed sand, a sand casting tool can be produced without creating core boxes or patterns. This is done by scanning a laser beam over the resin coated sand, sintering the binder inside the sand to build up the tool layer-by-layer. Molten material is then cast into the sand casting tool whereafter the sand tool is broken to remove the cast part. Extra material allowance, which could be machined or ground to ensure a flat surface (stock), can be placed on critical areas like shut-off surfaces [15 p 118].

3.3.2 Direct RP Fabrication of Injection Moulds

Direct fabrication describes a process where RT moulds can be manufactured directly by using a RP process. When these tools come out of the machine, they can be post-cured if necessary, and then the surface finish can be enhanced. SLS and Stereolithography are some of the processes used for this type of manufacturing.

a) Direct AIM™

A process called Direct AIM™ was developed by 3D Systems. A mould is created directly by Stereolithography, using a special build style, namely AIM. (AIM is the acronym for ACES Injection Mould and ACES is the acronym for Accurate Clear Epoxy Solid.)

Direct AIM™ produced moulds are used for the injection moulding of less complex parts for small prototype quantities. The Direct AIM™ fabricated moulds need some hand finishing to remove the stair step effect so as to improve the surface finish.

It is often necessary to backfill the grown insert with an epoxy to strengthen it for the injection moulding process.

The following must be considered when using the Direct AIM^{TM} produced inserts for injection moulding [3]:

- longer cycle times are necessary due to the lower thermal conductivity of the material;
- inserts must be placed inside a steel bolster and lower clamping forces must be applied due to the more fragile nature of the insert; and
- this process is not recommended to produce glass-filled plastic parts because of the abrasiveness of the material.

b) Laminated Tooling

Laminated tooling is produced by stacking layers of metal sheets, which replicates the designed model's geometry. These layers are produced by cutting the metal with 2-axis CNC milling, laser cutting or water jet cutting. The design of the model is sliced to the same layer thickness as the sheet metal being used. The cut slices are stacked and then bonded by clamping or fusion bonding to produce a cavity. Laminated tooling can be used for a variety of moulding techniques including blow moulding, injection moulding and vacuum forming in addition to metal pressure die casting and press tools [20 p RT/11].

c) RapidTool™

Polymer coated steel powder is used in the RapidTool™ SLS based process from 3D Systems, also formerly from DTM Corp. This process involves building parts from the sliced CAD data in a polymer coated steel powder. The laser inside the machine “glues” all the steel particles of the sliced cross-section together. The resulting “green” part is fully formed, but still needs oven processing before the part is completed. During the oven cycle, the metal part is debinded, infiltrated with bronze, sintered and heat annealed which produces a fully-dense mould [1 p 65].

d) DirectTool™

Electro Optical Systems (EOS) developed the DirectTool™ process, which produces parts with a layer thickness of up to 20 micron (0.0008 inches) directly inside the machine without secondary sintering or burnout cycles in a furnace. EOS has done research to limit the amount of secondary finishing required, enabling their customers to use moulds for production after a quick shot peening of the grown mould [3].

The benefits of using the DirectTool™ process are:

- small, complex parts that would be difficult to machine; and
- conformal cooling channels which can be incorporated into the mould [3].

e) RT with Alumide® for the EOSINT P-series Sintering Machines

During the EuroMold 2003 (Dec 2003), EOS GmbH released Alumide®, an aluminum-filled nylon material that allows the resulting metallic-looking, non-porous components to be machined easily and to withstand high temperatures. This offers various new possibilities for both direct manufacturing, as well as direct tooling applications.

The basic principle of the EOSINT P-series machine is the layer-wise solidification of thermoplastics by means of a CO_2 laser. The powder is preheated by four infrared heaters to approximately 10°C below its melting point to keep the amount of energy contributed by the laser as low as possible. The energy supplied by the laser is absorbed by the powder and leads to a local solidification of the material. The RT produced Alumide® insert is taken out of the machine and no secondary sintering or burnout cycles in a furnace are necessary. The parts, however, need some hand finishing to remove the stair step effect [8].

A typical application for Alumide® is to manufacture stiff parts with a metallic appearance for applications in automotive manufacture (e.g. wind tunnel tests or parts that are not safety relevant), tool inserts for injecting and moulding small production runs, illustrative models (metallic appearance), educational and jig manufacture. 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 [5].

3.3.3 Process Selection for the Research Project

A need arose in South African industry for a process that could deliver accurate parts in the final production material in quantities of 100 to 5000 parts in a timeframe of one to two weeks. The production of parts in the final material and in quantities of up to 5000 parts, will exclude processes like RP, Soft Tooling and some indirect RT techniques. In turn, to produce accurate parts will further exclude the other indirect RT techniques that are used in the casting process. To produce an insert in one week will exclude the conventional tooling processes.

This leaves SA industry with the following options:

- SLS – Chapter 4
- LS – Chapter 5

Table 3.3 shows the abovementioned processes, which are available in SA, as well as other processes which are available abroad.

Table 3.3a Commercially available direct tooling and manufacturing processes [3]

Process > >	**Space Puzzle Moulding™**	**TCT™**	**Direct AIM™**	**Copper Polyamide SLS**	**Direct Metal Laser Sintering (DMLS) (Bronze alloy)**	**CNC Aluminium Tooling**	**RapidTool™** SLS (Steel)	**DirectTool™** (Steel)
Suppliers	Protoform	Advanced Technology	3D Systems and SB's	3D Systems and SB's (formerly DTM's Products)	3D Systems and SB's (formerly DTM's Products)	EOS GmbH and SB's	3D Systems and SB's (formerly DTM's Products)	EOS GmbH and SB's
Lead Time	2 to 4 weeks	5 to 10 days	1 week	1 to 5 days	1 to 5 days	1 to 4 weeks	3 to 4 days for inserts with no finishing, 5 to 10 days if finish required, 2 to 5 weeks might be typical range	1 to 2 weeks
Applicable Quantities	Up to 1000	2 million parts guaranteed by company	10 to 50	1 to 500 (D)	1 to 500 (D)	100's to 1000	100's of Zn, Al, Mg die cast parts, 100,000's most plastics	100's die cast parts; 100,000's most plastics
Relative Cost	$2K to $10K; up to 50% of conventional mould cost		$2K to $5K				$4K to $10K	
Materials	Thermoplastic	Thermoplastic	Low temp, unfilled thermoplastics	Thermoplastic	Thermoplastic	Thermoplastic	Thermoplastic, metals	Thermoplastics, metals

Table 3.3b Commercially available direct tooling and manufacturing processes [3]

Process > >	**Space Puzzle Moulding**™	**TCT**™	**Direct AIM**™	**Copper Polyamide SLS**	**Direct Metal Laser Sintering (DMLS) (Bronze alloy)**	**CNC Aluminium Tooling**	**RapidTool**™ SLS (Steel)	**DirectTool**™ (Steel)
Tolerance (in/in) or as designated	Same as standard injection moulding: 0.001 to 0.002 in with hard Al tools	Same as standard injection moulding	+ - 0.002			+ - 0.002 overall	0.003 in layers; + - 0.003 in/in, 0.005 details ; 0.005 to 0.010 in for most dimensions	+ - 0.001 to 0.002 in/in
Hardness	Depends on material of puzzle segments		n/a	Shore D-2240			Rb 87	Brinell 60 to 80
Mould Parameters	Normal high volume moulding parameters for each plastic; up to or 700 metric ton clamping force; 5 oz. shot max.	Same as standard injection moulding	May require experimentation and experience	Up to 500 deg F	Up to 500 deg F		Typical injection moulding pressures and temperatures	
Surface Finish	Depends on material of puzzle segments	Any textures or polish, except optical.		500 µ in, as processed; 88 µ in after finishing	500 µ in, as processed; 88 µ in after finishing		5 microns or D-3; 1 -3 micro in or A-2 to A-3 after polishing	Rz = 20 microns (shot peened)

Table 3.3c Commercially available direct tooling and manufacturing processes [3]

Process > >	**Space Puzzle Moulding™**	**TCT™**	**Direct AIM™**	**Copper Polyamide SLS**	**Direct Metal Laser Sintering (DMLS) (Bronze alloy)**	**CNC Aluminium Tooling**	**RapidTool™** SLS (Steel)	**DirectTool™** (Steel)
Part Size Limitations	8.5 x 15 x 30.5 inches	Part must fit within 7.5 m^3/ inches		10 x 10 x 6 inches	10 x 10 x 6 inches		8 x 10 x 5 inches	10 x 10 x 7 inches
Strengths	Can use high volume mould parameters; aluminium mould segments can be made by high speed cutting, yielding 50% saving time on complex parts	Rapid turnaround; uses high volume mould parameters; any type of plastic; standard injection moulding tolerances	Direct fabrication of moulds	Close to hard tool cycle time and temperatures; conformal cooling; no burnout cycle	Close to hard tool cycle time and temperatures; conformal cooling; no burnout cycle	Conformal cooling, no burnout cycle	Die casting; can take typical injection mould pressures and temp ; largely unattended operation	No burnout; accuracy. surface finish is improving with new materials
Weaknesses	Manual loading and unloading and reassembly of mould for each shot; limited to about 1000 parts; cost per part higher than conventional process	Part size; cannot do optical finishes; not easy to incorporate conformal cooling or gradient materials	Severe materials and process limitations.	Limited tool life, lower pressures, conformal cooling channels have limitations due to powder removal	Limited tool life, lower pressures, conformal cooling channels have limitations due to powder removal	Limited tool life, lower pressures, conformal cooling channels have limitations due to powder removal	Requires burnout and infiltration cycle; may require finish machining; conformal cooling channels have limitations due to powder removal	May require finish machining; conformal cooling channels have limitations due to powder removal

Chapter 4: Rapid Tooling with the SLS Process

The SLS process (3D Systems' SLS™) utilizes a laser-based system and a variety of powdered materials. The SLS process that uses LaserForm™ A6 steel material is a fourth generation metals product. When comparing A6 to earlier LaserForm™ ST100 and ST200 materials, substantial improvements are noticed. These include mechanical properties, ease of handling, feature definition and overall accuracy. Metallurgical innovations, involving the precise blending of A6 steel powder, a binder system and tungsten carbide, made most of these improvements possible. A greatly refined SLS process control, strict alloying practices and efficient, high quality final oven process led to additional improvements. The LaserForm™ A6 steel material system enables rapid fabrication of production-capable mould inserts, dies and functional steel parts in a few days.

The SLS system produces parts by selectively fusing powder particles together. This forms an object representing the 3D-CAD data used for building the part. Although the resulting "green" metal part is a fully formed part, additional oven processing is still needed before the part is finished. A LaserForm™ sintering oven, where the part is exposed to a heated nitrogen environment, is used to post cure the part. During this oven processing, the metal part is debinded, then infiltrated, sintered and heat annealed. The binder is burnt off between 250^{0}C and 550^{0}C. At approximately 930^{0}C**,** the high quality infiltrant metal alloy begins to melt and infiltrate the porous part. This infiltration is achieved through a capillary wicking mechanism effectively filling every pore to deliver a full density metal part. The LaserForm™ process is illustrated in Figure 4.1

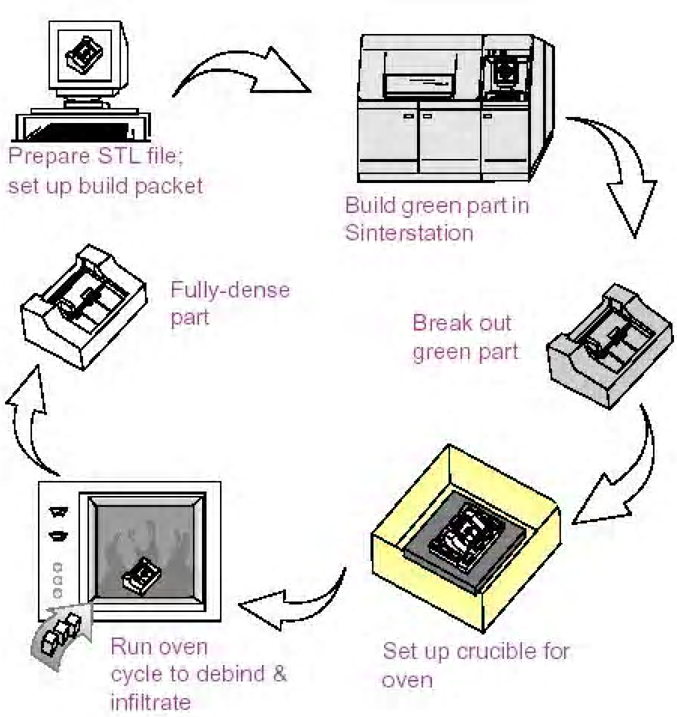


Figure 4.1 The LaserForm™ process [24]

4.1 THE LASERFORM™ PROCESS AS DESCRIBED BY 3D SYSTEMS [24]

The process starts with a CAD file of the part to be grown on the SLS machine. The CAD file is then exported as a .STL file. From practical experience it was found that a surface angle of 10 degrees and a tolerance of 0.01 mm should be used as settings to get a workable .STL file. The .STL file is then taken to the process computer of the machine where it is orientated and placed inside the building envelope of the Sinterstation 2000 machine as can be seen in Figure 4.2.

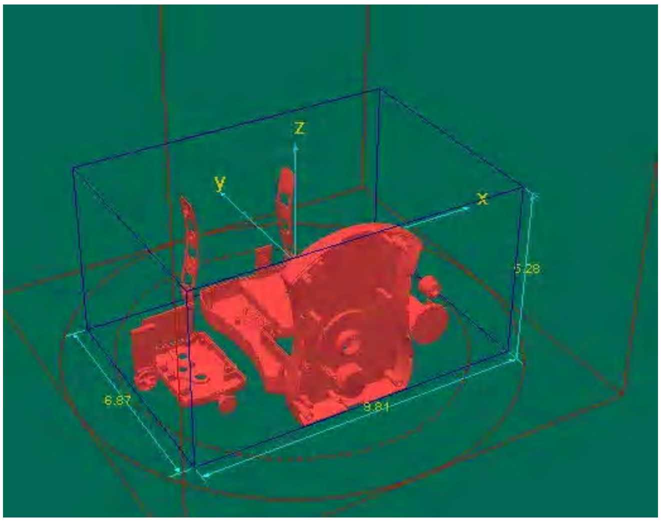


Figure 4.2 Build envelope of the Sinterstation 2000 machine

The orientation of parts is very important in order to minimize distortion and maximize accuracy. Upward-facing surfaces build flatter, and have a better surface finish. When it is preferable to keep the up-facing surface oriented upward, supports can be used for parts that have overhangs. These supports will have to be removed at a later stage. The alternative is to flip the part over to avoid overhanging structures, as can be seen from Figure 4.3.

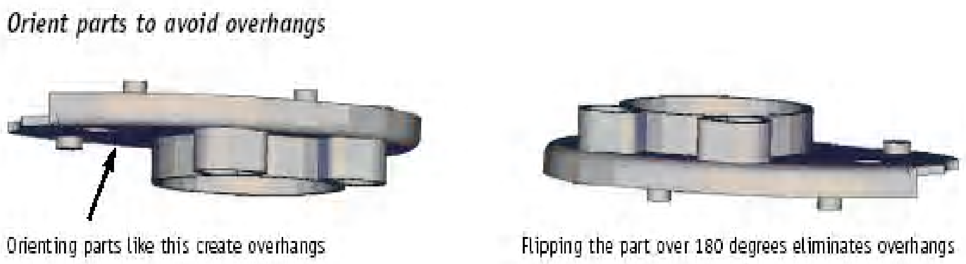


Figure 4.3 Orientation of parts for growing in the machine [24]

After orientation, the parts are scaled in x, y and z directions. The scaling values are obtained by growing scaling blocks that have known X, Y and Z readings as can be seen in Figure 4.4. Scaling factors are necessary because the process is exposed to high temperatures and shrinkages occur in the parts. These scaling blocks are also taken through the post-curing process because further shrinkages occur. After the post-curing, the scaling blocks are measured and compared with actual measurements to obtain the scaling values. These values are read into the machine's default settings which will serve as a reference from which all future parts can be scaled.

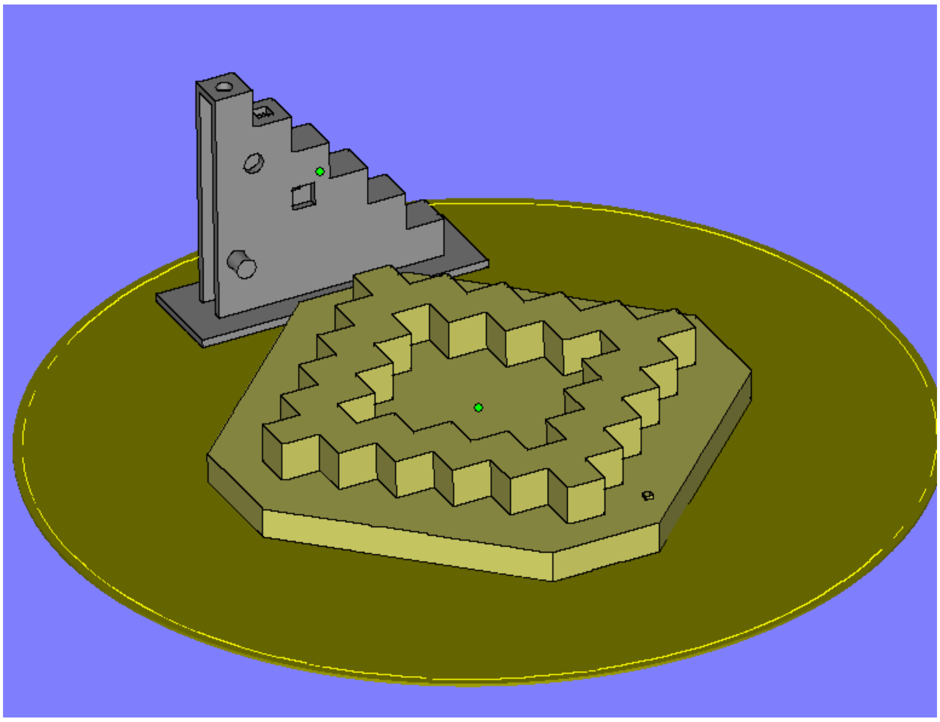


Figure 4.4 The scaling parts used to obtain X, Y and Z scaling values

A build profile (Figure 4.5 shows the “editor window” which has the entire temperature, roller speed and feed distance settings of the machine), is applied to all the parts in the build. The build profile is divided into three stages, namely:

- Warm up stage – Getting the machine warmed up to minimize distortion in the part;
- Build stage – Where the actual sintering of the material takes place; and
- A cool-down stage – Where powder is rolled over the part to minimize warp-age and curling in the part.

The abovementioned stages are set in mm in the Z direction of the build.

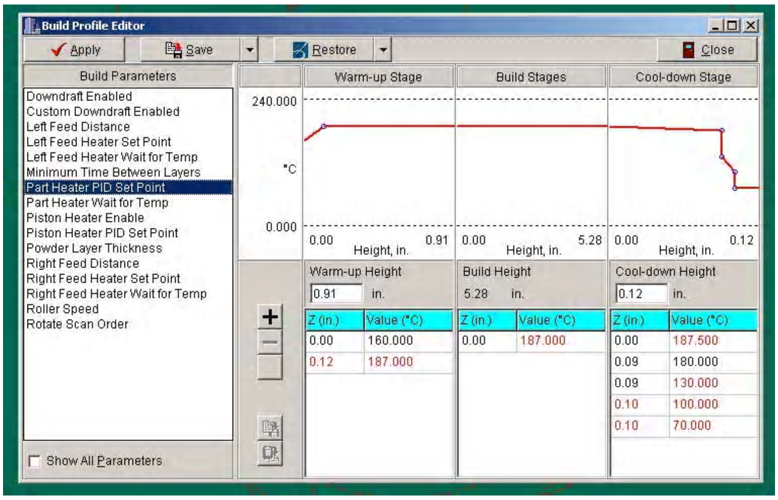


Figure 4.5 Build profile editor window

A part profile, shown in Figure 4.6, is then applied to each part in the build, which has the entire fill and outline laser power as well as the scan speed/spacing settings of the machine. These settings can be applied independently to the parts when a part needs more laser power.

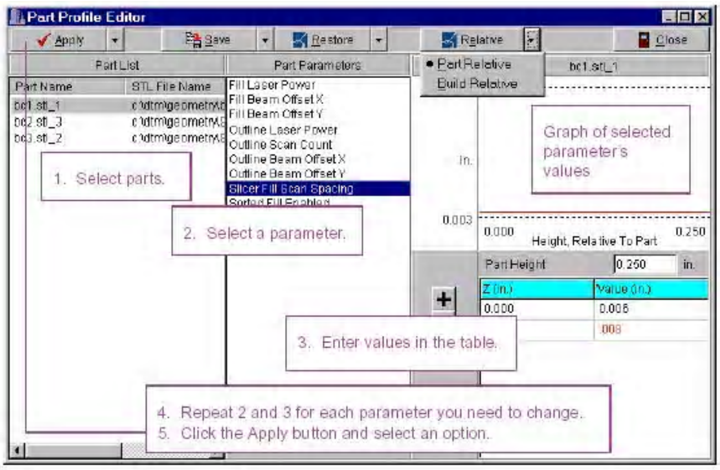


Figure 4.6 Part profile editor window

After these profiles have been applied, the build is verified and saved as a build packet, whereafter the build can start. As can be seen from Figure 4.7, the process is somewhat similar in principle to stereolithography. However, in this case, a laser beam is traced over the surface of a tightly compacted powder. A roller spreads the powder over the surface of a piston/powder bed. This layer of powder is accommodated by the piston moving down one object layer thickness. The powder feed cartridge consists of a cylinder and piston which moves upward incrementally to supply powder for the process.

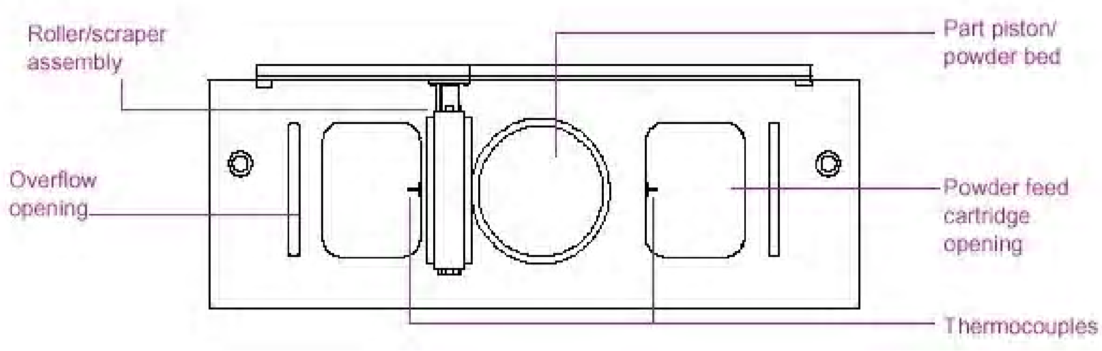


Figure 4.7 Layout of the SLS machine [24]

A scanner system controls the CO_2 laser which provides a concentrated infrared heating beam that melts the powder where it sinters. The entire fabrication chamber is sealed and maintained at a predefined temperature. This implies that heat from the laser needs only to elevate the temperature slightly to cause sintering of the binder inside the LaserForm™, greatly speeding up the process. Finding the temperature set point, which defines the temperature before scanning, is the first step to building a part using LaserForm™ material on an SLS system. To provide feedback on the building ability of LaserForm™ material at a certain temperature set point, the “grow bar.stl” part file is used, as shown in Figure 4.8. The part is a rectangular bar with a number of slots that vary in gap thickness, from 0.125 mm to 0.635 mm and are 6.350 mm deep. Feedback on the quantity of growth that occurred at a given exposure level is obtained from the slots. This can be used to choose correct temperature set points for future part building.

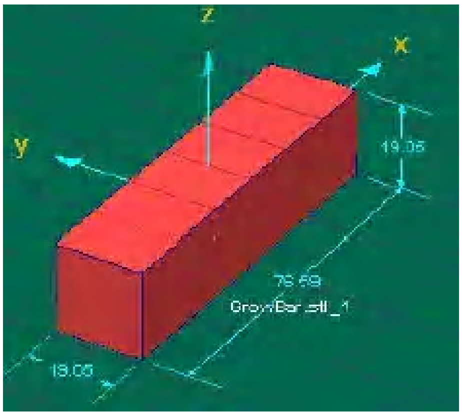


Figure 4.8 The “grow bar.stl” part file [24]

When using the SLS system, parts that have been built, but not yet processed in the oven cycle, are referred to as “green” parts. These “green” parts should be seen as fragile and thus, when the parts are designed, it is important to consider how they will be handled during breakout and the sintering/infiltration steps.

4.2 OVEN CYCLE OVERVIEW

The oven performs the following functions [24]:

- Debinding - Debinding occurs during ramp-up. The binder burns out of the “green” part at temperatures between 450^0C and 650^0C.
- Sintering - During further ramp-up, at approximately 700^0C, the steel powder that remains after the binder burns out, begins to sinter together.
- Infiltration - In this stage, the porous “brown” part produced in the sintering stage is infiltrated to produce a fully-dense part. During infiltration, the oven will heat to a predetermined set point.

- Cool-down – The part has to cool down naturally after the oven cycle. Nitrogen flow must be maintained until the temperature falls below 200^0C to ensure cooling down in a complete Nitrogen atmosphere [24].

The recommended oven cycle with cooling down times is shown in Figure 4.9.

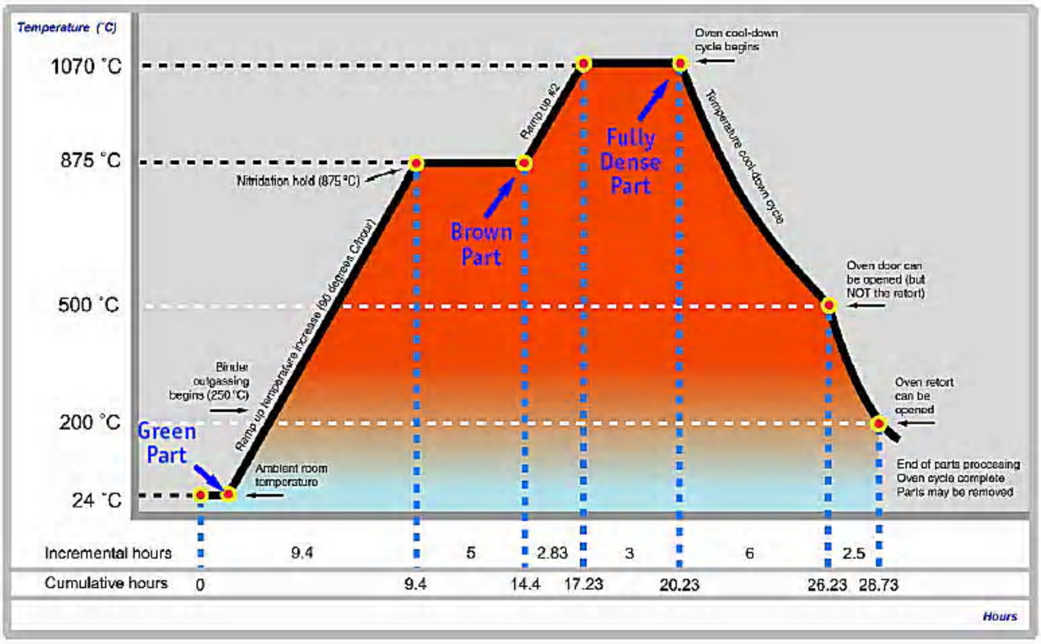


Figure 4.9 The recommended oven cycle [24]

An explanation of the segments of the oven cycle:

- Ramp1 (from 0 to 9.4 cumulative hours):
  - From room temperature to 875˚C @ 90˚C/hour
- Hold 1 (from 9.4 to 14.4 cumulative hours):
  - 5 hours
- Ramp 2 (from 14.4 to 17.23 cumulative hours):
  - From 875˚C to 1070^0C @ 90˚C/hour

- Hold 2 (from 17.23 to 20.23 cumulative hours):
    - 3 hours

An average oven cycle for LaserForm A6 material is approximately 23 hours.

4.2.1 Preparing “green” parts for the Oven Cycle

a) The amount of infiltrant needed can be calculated by weighing the “green” part. For LaserForm™ ST100, the amount of infiltrant required is 0.72 (72%) x the weight of the “green” part plus tabs.

The following equations are used to determine the infiltration efficiency of LaserForm™ ST100:

- Infiltration Efficiency = (weight of infiltrated part/weight of “green” part x 1.72) x 100 ***[E.1.]***
- (Weight of infiltrant) = (weight of part + weight of tabs) x 0.72 ***[E.2.]***

For LaserForm™ A6 material, the amount of infiltrant required is 0.85 (85%) of the weight of the “green” part plus tabs.

The following equations are used to determine the infiltration efficiency of LaserForm™ A6:

- Infiltration Efficiency = (weight of infiltrated part/weight of “green” part x 1.85) x 100 ***[E.3.]***
- (Weight of infiltrant) = (weight of part + weight of tabs) x 0.85 ***[E.4.]***

Infiltrant weighing within ±0.5% (0.850 ± 0.005) of the desired (calculated) weight is acceptable.

b)	Measure the parts' sizes to determine the crucible size needed.

c)	It must be ensured that the infiltrated part does not adhere to the alumina plate, coat the alumina plate with a fine layer of boron nitride powder, as seen in Figure 4.10. The coated alumina plate should now be placed into the crucible.

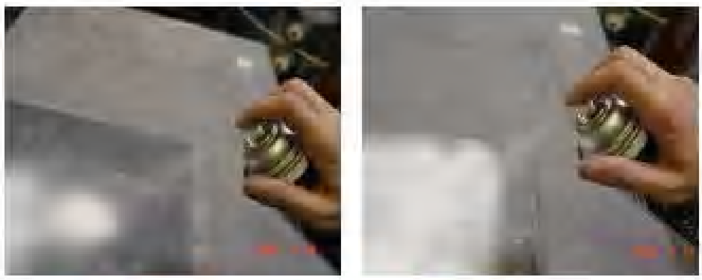


Figure 4.10 Coating an alumina plate with boron nitride powder [24]

d)	The parts are cleaned thoroughly to prevent excess material being sintered on the surface. The parts are then put on the alumina plate inside the crucible and the tabs are glued to the parts. It is important that a stable joint between the part and the tabs are obtained to ensure good infiltration of the bronze into the part. Super glue gel is used to glue the tabs to the part, but it is sometimes better to grow the tabs directly onto the part. The infiltrant that is placed on top of the tabs, as shown in Figure 4.11, is as far away from the part as possible to prevent corrosion on the part side.

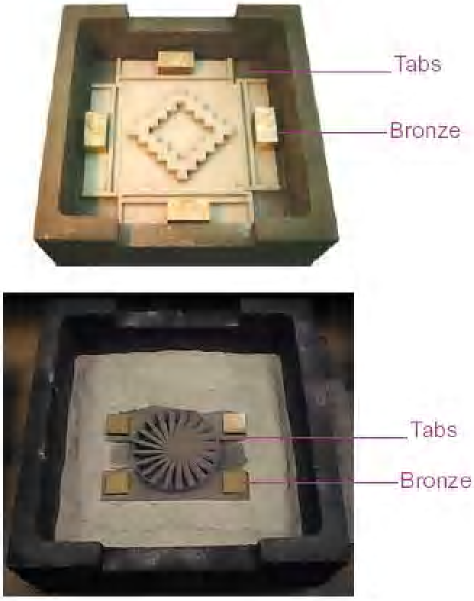


Figure 4.11 Placement of the infiltrant on the tabs [24]

e) Use fine alumina powder to cover the infiltrant and the part (240 grit), as shown in Figure 4.12. The alumina powder supports the part particles through the oven cycle. It is important to ensure that the alumina powder goes into all the holes and openings to prevent sagging of the part in the oven cycle.

Figure 4.12 Alumina powder covering the part [24]

f) The crucible is carefully transported into the oven, to prevent the infiltrant falling off the tabs. The oven cycle is then started.

g) The part is cooled down naturally before it is taken out of the oven. The alumina powder is removed from the crucible for re-use and the part is bead blasted for a better surface finish

4.3 BUILD SIZE LIMITS

4.3.1 Maximum Part Volume

The maximum recommended part volume (including infiltration tabs) is approximately 4.0 litres. A 20 x 20 x 10 cm volume approximates the 4.0 l limitation, but this specific dimension is just one possible combination of many alternatives [24].

4.3.2 Minimum Feature Size

Positive and negative features are limited to the capabilities of the machine. However, theoretically, parts or features as small as 0.75 mm should be possible, depending on the geometry. In practice, the frailness of the “green” part makes it difficult to clean and transport a part to the oven without breaking off 0.75 mm features [24].

4.4 TOOLING DESIGN CONSIDERATIONS FOR THE SINTERING PROCESS

Tooling inserts created by the SLS system and LaserForm™ A6 material can be considered to be the same as ordinary tool steel when heat treated. The following guidelines are used for designing and preparing data for building tooling inserts and other tooling masters on the SLS system:

4.4.1 Unsupported Standing Features: Dimensions

- A minimum thickness of 2 mm; and
- A width to height ratio of 1:4.

4.4.2 Ejector Pin Holes

Size and placement of ejector pin holes are critical. This is why ejector pin holes are added during post-processing.

4.4.3 Runners and Gates

Runners and gates can be incorporated into the design or put in as a secondary process. To be able to adjust runners and gates during the moulding process, leave the features undersize when growing it on the machine.

4.4.4 Conformal Cooling Lines

Conformal cooling lines can be designed on the CAD data and then grown directly into the inserts. Otherwise, cooling lines can be added mechanically after the inserts are completed. When designing the conformal cooling lines, ensure that a minimum diameter of 5 mm is used. Sharp turns or corners should be minimised, because it can become difficult to remove powder clogging the line. To minimise the possibility of excess air pressure damaging the insert by "blowing-out" the wall, it must be ensured that the cooling lines are no less than 3.2 mm to an outer wall surface. To ease the cleaning process, add a clean out hole at every sharp turn to enable compete powder removal.

4.4.5 Adding Stock to a Tool

On critical tolerances of the particular geometry, it is common practice to add stock to the parting line and to the outer insert walls. This can machined off on a secondary process.

4.4.6 Threads

Extra stock should be incorporated into the design of threads and should be tapped during post-processing.

4.4.7 Polishing

For areas that need polishing, stock in between 0.07 mm to 0.13 mm should be added.

4.4.8 Grinding Critical Surfaces

Additional stock of 0.23 mm should be added to critical areas such as parting planes and shut-offs to allow for grinding.

4.4.9 Squaring

It is necessary to add 0.75 mm of stock to sides and bottom of tools for squaring up the tool.

4.4.10 Overhanging Features

To prevent overhanging features from shifting, sagging or breaking it is essential to add support posts.

4.4.11 Adding Bases

To prevent parts from shifting during the building process it is important to add bases in the CAD design that can be used as anchors in the part bed [24].

Chapter 5: Rapid Tooling with the LS Process

5.1 THE EOSINT P 380 MACHINE

The basic principle of the EOSINT P-series machine is the layer-wise solidification of thermoplastics by means of a CO_2 laser. The powder is preheated by four infrared heaters to about 10°C below its melting point to keep the amount of energy contributed by the laser as low as possible. The energy supplied by the laser is absorbed by the powder and leads to a local solidification of the material. The temperature regulation is carried out via a control circuit, whereby the temperature is measured from a distance by a pyrometer, located in the upper front part of the building chamber. The powder is applied by a recoating system, which compresses the powder by means of its blade geometry. This compression increases the strength of the part and projecting parts will be supported by the compacted powder [8].

5.1.1 Physical Layout

The EOSINT P380 machine consists of the following components, as shown in Figure 5.1:

1. Lever for regulating the extraction (exhaust control)
2. Powder supply bins
3. Process chamber door
4. Powder collector bins
5. The removal (unloading) chamber door

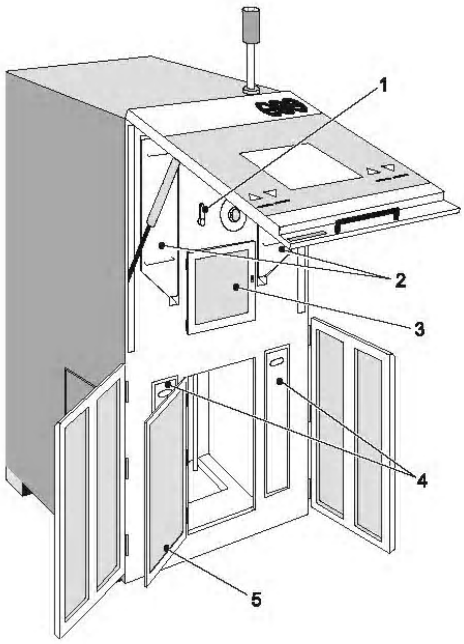


Figure 5.1 The layout of an EOSINT P380 machine [8]

5.1.2 The Optics Chamber

Figure 5.2 shows the optics chamber which contains the laser, shutter, three deflection mirrors, the beam expander optics and the scanner head with the F-Theta lens [8].

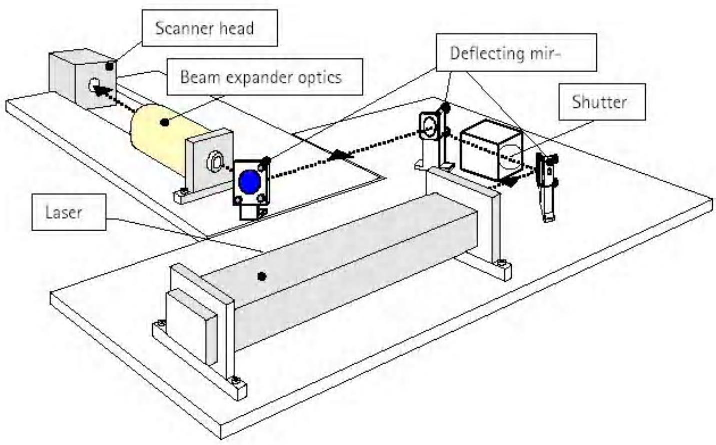


Figure 5.2 The optics chamber [8]

The components of the optics chamber:

a) Laser

The laser inside the P380 machine is a CO_2 laser with two tubes inside. Each tube has an output power of around 30 Watt and the two beams are merged together with the intention that just one beam leaves the laser head. The laser beam has a wave length of 10600 nm and lies in the invisible infrared part of the spectrum. Cooling of the laser is done by a chiller which contains cooling water with a temperature between 18°C and 25°C.

b) Shutter

The shutter is positioned after the first mirror and if the safety circuit is released, it closes off the laser beam.

c) Deflecting Mirrors

The role of the deflecting mirrors is to guide the laser beam parallel and centred into the beam expander.

d) Beam Expander Optics

The beam expander expands the beam to attain a larger laser beam which will result in a smaller focal diameter that betters the focus of the laser beam.

e) Scanner Head

After the beam expander, the laser beam moves into the scanner head. Inside the scanner head there are two adjustable moving coil mirrors which are driven by stepper motors. The moving mirrors direct the laser beam on the building envelope which gives an X and Y movement of the laser beam.

f) F-Theta Lens

The F-Theta lens ensures that the focal point of the parallel laser beam meets exactly in the plane on which the powder is applied. The lens is designed in such a way that the laser beam is focused on any area inside the build envelope. Nitrogen is also blown through a 0.4 mm gap around the lens to prevent particles of powder accumulating on the lens and also ensures the cooling of the lens.

5.1.3 The Process Chamber

The actual LS process takes place in the process chamber using the following components:

a) Heat Radiators

Four heat radiators are located above the building envelope and pre-heat the powder to 10°C below its melting point to keep the amount of energy contributed by the laser as low as possible.

b) Pyrometer

The pyrometer is a non-contact device that is used to measure the temperature of the powder surface.

c) Recoater

The recoater, shown in Figure 5.3, consists of two blades. These blades are slightly slanted on the inside in order to compress the powder during the recoating process.

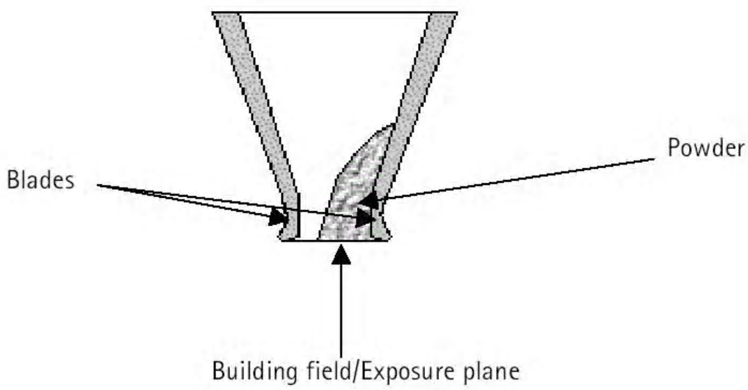


Figure 5.3 The recoater [8]

d) Powder Supply Bins

The powder supply bins are located on either side of the process chamber. These bins supply the recoater with powder by means of a metering drum filled with the required amount of powder. Compressed air is fed into the bottom of the powder bin, causing the powder to react similarly to a liquid, ensuring a consistent dosage of powder.

5.2 THE PROCESS AS DESCRIBED BY EOS [8]

The process cycle is divided into five steps [8]:

1. The powder is dispensed into the recoater, as shown in Figure 5.4. The dispensing is automatically regulated by the software.

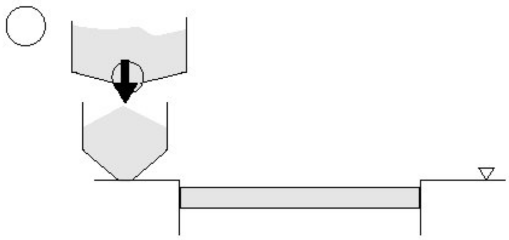


Figure 5.4 Dispensing the powder into the recoater

2. The powder is applied onto the platform, as shown in Figure 5.5, and this is called recoating.

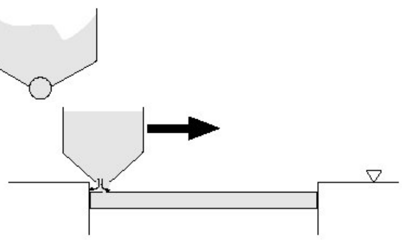


Figure 5.5 Recoating the powder onto the platform

3. The cross-section of the part is traced onto the powder bed by the laser, as shown in Figure 5.6.

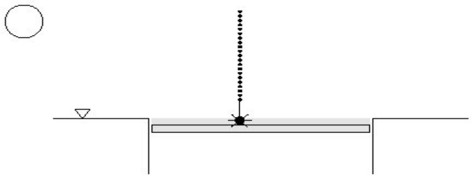


Figure 5.6 Laser exposure

4. The platform is lowered by a distance equal to a layer’s thickness, as shown in Figure 5.7.

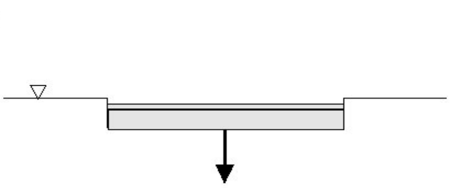


Figure 5.7 Lowering of the platform

5. The process is repeated and the part grows layer by layer, as shown in Figure 5.8.

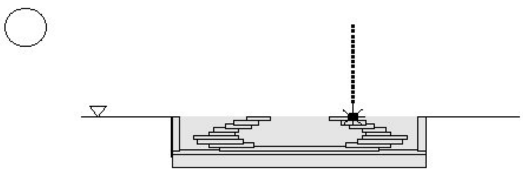


Figure 5.8 Layer-wise construction of the part

5.3 DATA PREPARATION

Figure 5.9 shows a few steps in the data preparation for the P380 machine [8].

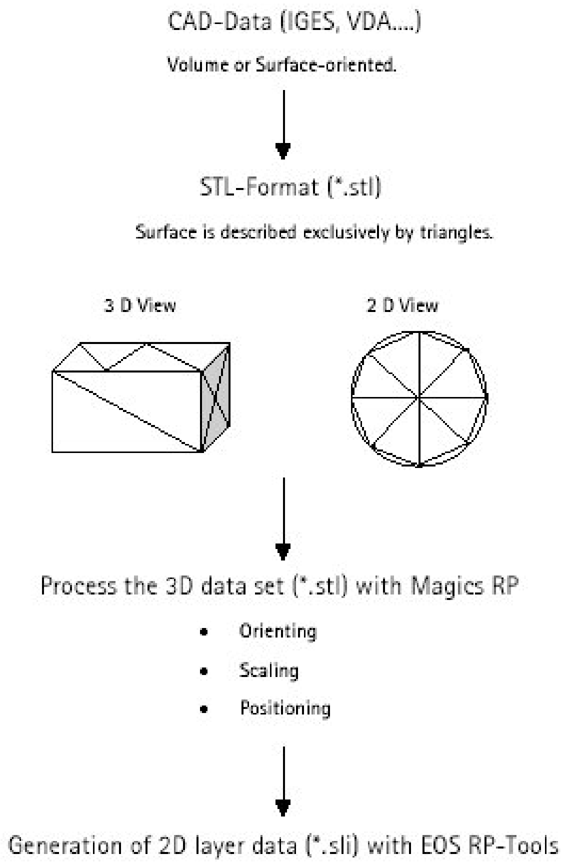


Figure 5.9 Data preparation [8]

a) Positioning Building Parts

As with other RP machines, the P380 starts with a CAD model that is exported to a .STL file. The .STL-Data is loaded into the processing software, e.g. Magics RP™ [16]. Within this process the parts are moved into an optimal building position by corresponding placement functions.

Indications for the optimal building position:

- The building part should be placed into the building area in a manner that avoids the building of unconnected partitions of the building parts into the free powder bed, as shown in Figure 5.10.

Figure 5.10 Optimal building position for unconnected partitions [8]

- Large, plain surfaces should lie on the top in order to avoid great surface differences from one layer to the other as shown in Figure 5.11.

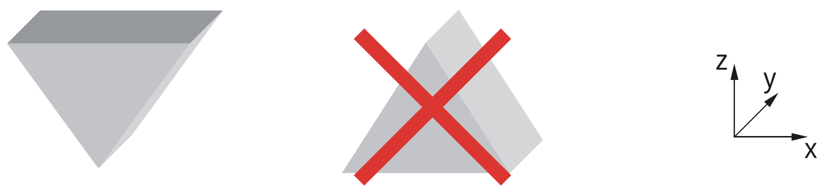


Figure 5.11 Optimal building position for large, planar surfaces [8]

b) Scaling the Building Parts

In order to compensate for the shrinkage while sintering, the building parts have to be scaled after the positioning process. The x/y/z-shrinkage that occurs during the sintering process depends on various parameters, namely:

- the position of the part,
- the geometry of the building parts,
- the exposure parameters, and
- the cool-down time after the completion of the job, amongst others.

In order to compensate for shrinkage during the process, shrinkage parts with known dimensions are grown and measured (as seen from Figure 5.12). This is done to obtain shrinkage values in X, Y and Z directions that can be applied for all the builds.

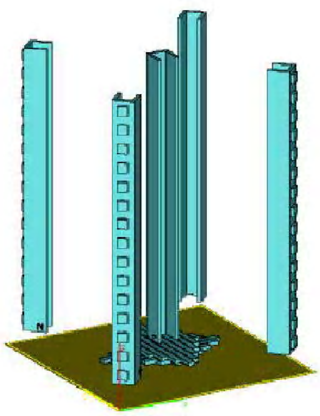


Figure 5.12 Shrinkage parts grown to obtain shrinkage values in the X, Y and Z directions

c) Slicing the .STL File

The .STL of the nested parts is imported into EOS RP Tools software. The RP Tools software slices the .STL file into 2D layer data, and the data is then imported into the PSW software of the machine, as shown in Figure 5.13. The slice cross-sectional data provides the laser beam with the X and Y coordinates.

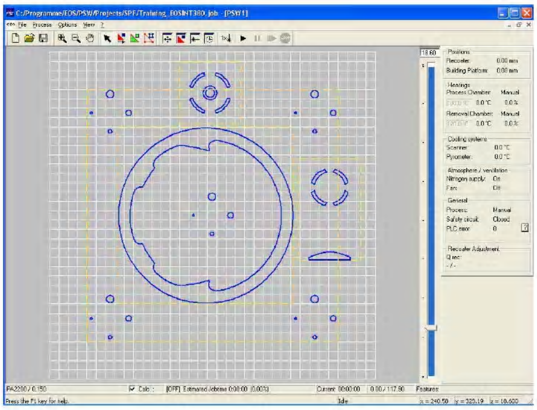


Figure 5.13 A cross-sectional view of parts to be produced in the PSW software on the P380 machine

5.4 BUILDING PARTS

5.4.1 Exposure Parameters

After loading the slice file into the PSW software of the P380 machine, the next step is to assign an exposure parameter to the parts. The exposure parameter determines how fast and where the scanner guides the laser beam. There are two main exposure types, namely sorted and unsorted and the others are variations of them.

As seen from Figure 5.14, the unsorted parameter is the slower of the two because the exposure is done in just one phase and the laser is put on and off in the same line. Unsorted gives the best surface finish because there are no weld marks as occurs with sorted where the first and second exposures meet. The sorted exposure type ensures the fastest part growing time of all the exposures. Regardless of which exposure type is selected, the laser will first perform a contour exposure followed by a hatch exposure.

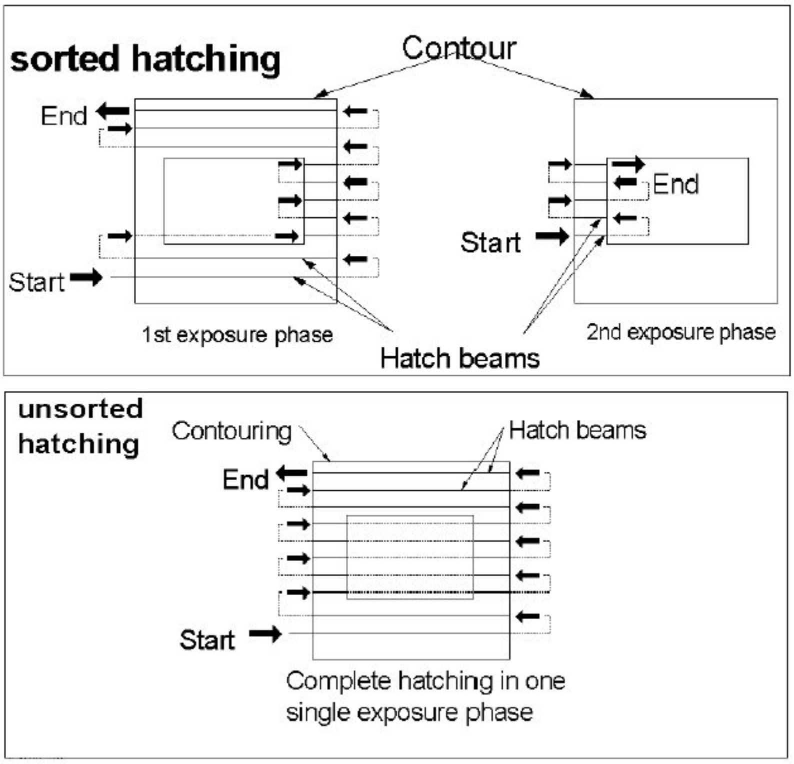


Figure 5.14 Differences between the sorted and unsorted exposure type [8]

The mechanical exposure type parameters are shown in Figures 5.15 and 5.16. The scanning speed is decreased to give more energy to the part being produced and ensures good bondage between the layers to result in stronger parts, hence the term “mechanical”. From the experimental work on the Alumide® material, the unsorted and mechanical exposure types were used.

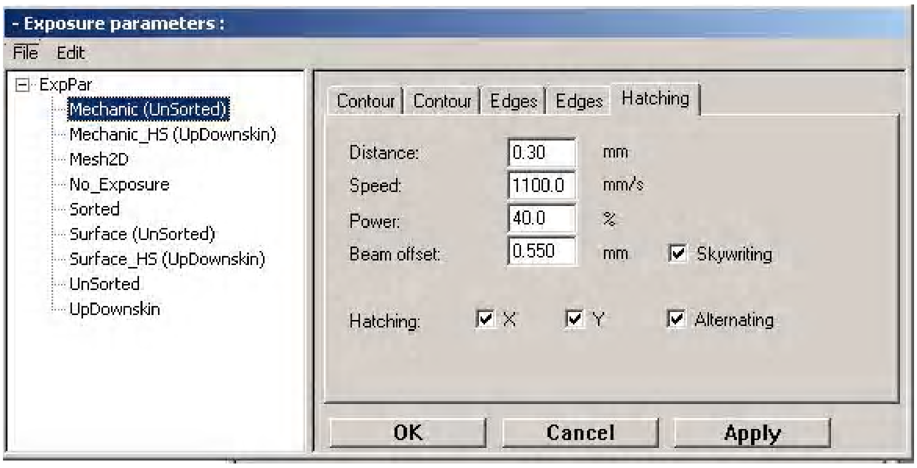


Figure 5.15 Hatching speed and power parameters of the mechanical exposure type

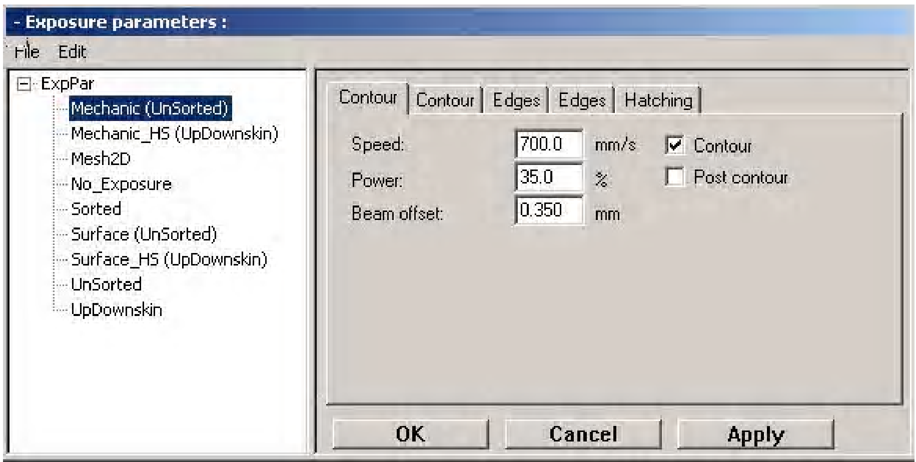


Figure 5.16 Contour speed and power parameters of the mechanical exposure type

The unsorted exposure type parameters are shown in Figures 5.17 and 5.18. The scanning speed is increased to give faster part production.

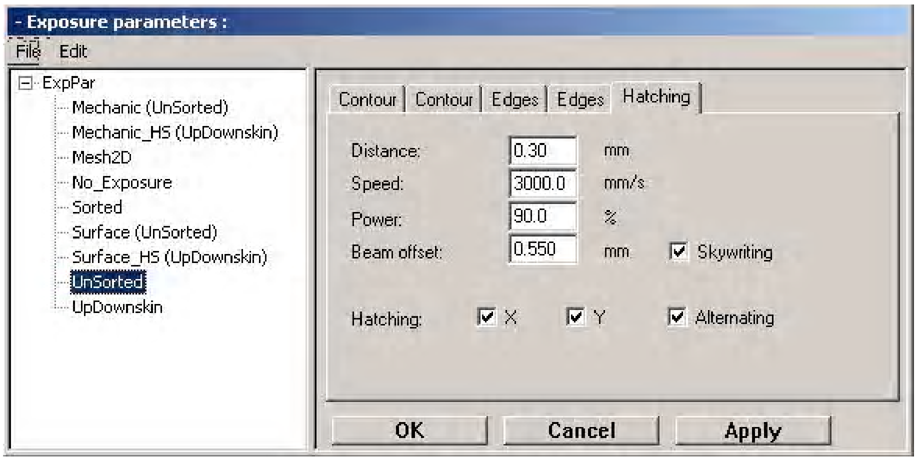


Figure 5.17 Hatching speed and power parameters of the unsorted exposure type

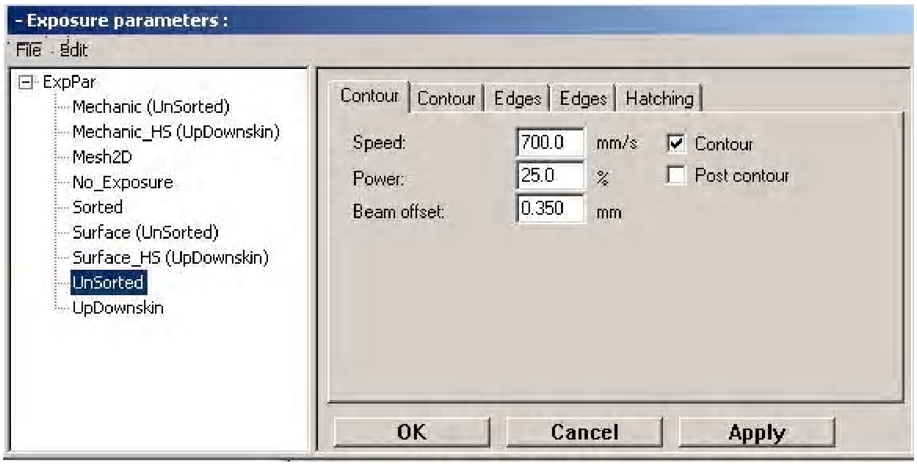


Figure 5.18 Contour speed and power parameters of the unsorted exposure type

The beam offset setting on all the exposure parameters is the offset value of the laser beam diameter, which ensures that the laser follows a path inside the part perimeter, as shown in Figure 5.19.

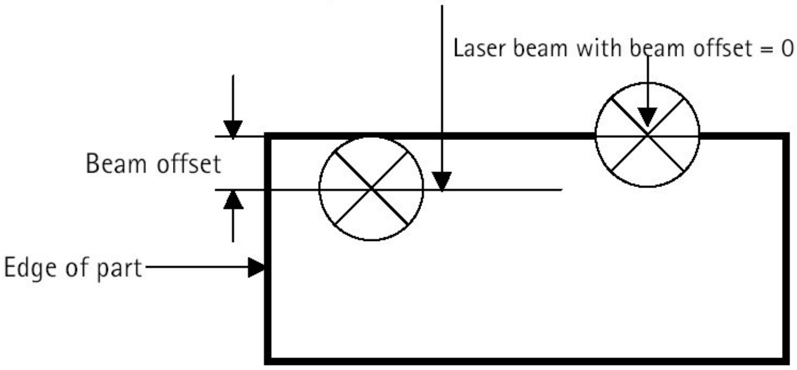


Figure 5.19 The laser beam, with and without beam offset [8]

5.4.2 Building Process

After assigning exposure parameters to the different slice files, a job file of the current build is saved. Recoating of 8-12 layers on the building area is necessary before the heating phase is started. Heating up the machine is done in the automatic heating-up mode at a process-chamber temperature of 160 °C and a removal-chamber temperature of 120 °C within a minimum period of 90 minutes. Thereafter the processing temperature is set on the machine. Normally, this processing temperature lies within a range of 178 °C to 180 °C. The building process can be started when the heating power has dropped to a value of < 30%.

5.4.3 Unpacking and Finishing of Parts

After finishing the job, a nitrogen purge of 600 minutes follows. The exchangeable frame should remain in the machine until the building area temperature has dropped below 80 °C. Slow and constant cooling down of Alumide® after being processed is recommended, thus avoiding deformation, varying thermal exposure and differences in tension. This is achieved by cooling down the exchangeable frame to room temperature. The parts are removed by hand from the exchangeable frame. Loose powder around the parts is removed with a brush. The remaining powder on the building parts is cleaned with the help of a blasting cubicle. Finally, either glass beads as a blasting abrasive, or conventional polishing methods are recommended.

CHAPTER 6: Experimental Work

As described in the Problem Statement of this research project, the following aspects were identified as research areas to prove that RT can be a solution for injection moulding:

- Durability of the moulds
- Lead times to produce the moulds
- Shrinkages during the injection moulding inside the moulds
- Accuracy of the grown inserts
- Cost of the grown inserts

The following case studies were completed to address the abovementioned aspects:

- Case Study 1: Grown Injection Moulding Inserts for “Big Jim” Toolboxes
  - Compares the lead times and cost between RT and conventional tooling of the LaserForm™ ST100 grown inserts
- Case Study 2: Grown Injection Moulding Inserts for Belt Sander Knobs
  - Shows lead times and cost of the LaserForm™ ST100 inserts
- Case Study 3: Alumide® Grown Inserts
  - Compares the lead times and cost between RT and conventional tooling of the Alumide® grown inserts

- Case Study 4: Shrinkage Test of Grown Inserts
    - o Identifies the shrinkages during injection moulding inside the LaserForm™ ST100, LaserForm™ A6 and Alumide® grown inserts as well as the accuracy of the inserts.
- Case Study 5: Durability Test of Grown Inserts
    - o Identifies the durability of the LaserForm™ ST100, LaserForm™ A6 and Alumide® grown inserts
- Case Study 6: Gynaecological Product Development
    - o Shows the benefit of combining conventional tooling with RT processes.

Table 6.1 The scaling values used in the abovementioned case studies

SCALING DIRECTION	LASERFORM™ ST100	LASERFORM™ A6	ALUMIDE®
X	1.0195	1.0353	1.0122
Y	1.0204	1.0349	1.0159
Z	1.0125	1.0232	1.0107

The data sheets for LaserForm™ ST100, LaserForm™ A6 and Alumide® are found in Appendixes B, C and D. Where readings could not be taken on test specimens (part length, width or depth was not completely moulded) an "X" was used to indicate this as shown below:

Number	**Reading Z**
Actual Dim	***3.15***
Right Part	
1.1	**X**
Deviation	**X**

6.1 CASE STUDY 1: GROWN INJECTION MOULDING INSERTS FOR "BIG JIM" TOOLBOXES

Introduction

The aim was to manufacture a complete mould using conventional tooling, and then manufacture one set of inserts using the SLS process. The grown inserts would then be fixed into the mould and used in production to determine the suitability of this process in the manufacturing chain.

The comparison is based on the manufacture of one core, one cavity and one slide with the total assembled dimensions of X = 130 mm, Y = 117 mm and Z = 104 mm, inserted into a 4-cavity injection mould for a locking clip on a toolbox.

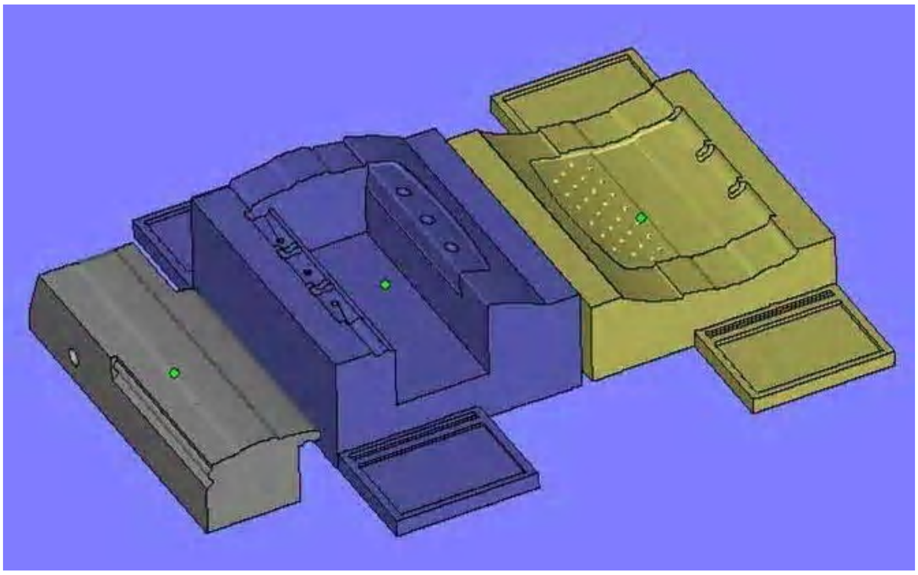


Figure 6.1 Design of the individual inserts and sliding core

The Design Process

The Big Jim toolbox clip was designed at Nu-Era Tool & Die whereafter a SLS prototype was grown at the Centre for Rapid Prototyping and Manufacturing (CRPM). Once the client had approved the prototype, the mould was designed in Solid Edge by subtracting the product's geometry from a mould base geometry to create a cavity. Loose inserts were designed for this mould to ease the removal and adding of the experimental inserts into the mould. The insert designs were changed to suit the two different processes to be used in their manufacturing.

For the conventional tooling process the inserts were completely dimensioned, electrodes were extracted from the mould design and the cooling was designed in the conventional linear manner. For the SLS process, tabs were added to the design for bronze infiltration, and the cooling channels were designed in a maze and helical design.

The Conventional Tooling Manufacturing Process

The mould base was manufactured using the process normally associated with a mould of this nature, in the tool room at Nu-Era Tool and Die.

The inserts were manufactured using the following process:

1) 1.2311 (M201) Tool steel was ordered. The M201 tool steel is suited for spark eroding and is wear resistant as opposed to the plastic used in

injection moulding. The lead-times for ordering the metal to delivery on the premises were 5 days.

2) Graphite (Poco EDM100) was ordered for the manufacture of electrodes. Poco EDM100 graphite was used instead of copper because the graphite has better roughing wear characteristics than copper and the graphite is machined and polished easily. The lead-times for ordering the graphite to delivery on the premises were 3 days
3) Steel was blocked up using conventional milling methods.
4) Cooling channels were drilled and tapped using conventional drilling and tapping methods.
5) Steel was ground to size using conventional grinding techniques.
6) Shut-off faces were milled using CAM and CNC milling techniques.
7) Electrodes were manufactured using CAM and CNC milling techniques.
8) The steel was then spark eroded using EDM techniques.
9) The electrodes were then re-cut using CNC milling techniques.
10) The steel was then given a spark finish to the required tolerance and surface finish. The lead-times for the manufacturing of the electrodes for the roughing, finishing as well as the re-cut for the final spark process was one and a half days.
11) The shut-off was polished and checked using hand polishing techniques.

The total cost of one set of inserts (1 cavity, 1 core and 1 slide) is detailed below:

Conventional Machining Cost Analysis

CNC machining of inserts	=	R 6 700-00
Material cost of inserts	=	R 5 500-00
Finishing of inserts	=	R 700-00
TOTAL	=	**R 12 900-00**

Conventional Machining Lead Time Analysis

CNC machining of two inserts (include tool path generation)	=	30 hours
Finishing time	=	7 hours
TOTAL	**=**	**37 hours**

(Manufacturing took ±4.5 days to complete if an 8 hour work day is taken, which excludes the ordering of the metal.)

The SLS Manufacturing Process

The files were prepared in a conventional manner for this process using suggested scaling factors. The parts were grown in a LaserForm™ ST-100 material in the Sinterstation 2000 system. The “green” parts were then treated in an oven in the conventional debinding, sintering, bronze infiltration and cool-down method.

The total cost of one set of inserts (1 cavity, 1 core and 1 slide) is detailed below:

<u>SLS Cost Analysis:</u>

Growing time on SLS machine	=	R 13 770-00
Material cost - LaserForm™ ST 100 inserts (1 792 988 mm^3)	=	R 19 000-00
Finishing of inserts	=	R 400-00
TOTAL	=	**R 33 170-00**

<u>SLS Growing Time Analysis:</u>

Growing time of three inserts on DTM 2000 machine	=	60 hours
Post processing time of inserts inside the oven cycle	=	24 hours
Finishing time	=	4 hours
TOTAL	**=**	**88 hours**

(Manufacturing took ± 4 days to complete because machine and oven cycle can run through the night)

Some dimensions were checked on the x, y and z axis as shown in Table 6.2. Figure 6.2 shows the accuracy results of one set of inserts (1 cavity, 1 core and 1 slide) grown on the SLS machine in LaserForm™ ST100 material.

Table 6.2 The accuracy of the SLS grown inserts

	Should be	Final Dimension	Deviation %
X	77.353 mm	77.000 mm	-0.456 %
Y	85.260 mm	85.510 mm	0.292 %
Z	39.124 mm	39.150 mm	0.066 %

Figure 6.2 The SLS grown inserts

Results

During the evaluation of the inserts that were manufactured using the SLS process, it was clear that the inserts would not be able to be used in the mould.

The following critical defects were found as shown in Figures 6.3 to 6.6:

1. The dimensions of the parts were not up to the required standard to suit slide fits.
2. The surface finish was not of the required standard.
3. There was porosity that would cause plastic to stick in the mould.
4. The shut-off shape had deviations from core to cavity.
5. The cooling channels were blocked during bronze infiltration.

Figure 6.3 SLS Cavity showing poor surface finish

Figure 6.4 SLS Core showing shut-off detail

Figure 6.5 SLS Slide showing poor lip detail

Figure 6.6 SLS Core showing porosity and edge deformation

The inserts manufactured using conventional tooling as shown in Figures 6.7 and 6.8 were of the required standard and the mould went into production one week behind schedule. This was due to complications in machining the shut-off between core and cavity.

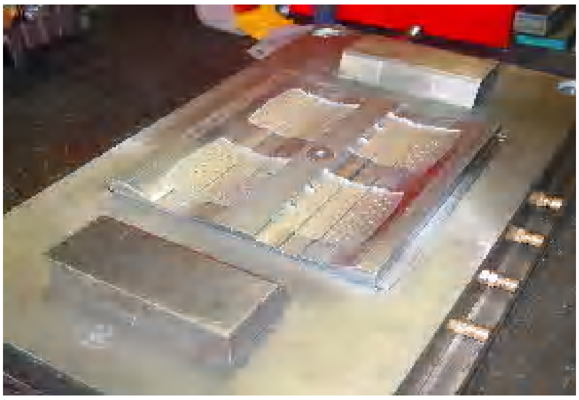


Figure 6.7 Fixed mould half

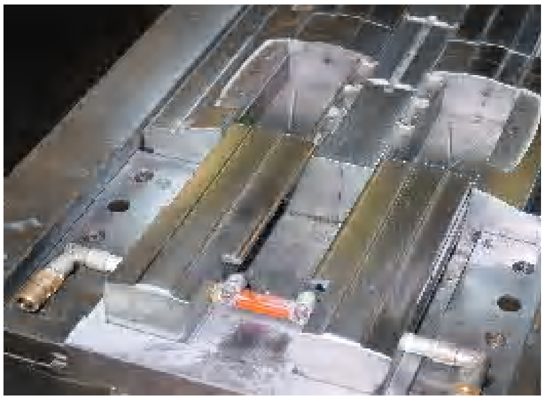


Figure 6.8 Moving mould half

Summary

In retrospect, the insert geometry was too big to grow with the SLS process, as seen from the cost indicated in Table 6.3. The geometry was also easy to manufacture using normal CNC milling. Small injection moulding inserts that need a lot of EDM work are more suited to the SLS manufacturing process.

The parts were grown flat on the machine bed causing inaccurate results as well as a surface finish that was not acceptable for plastic injection moulding. To grow the parts upright on the machine bed would result in better surface finish and accuracy, but it would have taken too much building time and would have been very expensive.

Table 6.3 A cost comparison between the SLS and Conventional Tooling produced insert

	SLS produced insert	Conventional Tooling produced insert
Insert cost	R 33 170.00	R 12 900.00
Production time of insert	88 hours	37 hours
Largest dimension deviation	0.353 mm	0.05 mm

Larger building volume (1 792 988 mm^3) of the inserts lead to higher cost of the SLS produced inserts. This can be seen in that the material cost of the insert amounts to R 19 000 of the total costs of R 33 170. The tooling made through conventional manufacturing, adhered to the required tolerances which is 0.05 mm.

6.2 CASE STUDY 2: GROWN INJECTION MOULDING INSERTS FOR BELT SANDER KNOBS

The CRPM was involved in the development of belt sanders for a local company. The knobs as shown in Figures 6.9 and 6.10, are used in the assembly of these sanders. After the product development was completed, an order was placed for 50 belt sanders. On each belt sander 5 knobs are used to assemble various parts. For the first 50 sanders Reaction Injection Moulding (RIM) was used in a trial to manufacture the 250 knobs. The RIM casting process took a long time and the scrap rate was quite high. The client needed 200 belt sanders per month, which required 1000 knobs to be manufactured per month. These quantities were too high for soft tooling. It was decided to grow two LaserForm™ ST100 inserts on the SLS machine, which could be fitted in a steel bolster with the normal pins and bushes associated with injection moulding as shown in Figures 6.11 and 6.12.

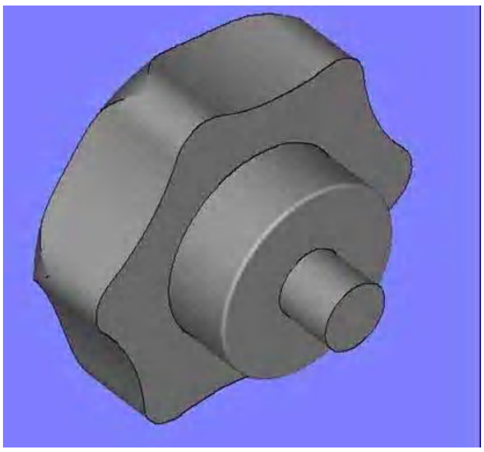


Figure 6.9 Knob design

Figure 6.10 Belt sander assembly

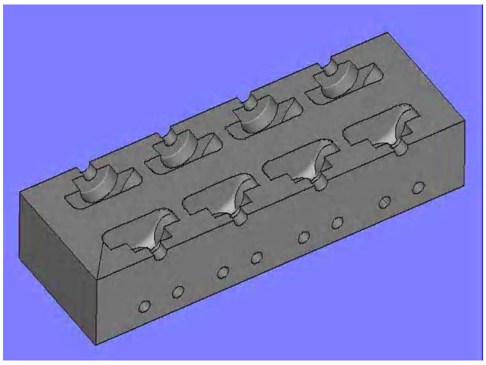


Figure 6.11 Design of the knob insert

Figure 6.12 LaserForm™ ST100 grown inserts

The combined top and bottom insert size was, X = 160 mm, Y = 55 mm and Z = 60 mm, in an eight cavity tool. The bolster, as shown in Figures 6.13 and 6.14, can be reused for other inserts in future projects.

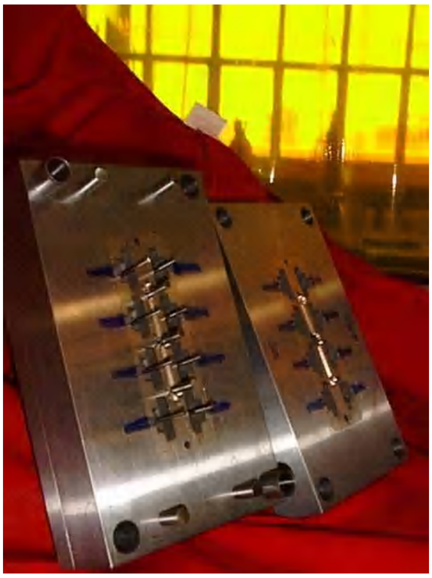


Figure 6.13 SLS grown inserts fitted into the steel bolster

Figure 6.14 Bolster fitted inside the injection moulder

Pockets/cavities were machined into the bolster as well as into the insert, to locate the screw threads, that were positioned in such a way that the plastic injected material would flow onto the screw threads to become the knobs. Screws with hexagon heads were inserted into the mould. The screws were kept in place with magnets. The plastic was then injected into the mould onto the hexagon head and the threaded knobs were ejected as seen from Figures 6.15 and 6.16.

Figure 6.15 First off tool samples

Figure 6.16 Injection moulded parts with screw threads

Some hand finishing inside the insert was necessary to ease the ejection of the parts, removing the stair step effect that was produced by the layered manufacturing of the SLS machine. The parts were produced on a 120 ton injection moulder, in ABS (Acrylonitrile Butadiene Styrene) material. The injection temperature, as seen from Table 6.4, was approximately 200˚C and the cycle-time was 80 seconds.

Table 6.4 The injection moulding settings

Injection temperature	200 ˚C
Cycle time	80 seconds
Cooling time	25 seconds
Holding pressure time	1 second

Summary

A total of 3500 parts were produced inside the inserts without any wear inside the tool. The project is continuing and more knobs will be produced.

<u>SLS Cost Analysis:</u>

Growing time on SLS machine	=	R 5508-00
Material cost – LaserForm™ ST 100 inserts (675 514 mm^3)	=	R 7158-00
Finishing of inserts	=	R 800-00
TOTAL	=	**R 13 466-00**

<u>SLS Growing Time Analysis:</u>

Growing time of two inserts on DTM 2000 machine	=	24 hours
Post processing time of inserts inside the oven cycle	=	24 hours
Finishing time	=	8 hours
TOTAL	**=**	**56 hours**

(± 3 days to complete because machine and oven cycle can run through the night)

Conventional Machining Cost Analysis:

CNC machining of inserts	=	R 14000-00
Material cost of inserts	=	R 200-00
Finishing of inserts	=	R 800-00
TOTAL	=	**R 15 000-00**

Conventional Machining Lead Time Analysis:

CNC machining of two inserts (include tool path generation)	=	36 hours
Finishing time	=	2 hours
TOTAL	**=**	**38 hours**

(± 4.75 days to complete if an 8 hour work day is taken)

Manufacturing the Bolster for this project (can be re-used for other inserts):

Bolster made for inserts – material + pins and bushes	=	R 8000-00
Time taken to machine bolster – (one person)	=	100 hours

When comparing the cost analysis of the SLS process to that of the conventional machining process, it is clear that the insert's geometry best suited the SLS process. The material cost of the SLS process accounted for 53% of the total costs associated with the insert and if the grown geometry can be optimised, the cost can be lowered. The lead-time of the SLS process was 56 hours, but keep in mind that the machines, as well as the oven cycle, can run through the night (3 days to manufacture) without any supervision. The 38 hours lead-time of the conventional machining will represent approximately 5 working days to manufacture the inserts. Some tool-making companies do not run their CNC machines without supervision for fear that a tool can break and damage the surface of the moulds that they produce. The 38 and 56 hour lead times are only attainable by using the bolster principle. The bolster principle refers to the manner in which a full injection moulding tool is produced with pins, bushes, ejector plate and the sprue in position. The insert sizes are machined into the mould whereafter the grown/machined inserts are bolted into these cavities. This bolster is then re-used for other projects where the insert sizes are similar. In this case study, the bolster principle saved approximately 100 hours which resulted in more or less a two and a half week shorter lead-time. The significance of the bolster principle is that once the mould is made, each similar project there after will enjoy the same benefit of saving two and a half weeks.

6.3 CASE STUDY 3: ALUMIDE® GROWN INSERTS

Technimark has successfully developed some pre-paid electricity meters. Based on their experience, they decided to tender for a new development aimed at the South American market. The tender-process required the submission of injection moulded parts with the tender documents, to prove they had the capacity to manufacture the product. Not knowing whether they would be successful in this tender, they decided to keep with standard commercially available or in-house parts, which meant they only had to introduce special jigs and fixtures to develop a new risk- free project. Figure 6.17 shows CAD images of both sides of the parts required. Part design was done taking into consideration the strength of the various growing processes. Shut-off was kept to a minimum. In areas where shut-off was required, the cross-sectional (surface) area was increased, which would not be the case if conventional tooling was used.

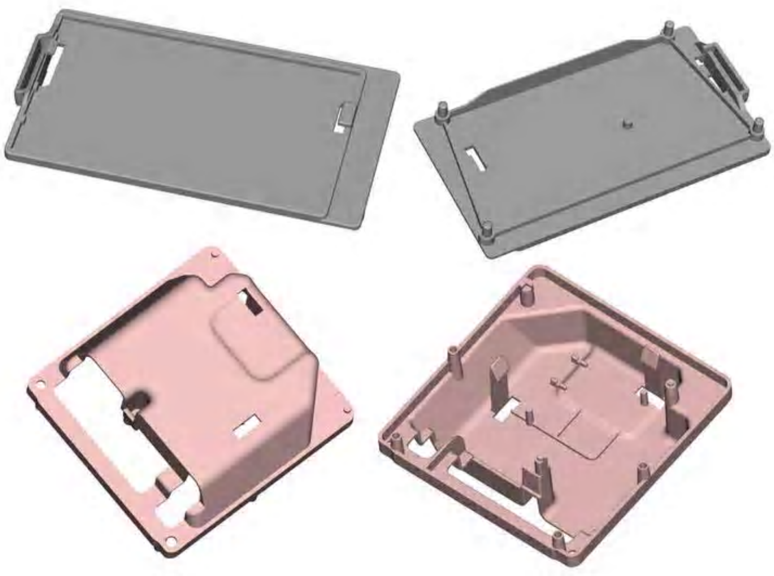


Figure 6.17 CAD images of the two required parts

The parts would, inter alia, be used to house electronic parts and PC boards. The challenge faced by the client was a huge one – four mould halves were needed, with less than four weeks available to manufacture – approximately one-third of the conventional time needed, conservatively estimated. Taking into account the nature of the development and the tender process, it was a major financial risk and a conservative budget was drawn up. The results, however, showed that the risks taken were worthwhile. Instead of complete moulds, only inserts were grown that fitted into bolsters. Both the grown mould inserts and the bolsters were designed without any provision for cooling. Four reference holes were grown as part of the mould insert to aid fitment of the inserts into the bolster, which ensured that the mould inserts would line up, and not result in a mould mismatch.

A machining allowance of 0,3mm was left on the split line and all shut-off areas on the mould in order to fit the inserts and to allow for growing tolerances. This eventually proved to be a difficult and time-consuming exercise. The growing accuracy was acceptable and the machining allowance on the grown inserts therefore was not necessary. Only basic mould finishing and polishing was done. The moulds flashed slightly and this had to be trimmed away. Only the rib areas were finished to aid mould release. The moulds required 23 hours of prototyping (one build volume), with four days of finishing and fitting. This meant that the injection-moulding could start in less than a week after finalizing the design. Figure 6.18 shows the moulds grown in Alumide®.

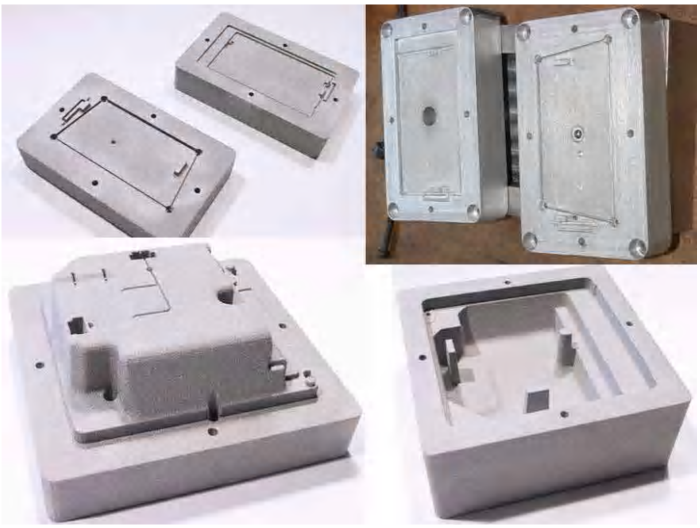


Figure 6.18 Mould tools grown in Alumide®

Approximate mould cost was R23 000, as opposed to R90 000 with conventional tooling (conservatively estimated). Figure 6.19 shows the first off-tool samples which were injection-moulded in the Alumide® tools, using the required engineering materials. As the parts fitted (snapped) together, the shrinkage was acceptable. The following injection-moulding settings were used on a 25 tonne machine:

- Clamping force: Full load of 25 tonnes
- Injection pressure:
    - 30Bar (1st Stage)
    - 20 Bar (2nd stage)
- Holding pressure: 20 Bar
- Cycle time four minutes.
- Cooling was done with compressed air through four air nozzles

- Mould release agent was spread between every mould cycle

[5]

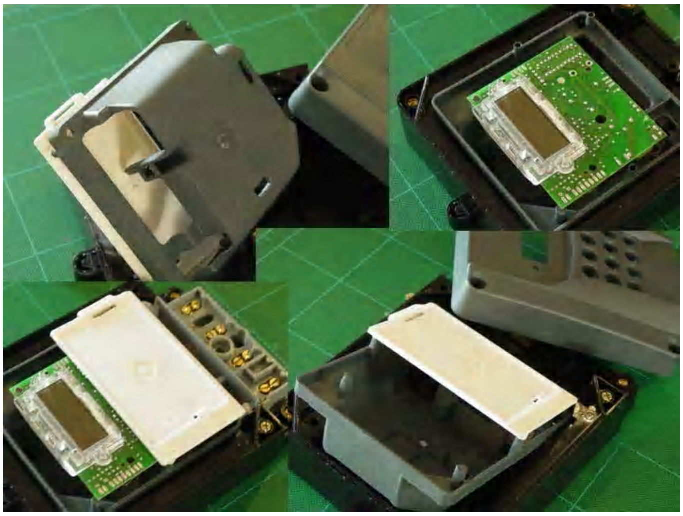


Figure 6.19 First-off-tool injection-moulded parts fitted with components

In Figure 6.20 the problem areas are enlarged, pointing out injection moulding problems. The intended features failed as the ratio between depth and cross-sectional area was too large. By having the injection moulded parts at hand, other moulded bosses could be used to fix the problem areas, by adding onto the existing parts without having to redesign the mould.

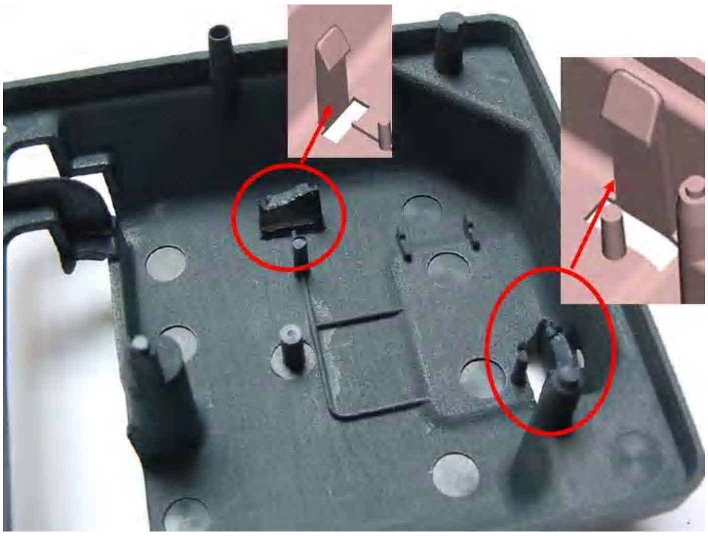


Figure 6.20 Injection moulding problem areas

Summary

- The company has done 30 trial samples in flame retardant ABS
- With further tests done, 850 samples were moulded – initially air-cooled
- No visible mould damage or wear
- Growing cost (incl material) of the inserts on the EOS P380 = R 23 000
- Growing time of the inserts on the EOS P380 = 23 hours
- Finishing and fitment time of the inserts = 4 days

[This case study was published in Assembly Automation Journal, Vol. 25 No.4, 2005, p. 306 - 308]

6.4 CASE STUDY 4: SHRINKAGE TEST OF GROWN INSERTS

In this case study, the aim was to test the shrinkages during injection moulding inside the grown inserts. The materials used to grow the inserts were LaserForm™ ST100, LaserForm™ A6 Tool Steel and Alumide®. These inserts were fitted into a steel bolster, which in turn, was fitted into a 90 ton injection moulder, as can be seen from Figures 6.21 and 6.22. An aluminium plate was inserted into the bolster on the opposite side to the grown inserts, as can be seen in Figure 6.23. The aluminium plate was kept on the fixed cavity and the three grown inserts were inserted into the moving cavity of the bolster. All the settings on the injection moulder were maintained during the growing of the abovementioned inserts. Polypropylene H02613 from DOW Plastic was injected into the mould to produce the test specimens, as can be seen from Figure 6.24. The injection moulded parts were removed by hand, because no provision was made for ejector pins through the grown inserts. The surface temperatures of the inserts were measured by a Raytek Raynger non-contact thermometer, just after the parts were removed from the cavity (after injection). The test specimens were marked and grouped into LaserForm™ ST100, LaserForm™ A6 Tool Steel and Alumide®.

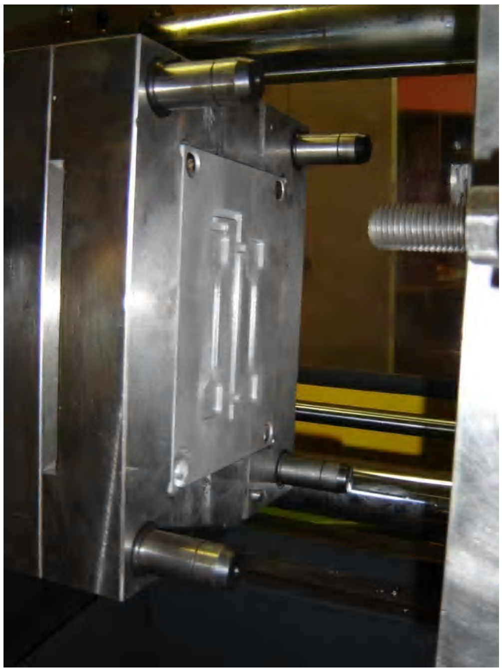


Figure 6.21 Empty bolster

Figure 6.22 Grown insert bolted into the bolster

Figure 6.23 Aluminium insert bolted opposite the grown insert

Figure 6.24 Injection moulded parts produced from tool

ALUMIDE® GROWN INSERT

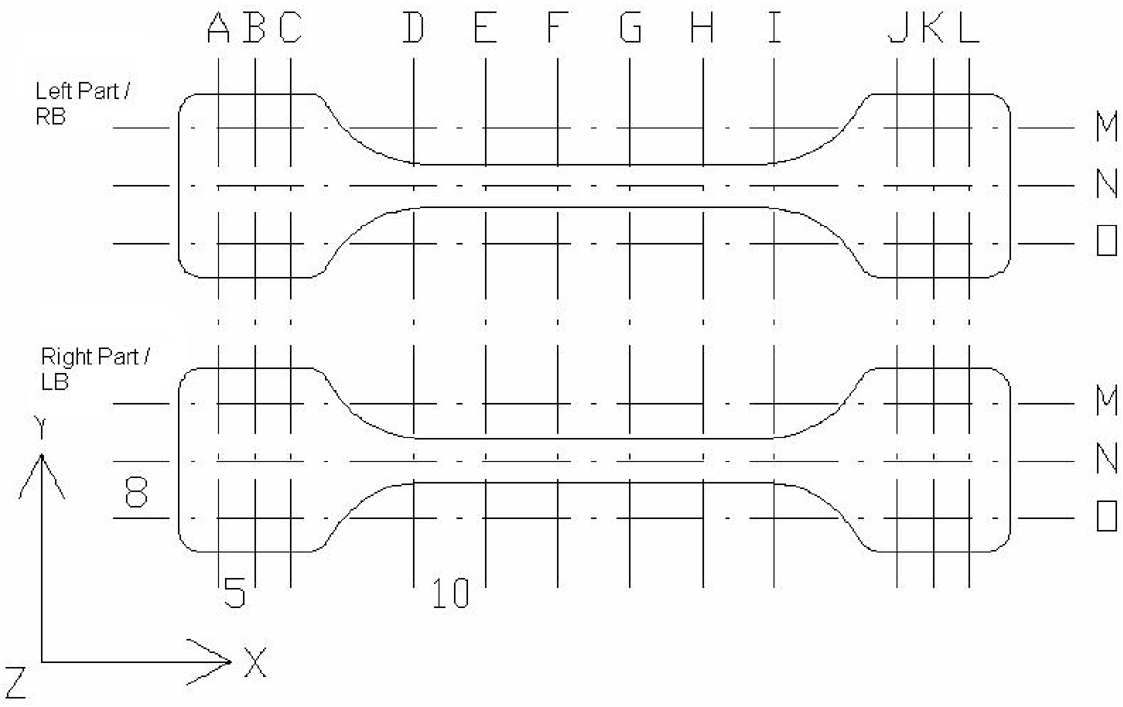


Figure 6.25 Schematic view of how the measurements were taken by the Renishaw scanner: Alumide®

After growing the Alumide® insert, the measurements A to O were taken, by using a Renishaw touch probe scanner, as shown in Figure 6.25. These measurements were taken in order to compare the actual grown dimensions with the design dimensions, as shown in Table 6.5 and 6.6. The deviation from the design dimensions is indicated in Table 6.7 and Table 6.8. In order to measure the parts produced during injection moulding, and draw a comparison between Alumide®, LaserForm™ A6 and LaserForm™ ST100, the inserts were CNC machined.

The added stock in the Z direction, as shown in Table 6.6, was taken off to ensure a good shut-off surface, whereafter the required depth (in Z direction) was machined into the insert.

After the insert was CNC machined, the A to O measurements were taken again, seen in Table 6.9, in order to compare them with the dimensions of the parts produced inside the cavity. Table 6.10 indicates the average readings of the dimensions of the CNC machined insert. This was used for ease of comparison between the dimensions of the injection moulded parts and the CNC machined insert. This is indicated in Tables 6.11 to 6.16. As can be seen from the results, the Alumide® produced insert showed good accuracy in the X and Y direction when compared to the design dimensions.

Table 6.5 CAD design dimensions of the insert

Section	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**
Left															
Y (mm)	25.4	25.4	25.4		6.3	6.3	6.3	6.3		25.4	25.4	25.4			
X (mm)													115	115	115
Z (mm)	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15			
Right															
Y (mm)	25.4	25.4	25.4		6.3	6.3	6.3	6.3		25.4	25.4	25.4			
X (mm)													115	115	115
Z (mm)	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15			

Table 6.6 Alumide® grown insert dimensions

Section	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**
Left															
Y (mm)	25.22	25.13	25.12		6.30	6.25	6.26	6.26		25.10	25.15	25.23			
X (mm)													114.99	114.89	114.92
Z (mm)	3.26	3.27	3.27	3.30	3.28	3.26	3.26	3.27	3.25	3.26	3.26	3.27			
Right															
Y (mm)	25.20	25.33	25.17		6.33	6.33	6.36	6.38		25.19	25.28	25.27			
X (mm)													114.95	114.86	114.92
Z (mm)	3.33	3.34	3.33	3.33	3.33	3.32	3.33	3.31	3.31	3.30	3.31	3.29			
In the design, 0.3 mm stock was extruded on the surface of the mould in the Z direction, to surface grind after growing															

Table 6.7 Design dimensions minus Alumide® grown insert dimensions in mm

Section	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Left															
Y (mm)	0.18	0.27	0.28		0.00	0.05	0.04	0.04		0.30	0.25	0.17			
X (mm)													0.01	0.11	0.08
Z (mm)	-0.11	-0.12	-0.12	-0.15	-0.13	-0.11	-0.11	-0.12	-0.10	-0.11	-0.11	-0.12			
Right															
Y (mm)	0.20	0.07	0.23		-0.03	-0.03	-0.06	-0.08		0.21	0.12	0.13			
X (mm)													0.05	0.14	0.08
Z (mm)	-0.18	-0.19	-0.18	-0.18	-0.18	-0.17	-0.18	-0.16	-0.16	-0.15	-0.16	-0.14			
In the design, 0.3 mm stock was extruded on the surface of the mould in the Z direction, to surface grind after growing															

Table 6.8 Design dimensions minus Alumide® grown insert dimensions in %

Section	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Left															
Y (%)	0.73	1.08	1.11		0.02	0.87	0.65	0.62		1.19	0.98	0.67			
X (%)													0.01	0.10	0.07
Z (%)	-3.62	-3.94	-3.68	-4.63	-4.19	-3.46	-3.59	-3.75	-3.27	-3.37	-3.56	-3.65			
Right															
Y (%)	0.77	0.28	0.90		-0.48	-0.46	-0.90	-1.30		0.82	0.46	0.51			
X (%)													0.04	0.12	0.07
Z (%)	-5.75	-5.94	-5.59	-5.68	-5.56	-5.43	-5.56	-5.17	-5.05	-4.86	-5.14	-4.57			
In the design, 0.3 mm stock was extruded on the surface of the mould in the Z direction, to surface grind after growing															

Table 6.9 CNC machined Alumide® grown insert dimensions

Section	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**
Left															
Y (mm)	25.39	25.39	25.39		6.36	6.35	6.37	6.37		25.38	25.38	25.39			
X (mm)													115.01	115.00	115.00
Z (mm)	3.13	3.13	3.12	3.09	3.08	3.08	3.08	3.09	3.09	3.13	3.15	3.15			
Right															
Y (mm)	25.81	25.83	25.82		6.79	6.79	6.77	6.79		25.78	25.79	25.80			
X (mm)													115.03	115.03	115.02
Z (mm)	3.21	3.20	3.19	3.15	3.14	3.12	3.12	3.12	3.12	3.14	3.14	3.14			

Table 6.10 CNC machined Alumide® grown insert average dimensions

Section	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**
Left															
Y (mm)	25.39				6.36					25.39					
X (mm)													115.00		
Z (mm)	3.11														
Right															
Y (mm)	25.82				6.79					25.79					
X (mm)													115.03		
Z (mm)	3.15														

Table 6.11 Shrinkage in mm of right parts

Number	**Reading J**	**Reading A**	**Reading E**	**Reading M**	**Reading Z**
Actual Dim	***25.79***	***25.82***	***6.79***	***115.03***	***3.15***
Right Part					
1.1	25.45	25.48	6.73	112.74	X
Deviation	*0.34*	*0.34*	*0.06*	*2.29*	X
1.2	25.32	25.41	6.75	112.7	3.11
Deviation	*0.47*	*0.41*	*0.04*	*2.33*	*0.04*
1.3	25.45	25.45	6.74	112.72	3.14
Deviation	*0.34*	*0.37*	*0.05*	*2.31*	*0.01*
1.4	25.47	25.44	6.74	112.69	3.13
Deviation	*0.32*	*0.38*	*0.05*	*2.34*	*0.02*
1.5	25.43	25.42	6.75	112.72	3.14
Deviation	*0.36*	*0.4*	*0.04*	*2.31*	*0.01*
1.6	25.42	25.45	6.76	112.74	3.14
Deviation	*0.37*	*0.37*	*0.03*	*2.29*	*0.01*
1.7	25.4	25.44	6.76	112.75	3.13
Deviation	*0.39*	*0.38*	*0.03*	*2.28*	*0.02*
1.8	25.4	25.39	6.77	112.7	3.1
Deviation	*0.39*	*0.43*	*0.02*	*2.33*	*0.05*
1.9	25.43	25.42	6.76	112.74	3.12
Deviation	*0.36*	*0.4*	*0.03*	*2.29*	*0.03*
2.0	25.41	25.38	6.76	112.71	3.12
Deviation	*0.38*	*0.44*	*0.03*	*2.32*	*0.03*
2.1	25.37	25.45	6.77	112.7	3.1
Deviation	*0.42*	*0.37*	*0.02*	*2.33*	*0.05*
2.2	25.4	25.46	6.77	112.75	3.1
Deviation	*0.39*	*0.36*	*0.02*	*2.28*	*0.05*
2.3	25.39	25.39	6.76	112.79	3.1
Deviation	*0.4*	*0.43*	*0.03*	*2.24*	*0.05*
2.4	25.39	25.4	6.78	112.73	3.11
Deviation	*0.4*	*0.42*	*0.01*	*2.3*	*0.04*
2.5	25.39	25.38	6.76	112.7	3.1
Deviation	*0.4*	*0.44*	*0.03*	*2.33*	*0.05*
2.6	25.35	25.39	6.76	112.79	3.1
Deviation	*0.44*	*0.43*	*0.03*	*2.24*	*0.05*
2.7	25.39	25.43	6.76	112.81	3.1
Deviation	*0.4*	*0.39*	*0.03*	*2.22*	*0.05*
2.8	25.38	25.42	6.77	112.83	3.09
Deviation	*0.41*	*0.4*	*0.02*	*2.2*	*0.06*
2.9	25.33	25.37	6.76	112.81	3.1
Deviation	*0.46*	*0.45*	*0.03*	*2.22*	*0.05*

Table 6.11 Continued

Number	Reading J	Reading A	Reading E	Reading M	Reading Z
Actual Dim	***25.79***	***25.82***	***6.79***	***115.03***	***3.15***
Right Part					
2.10	25.36	25.37	6.76	112.79	3.11
Deviation	*0.43*	*0.45*	*0.03*	*2.24*	*0.04*
2.11	25.36	25.42	6.77	112.81	3.08
Deviation	*0.43*	*0.4*	*0.02*	*2.22*	*0.07*
2.12	25.38	25.41	6.77	112.79	3.1
Deviation	*0.41*	*0.41*	*0.02*	*2.24*	*0.05*
2.13	25.34	25.42	6.77	112.78	3.1
Deviation	*0.45*	*0.4*	*0.02*	*2.25*	*0.05*
2.14	25.42	25.39	6.76	112.76	3.1
Deviation	*0.37*	*0.43*	*0.03*	*2.27*	*0.05*
2.15	25.4	25.38	6.77	112.81	3.1
Deviation	*0.39*	*0.44*	*0.02*	*2.22*	*0.05*
2.16	25.4	25.42	6.77	112.82	3.11
Deviation	*0.39*	*0.4*	*0.02*	*2.21*	*0.04*

Table 6.12 Shrinkage in % of right parts

Number	Reading J	Reading A	Reading E	Reading M	Reading Z
Actual Dim	***25.79***	***25.82***	***6.79***	***115.03***	***3.15***
Right Part					
1.1	25.45	25.48	6.73	112.74	X
Deviation %	*1.32*	*1.32*	*0.88*	*1.99*	X
1.2	25.32	25.41	6.75	112.7	3.11
Deviation %	*1.82*	*1.59*	*0.59*	*2.03*	*1.27*
1.3	25.45	25.45	6.74	112.72	3.14
Deviation %	*1.32*	*1.43*	*0.74*	*2.01*	*0.32*
1.4	25.47	25.44	6.74	112.69	3.13
Deviation %	*1.24*	*1.47*	*0.74*	*2.03*	*0.63*
1.5	25.43	25.42	6.75	112.72	3.14
Deviation %	*1.40*	*1.55*	*0.59*	*2.01*	*0.32*
1.6	25.42	25.45	6.76	112.74	3.14
Deviation %	*1.43*	*1.43*	*0.44*	*1.99*	*0.32*
1.7	25.4	25.44	6.76	112.75	3.13
Deviation %	*1.51*	*1.47*	*0.44*	*1.98*	*0.63*

Table 6.12 Continued

Number	Reading J	Reading A	Reading E	Reading M	Reading Z
Actual Dim	***25.79***	***25.82***	***6.79***	***115.03***	***3.15***
Right Part					
1.8	25.4	25.39	6.77	112.7	3.1
Deviation %	*1.51*	*1.67*	*0.29*	*2.03*	*1.59*
1.9	25.43	25.42	6.76	112.74	3.12
Deviation %	*1.40*	*1.55*	*0.44*	*1.99*	*0.95*
2.0	25.41	25.38	6.76	112.71	3.12
Deviation %	*1.47*	*1.70*	*0.44*	*2.02*	*0.95*
2.1	25.37	25.45	6.77	112.7	3.1
Deviation %	*1.63*	*1.43*	*0.29*	*2.03*	*1.59*
2.2	25.4	25.46	6.77	112.75	3.1
Deviation %	*1.51*	*1.39*	*0.29*	*1.98*	*1.59*
2.3	25.39	25.39	6.76	112.79	3.1
Deviation %	*1.55*	*1.67*	*0.44*	*1.95*	*1.59*
2.4	25.39	25.4	6.78	112.73	3.11
Deviation %	*1.55*	*1.63*	*0.15*	*2.00*	*1.27*
2.5	25.39	25.38	6.76	112.7	3.1
Deviation %	*1.55*	*1.70*	*0.44*	*2.03*	*1.59*
2.6	25.35	25.39	6.76	112.79	3.1
Deviation %	*1.71*	*1.67*	*0.44*	*1.95*	*1.59*
2.7	25.39	25.43	6.76	112.81	3.1
Deviation %	*1.55*	*1.51*	*0.44*	*1.93*	*1.59*
2.8	25.38	25.42	6.77	112.83	3.09
Deviation %	*1.59*	*1.55*	*0.29*	*1.91*	*1.90*
2.9	25.33	25.37	6.76	112.81	3.1
Deviation %	*1.78*	*1.74*	*0.44*	*1.93*	*1.59*
2.10	25.36	25.37	6.76	112.79	3.11
Deviation %	*1.67*	*1.74*	*0.44*	*1.95*	*1.27*
2.11	25.36	25.42	6.77	112.81	3.08
Deviation %	*1.67*	*1.55*	*0.29*	*1.93*	*2.22*
2.12	25.38	25.41	6.77	112.79	3.1
Deviation %	*1.59*	*1.59*	*0.29*	*1.95*	*1.59*
2.13	25.34	25.42	6.77	112.78	3.1
Deviation %	*1.74*	*1.55*	*0.29*	*1.96*	*1.59*
2.14	25.42	25.39	6.76	112.76	3.1
Deviation %	*1.43*	*1.67*	*0.44*	*1.97*	*1.59*
2.15	25.4	25.38	6.77	112.81	3.1
Deviation %	*1.51*	*1.70*	*0.29*	*1.93*	*1.59*
2.16	25.4	25.42	6.77	112.82	3.11
Deviation %	*1.51*	*1.55*	*0.29*	*1.92*	*1.27*

Table 6.13 Deviation in % of right parts

1.1 Deviation	1.32	1.32	0.88	1.99	X
1.2 Deviation	1.82	1.59	0.59	2.03	1.27
1.3 Deviation	1.32	1.43	0.74	2.01	0.32
1.4 Deviation	1.24	1.47	0.74	2.03	0.63
1.5 Deviation	1.40	1.55	0.59	2.01	0.32
1.6 Deviation	1.43	1.43	0.44	1.99	0.32
1.7 Deviation	1.51	1.47	0.44	1.98	0.63
1.8 Deviation	1.51	1.67	0.29	2.03	1.59
1.9 Deviation	1.40	1.55	0.44	1.99	0.95
2.0 Deviation	1.47	1.70	0.44	2.02	0.95
2.1 Deviation	1.63	1.43	0.29	2.03	1.59
2.2 Deviation	1.51	1.39	0.29	1.98	1.59
2.3 Deviation	1.55	1.67	0.44	1.95	1.59
2.4 Deviation	1.55	1.63	0.15	2.00	1.27
2.5 Deviation	1.55	1.70	0.44	2.03	1.59
2.6 Deviation	1.71	1.67	0.44	1.95	1.59
2.7 Deviation	1.55	1.51	0.44	1.93	1.59
2.8 Deviation	1.59	1.55	0.29	1.91	1.90
2.9 Deviation	1.78	1.74	0.44	1.93	1.59
2.10 Deviation	1.67	1.74	0.44	1.95	1.27
2.11 Deviation	1.67	1.55	0.29	1.93	2.22
2.12 Deviation	1.59	1.59	0.29	1.95	1.59
2.13 Deviation	1.74	1.55	0.29	1.96	1.59
2.14 Deviation	1.43	1.67	0.44	1.97	1.59
2.15 Deviation	1.51	1.70	0.29	1.93	1.59
2.16 Deviation	1.51	1.55	0.29	1.92	1.27
Average %	**1.54**	**1.57**	**0.43**	**1.98**	**1.30**

Table 6.14 Shrinkage in mm of left parts

Number	Reading J	Reading A	Reading E	Reading M	Reading Z
Actual Dim	***25.39***	***25.39***	***6.36***	***115.03***	***3.11***
Left Part					
1.1	25.04	24.97	6.3	112.77	X
Deviation	*0.35*	*0.42*	*0.06*	*2.26*	X
1.2	24.94	24.93	6.33	112.67	X
Deviation	*0.45*	*0.46*	*0.03*	*2.36*	X
1.3	25.01	24.97	6.32	112.68	X
Deviation	*0.38*	*0.42*	*0.04*	*2.35*	X
1.4	25.02	24.96	6.33	112.73	X
Deviation	*0.37*	*0.43*	*0.03*	*2.3*	X
1.5	25	24.95	6.33	112.75	X
Deviation	*0.39*	*0.44*	*0.03*	*2.28*	X
1.6	25.03	24.98	6.33	112.67	X
Deviation	*0.36*	*0.41*	*0.03*	*2.36*	X
1.7	25.03	24.98	6.34	112.69	X
Deviation	*0.36*	*0.41*	*0.02*	*2.34*	X
1.8	24.99	24.93	6.32	X	3.1
Deviation	*0.4*	*0.46*	*0.04*	X	*0.01*
1.9	25.01	24.93	6.33	112.72	3.11
Deviation	*0.38*	*0.46*	*0.03*	*2.31*	*0*
2.0	24.93	24.96	6.33	112.69	3.11
Deviation	*0.46*	*0.43*	*0.03*	*2.34*	*0*
2.1	24.95	24.91	6.32	X	3.1
Deviation	*0.44*	*0.48*	*0.04*	X	*0.01*
2.2	24.99	24.96	6.32	X	3.09
Deviation	*0.4*	*0.43*	*0.04*	X	*0.02*
2.3	24.93	24.99	6.32	112.71	3.1
Deviation	*0.46*	*0.4*	*0.04*	*2.32*	*0.01*
2.4	24.97	24.98	6.32	112.73	3.11
Deviation	*0.42*	*0.41*	*0.04*	*2.3*	*0*
2.5	24.96	24.94	6.33	112.71	3.11
Deviation	*0.43*	*0.45*	*0.03*	*2.32*	*0*
2.6	24.93	24.99	6.33	112.7	3.11
Deviation	*0.46*	*0.4*	*0.03*	*2.33*	*0*
2.7	24.98	24.98	6.32	112.69	3.11
Deviation	*0.41*	*0.41*	*0.04*	*2.34*	*0*
2.8	24.99	24.98	6.33	112.74	3.11
Deviation	*0.4*	*0.41*	*0.03*	*2.29*	*0*
2.9	24.97	24.96	6.33	112.75	3.11
Deviation	*0.42*	*0.43*	*0.03*	*2.28*	*0*

Table 6.14 Continued

Number	Reading J	Reading A	Reading E	Reading M	Reading Z
Actual Dim	***25.39***	***25.39***	***6.36***	***115.03***	***3.11***
Left Part					
2.10	24.99	25.03	6.32	112.69	3.11
Deviation	*0.4*	*0.36*	*0.04*	*2.34*	*0*
2.11	24.98	24.95	6.33	X	3.1
Deviation	*0.41*	*0.44*	*0.03*	X	*0.01*
2.12	25.01	25	6.33	112.73	3.11
Deviation	*0.38*	*0.39*	*0.03*	*2.3*	*0*
2.13	24.98	24.99	6.31	112.7	3.1
Deviation	*0.41*	*0.4*	*0.05*	*2.33*	*0.01*
2.14	24.97	24.99	6.32	112.72	3.11
Deviation	*0.42*	*0.4*	*0.04*	*2.31*	*0*
2.15	24.97	25.02	6.33	112.75	3.1
Deviation	*0.42*	*0.37*	*0.03*	*2.28*	*0.01*
2.16	24.98	25	6.33	112.76	3.1
Deviation	*0.41*	*0.39*	*0.03*	*2.27*	*0.01*

Table 6.15 Shrinkage in % of left parts

Number	Reading J	Reading A	Reading E	Reading M	Reading Z
Actual Dim	***25.39***	***25.39***	***6.36***	***115.03***	***3.11***
Left Part					
1.1	25.04	24.97	6.3	112.77	X
Deviation %	*1.38*	*1.65*	*0.94*	*1.96*	X
1.2	24.94	24.93	6.33	112.67	X
Deviation %	*1.77*	*1.81*	*0.47*	*2.05*	X
1.3	25.01	24.97	6.32	112.68	X
Deviation %	*1.50*	*1.65*	*0.63*	*2.04*	X
1.4	25.02	24.96	6.33	112.73	X
Deviation %	*1.46*	*1.69*	*0.47*	*2.00*	X
1.5	25	24.95	6.33	112.75	X
Deviation %	*1.54*	*1.73*	*0.47*	*1.98*	X
1.6	25.03	24.98	6.33	112.67	X
Deviation %	*1.42*	*1.61*	*0.47*	*2.05*	X
1.7	25.03	24.98	6.34	112.69	X
Deviation %	*1.42*	*1.61*	*0.31*	*2.03*	X

Table 6.15 Continued

Number	Reading J	Reading A	Reading E	Reading M	Reading Z
Actual Dim	***25.39***	***25.39***	***6.36***	***115.03***	***3.11***
Left Part					
1.8	24.99	24.93	6.32	X	3.10
Deviation %	*1.58*	*1.81*	*0.63*	X	*0.32*
1.9	25.01	24.93	6.33	112.72	3.11
Deviation %	*1.50*	*1.81*	*0.47*	*2.01*	*0.00*
2.0	24.93	24.96	6.33	112.69	3.11
Deviation %	*1.81*	*1.69*	*0.47*	*2.03*	*0.00*
2.1	24.95	24.91	6.32	X	3.1
Deviation %	*1.73*	*1.89*	*0.63*	X	*0.32*
2.2	24.99	24.96	6.32	X	3.09
Deviation %	*1.58*	*1.69*	*0.63*	X	*0.64*
2.3	24.93	24.99	6.32	112.71	3.1
Deviation %	*1.81*	*1.58*	*0.63*	*2.02*	*0.32*
2.4	24.97	24.98	6.32	112.73	3.11
Deviation %	*1.65*	*1.61*	*0.63*	*2.00*	*0.00*
2.5	24.96	24.94	6.33	112.71	3.11
Deviation %	*1.69*	*1.77*	*0.47*	*2.02*	*0.00*
2.6	24.93	24.99	6.33	112.7	3.11
Deviation %	*1.81*	*1.58*	*0.47*	*2.03*	*0.00*
2.7	24.98	24.98	6.32	112.69	3.11
Deviation %	*1.61*	*1.61*	*0.63*	*2.03*	*0.00*
2.8	24.99	24.98	6.33	112.74	3.11
Deviation %	*1.58*	*1.61*	*0.47*	*1.99*	*0.00*
2.9	24.97	24.96	6.33	112.75	3.11
Deviation %	*1.65*	*1.69*	*0.47*	*1.98*	*0.00*
2.10	24.99	25.03	6.32	112.69	3.11
Deviation %	*1.58*	*1.42*	*0.63*	*2.03*	*0.00*
2.11	24.98	24.95	6.33	X	3.1
Deviation %	*1.61*	*1.73*	*0.47*	X	*0.32*
2.12	25.01	25	6.33	112.73	3.11
Deviation %	*1.50*	*1.54*	*0.47*	*2.00*	*0.00*
2.13	24.98	24.99	6.31	112.7	3.1
Deviation %	*1.61*	*1.58*	*0.79*	*2.03*	*0.32*
2.14	24.97	24.99	6.32	112.72	3.11
Deviation %	*1.65*	*1.58*	*0.63*	*2.01*	*0.00*
2.15	24.97	25.02	6.33	112.75	3.1
Deviation %	*1.65*	*1.46*	*0.47*	*1.98*	*0.32*
2.16	24.98	25	6.33	112.76	3.1
Deviation %	*1.61*	*1.54*	*0.47*	*1.97*	*0.32*

Table 6.16 Deviation in % of left parts

1.1 Deviation	1.38	1.65	0.94	1.96	X
1.2 Deviation	1.77	1.81	0.47	2.05	X
1.3 Deviation	1.50	1.65	0.63	2.04	X
1.4 Deviation	1.46	1.69	0.47	2.00	X
1.5 Deviation	1.54	1.73	0.47	1.98	X
1.6 Deviation	1.42	1.61	0.47	2.05	X
1.7 Deviation	1.42	1.61	0.31	2.03	X
1.8 Deviation	1.58	1.81	0.63	X	0.32
1.9 Deviation	1.50	1.81	0.47	2.01	0.00
2.0 Deviation	1.81	1.69	0.47	2.03	0.00
2.1 Deviation	1.73	1.89	0.63	X	0.32
2.2 Deviation	1.58	1.69	0.63	X	0.64
2.3 Deviation	1.81	1.58	0.63	2.02	0.32
2.4 Deviation	1.65	1.61	0.63	2.00	0.00
2.5 Deviation	1.69	1.77	0.47	2.02	0.00
2.6 Deviation	1.81	1.58	0.47	2.03	0.00
2.7 Deviation	1.61	1.61	0.63	2.03	0.00
2.8 Deviation	1.58	1.61	0.47	1.99	0.00
2.9 Deviation	1.65	1.69	0.47	1.98	0.00
2.10 Deviation	1.58	1.42	0.63	2.03	0.00
2.11 Deviation	1.61	1.73	0.47	X	0.32
2.12 Deviation	1.50	1.54	0.47	2.00	0.00
2.13 Deviation	1.61	1.58	0.79	2.03	0.32
2.14 Deviation	1.65	1.58	0.63	2.01	0.00
2.15 Deviation	1.65	1.46	0.47	1.98	0.32
2.16 Deviation	1.61	1.54	0.47	1.97	0.32
Average %	**1.60**	**1.65**	**0.55**	**2.01**	**0.15**

LASERFORM™ ST 100 GROWN INSERT

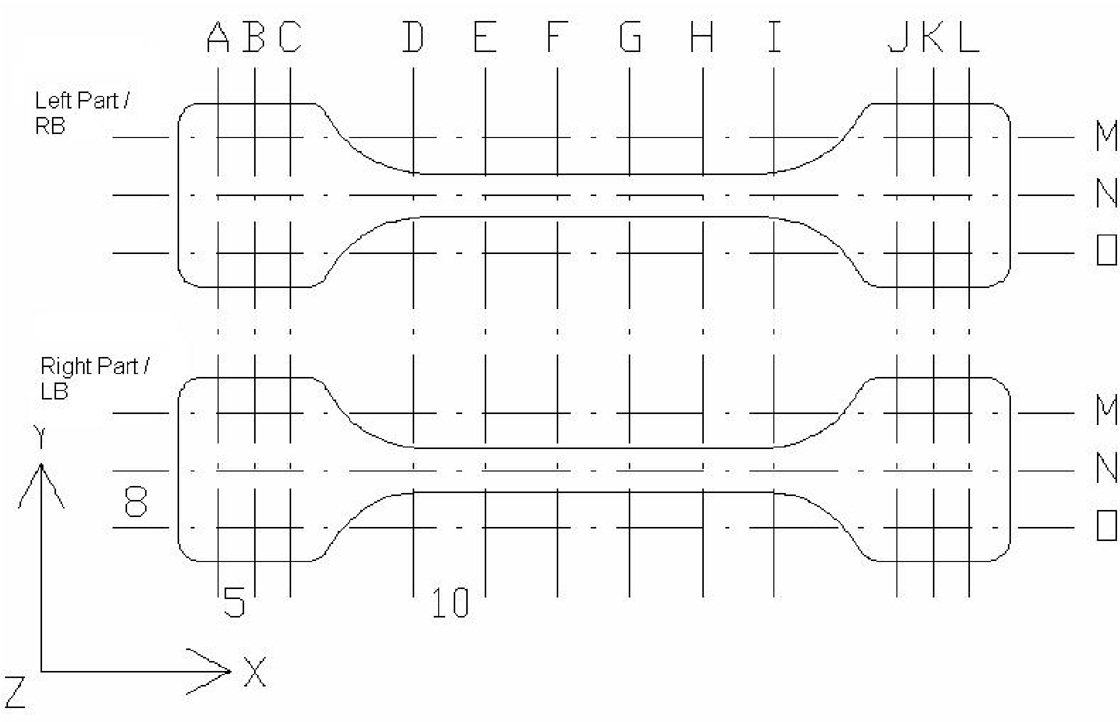


Figure 6.26 Schematic view of how the measurements were taken by the Renishaw scanner: LaserForm™ ST100

Similar to the procedure followed with the Alumide®, as described on p.106, an insert was grown in LaserForm™ ST100. Again, as described before, the measurements A to O were taken, by using a Renishaw touch probe scanner, as shown in Figure 6.26. The actual grown dimensions and the design dimensions are shown in Table 6.18 and 6.19. The deviation from the design dimensions is indicated in Table 6.20 and 6.21. In order to measure the parts produced during injection moulding, and draw a comparison between Alumide®, LaserForm™ A6 and LaserForm™ ST100, the inserts were again CNC machined as before. The added stock in the Z direction, as shown in Table 6.19, was taken off to ensure a good shut-off surface, whereafter the required depth (in Z direction) was machined into the insert. After the inserts were CNC machined, the A to O measurements were taken again, seen in Table 6.22, in order to compare it with the dimensions of the parts produced inside the cavity. Table 6.23 indicates the average readings of the dimensions of the CNC machined insert. This was used for ease of comparison between the dimensions of the injection moulded parts and the CNC machined insert, as indicated in Table 6.24 to 6.29.

Infiltration Efficiency of the LaserForm™ ST100 Grown Insert

The following equations are used to determine the infiltration efficiency:

- Infiltration Efficiency = (Weight of infiltrated part/Weight of “green” part x 1.72) x 100 ***[E.1.]***
- (Weight of infiltrant) = (weight of part + weight of tabs) x 0.72 ***[E.2.]***

3D SYSTEMS (process developers) recommends that the infiltration efficiency of inserts has to be 95% or higher.

Table 6.17 Infiltration efficiency of the LaserForm™ ST100 grown insert

NAME	WEIGHT OF “GREEN” PART	WEIGHT OF TABS	WEIGHT OF BRONZE	WEIGHT OF INFILTRATED PART	INFILTRATION EFFICIENCY
LaserForm™ ST100	3365 grams	0	2423 grams	5711 grams	98.67%

Table 6.18 CAD design dimensions of the insert

Section	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**
Left															
Y (mm)	25.4	25.4	25.4		6.3	6.3	6.3	6.3		25.4	25.4	25.4			
X (mm)													115	115	115
Z (mm)	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15			
Right															
Y (mm)	25.4	25.4	25.4		6.3	6.3	6.3	6.3		25.4	25.4	25.4			
X (mm)													115	115	115
Z (mm)	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15			

Table 6.19 LaserForm™ ST100 grown insert dimensions

Section	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**
Left															
Y (mm)	25.05	25.06	25.06		6.08	6.09	6.09	6.07		25.04	25.06	24.98			
X (mm)													114.81	114.88	114.92
Z (mm)	3.55	3.55	3.57	3.57	3.57	3.55	3.58	3.58	3.58	3.61	3.59	3.60			
Right															
Y (mm)	25.10	25.13	25.14		6.10	6.10	6.10	6.11		25.05	25.10	25.11			
X (mm)													114.91	114.92	114.95
Z (mm)	3.60	3.60	3.61	3.63	3.66	3.65	3.66	3.67	3.65	3.65	3.62	3.63			
In the design, 0.5 mm stock was extruded on the surface of the mould in the Z direction, to surface grind after growing															

Table 6.20 Design dimensions minus LaserForm™ ST 100 grown insert dimensions in mm

Section	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Left															
Y (mm)	0.35	0.34	0.34		0.22	0.21	0.21	0.23		0.36	0.34	0.42			
X (mm)													0.19	0.12	0.08
Z (mm)	-0.40	-0.40	-0.42	-0.42	-0.42	-0.40	-0.43	-0.43	-0.43	-0.46	-0.44	-0.45			
Right															
Y (mm)	0.30	0.27	0.26		0.20	0.20	0.21	0.19		0.35	0.30	0.29			
X (mm)													0.09	0.08	0.05
Z (mm)	-0.45	-0.45	-0.46	-0.48	-0.51	-0.50	-0.51	-0.52	-0.50	-0.50	-0.47	-0.48			
In the design, 0.5 mm stock was extruded on the surface of the mould in the Z direction, to surface grind after growing															

Table 6.21 Design dimensions minus LaserForm™ ST100 grown insert dimensions in %

Section	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Left															
Y (%)	1.37	1.36	1.34		3.54	3.33	3.40	3.59		1.41	1.35	1.64			
X (%)													0.17	0.11	0.07
Z (%)	-12.60	-12.73	-13.17	-13.24	-13.37	-12.83	-13.71	-13.52	-13.68	-14.67	-14.06	-14.25			
Right															
Y (%)	1.17	1.08	1.04		3.22	3.22	3.25	2.95		1.38	1.19	1.13			
X (%)													0.08	0.07	0.04
Z (%)	-14.13	-14.19	-14.54	-15.24	-16.16	-15.78	-16.03	-16.35	-15.78	-15.84	-14.79	-15.11			
In the design, 0.5 mm stock was extruded on the surface of the mould in the Z direction, to surface grind after growing															

Table 6.22 CNC machined LaserForm™ ST100 grown insert dimensions

Section	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**
Left															
Y (mm)	25.39	25.42	25.41		6.48	6.52	6.56	6.62		25.69	25.73	25.68			
X (mm)													115.03	115.06	115.04
Z (mm)	3.56	3.59	3.59	3.60	3.60	3.60	3.60	3.60	3.60	3.59	3.59	3.59			
Right															
Y (mm)	25.68	25.69	25.66		6.57	6.54	6.52	6.50		25.40	25.41	25.41			
X (mm)													115.17	115.18	115.14
Z (mm)	3.55	3.55	3.55	3.55	3.55	3.55	3.55	3.55	3.55	3.55	3.55	3.55			

Table 6.23 CNC machined LaserForm™ ST100 grown insert average dimensions

Section	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**
Left															
Y (mm)	25.41				6.54					25.70					
X (mm)													115.05		
Z (mm)	3.59														
Right															
Y (mm)	25.67				6.53					25.41					
X (mm)													115.16		
Z (mm)	3.55														

Table 6.24 Shrinkage in mm of right parts

Number	Reading 1	Reading 2	Reading 3	Reading 4	Reading 5
Actual Dim	***25.41***	***25.67***	***6.53***	***115.16***	***3.55***
Right Part					
4.1	24.81	25.06	6.45	112.76	3.46
Deviation	*0.6*	*0.61*	*0.08*	*2.4*	*0.09*
4.2	24.83	25.07	6.45	112.79	3.48
Deviation	*0.58*	*0.6*	*0.08*	*2.37*	*0.07*
4.3	24.85	25.08	6.44	112.83	3.5
Deviation	*0.56*	*0.59*	*0.09*	*2.33*	*0.05*
4.4	24.85	25.09	6.46	112.87	3.5
Deviation	*0.56*	*0.58*	*0.07*	*2.29*	*0.05*
4.5	24.78	25.06	6.43	112.72	3.45
Deviation	*0.63*	*0.61*	*0.1*	*2.44*	*0.1*
4.6	24.83	25.07	6.44	112.71	3.47
Deviation	*0.58*	*0.6*	*0.09*	*2.45*	*0.08*
4.7	24.84	25.08	6.45	112.74	3.47
Deviation	*0.57*	*0.59*	*0.08*	*2.42*	*0.08*
4.8	24.78	25.06	6.42	112.70	3.47
Deviation	*0.63*	*0.61*	*0.11*	*2.46*	*0.08*
4.9	24.78	25.02	6.45	112.7	3.46
Deviation	*0.63*	*0.65*	*0.08*	*2.46*	*0.09*
4.10	24.77	25.05	6.43	112.71	3.47
Deviation	*0.64*	*0.62*	*0.1*	*2.45*	*0.08*
4.11	24.79	25.07	6.46	112.75	3.45
Deviation	*0.62*	*0.6*	*0.07*	*2.41*	*0.1*
4.12	24.75	25.03	6.45	112.74	3.45
Deviation	*0.66*	*0.64*	*0.08*	*2.42*	*0.1*
4.13	24.75	25.01	6.42	112.76	3.46
Deviation	*0.66*	*0.66*	*0.11*	*2.4*	*0.09*
4.14	24.77	25.06	6.44	112.7	3.45
Deviation	*0.64*	*0.61*	*0.09*	*2.46*	*0.1*
4.15	24.75	25.03	6.43	112.76	3.46
Deviation	*0.66*	*0.64*	*0.1*	*2.4*	*0.09*
4.16	24.78	25.03	6.45	112.7	3.44
Deviation	*0.63*	*0.64*	*0.08*	*2.46*	*0.11*
4.17	24.77	25.01	6.44	112.72	3.47
Deviation	*0.64*	*0.66*	*0.09*	*2.44*	*0.08*
4.18	24.77	25.03	6.43	112.74	3.46
Deviation	*0.64*	*0.64*	*0.1*	*2.42*	*0.09*
4.19	24.78	25.03	6.43	112.75	3.47
Deviation	*0.63*	*0.64*	*0.1*	*2.41*	*0.08*

Table 6.24 Continued

Number	**Reading 1**	**Reading 2**	**Reading 3**	**Reading 4**	**Reading 5**
Actual Dim	***25.41***	***25.67***	***6.53***	***115.16***	***3.55***
Right Part					
4.20	24.75	25.01	6.43	112.73	3.47
Deviation	*0.66*	*0.66*	*0.1*	*2.43*	*0.08*
4.21	24.77	25.03	6.44	112.73	3.47
Deviation	*0.64*	*0.64*	*0.09*	*2.43*	*0.08*
4.22	24.78	25.03	6.44	112.76	3.46
Deviation	*0.63*	*0.64*	*0.09*	*2.4*	*0.09*
4.23	24.74	25	6.43	112.72	3.47
Deviation	*0.67*	*0.67*	*0.1*	*2.44*	*0.08*
4.24	24.76	25.01	6.44	112.71	3.47
Deviation	*0.65*	*0.66*	*0.09*	*2.45*	*0.08*
4.25	24.76	25	6.44	112.7	3.48
Deviation	*0.65*	*0.67*	*0.09*	*2.46*	*0.07*
4.26	24.77	25	6.46	112.76	3.47
Deviation	*0.64*	*0.67*	*0.07*	*2.4*	*0.08*
4.27	24.77	25.05	6.43	X	3.5
Deviation	*0.64*	*0.62*	*0.1*	X	*0.05*
4.28	24.72	25.04	6.44	112.71	3.47
Deviation	*0.69*	*0.63*	*0.09*	*2.45*	*0.08*
4.29	24.75	25.02	6.45	112.74	3.45
Deviation	*0.66*	*0.65*	*0.08*	*2.42*	*0.1*
4.30	24.75	25.03	6.43	112.76	3.47
Deviation	*0.66*	*0.64*	*0.1*	*2.4*	*0.08*

Table 6.25 Shrinkage in % of right parts

Number	Reading 1	Reading 2	Reading 3	Reading 4	Reading 5
Actual Dim	***25.41***	***25.67***	***6.53***	***115.16***	***3.55***
Right Part					
4.1	24.81	25.06	6.45	112.76	3.46
Deviation %	*2.36*	*2.38*	*1.23*	*2.08*	*2.54*
4.2	24.83	25.07	6.45	112.79	3.48
Deviation %	*2.28*	*2.34*	*1.23*	*2.06*	*1.97*
4.3	24.85	25.08	6.44	112.83	3.5
Deviation %	*2.20*	*2.30*	*1.38*	*2.02*	*1.41*
4.4	24.85	25.09	6.46	112.87	3.5
Deviation %	*2.20*	*2.26*	*1.07*	*1.99*	*1.41*
4.5	24.78	25.06	6.43	112.72	3.45
Deviation %	*2.48*	*2.38*	*1.53*	*2.12*	*2.82*
4.6	24.83	25.07	6.44	112.71	3.47
Deviation %	*2.28*	*2.34*	*1.38*	*2.13*	*2.25*
4.7	24.84	25.08	6.45	112.74	3.47
Deviation %	*2.24*	*2.30*	*1.23*	*2.10*	*2.25*
4.8	24.78	25.06	6.42	112.70	3.47
Deviation %	*2.48*	*2.38*	*1.68*	*2.14*	*2.25*
4.9	24.78	25.02	6.45	112.7	3.46
Deviation %	*2.48*	*2.53*	*1.23*	*2.14*	*2.54*
4.10	24.77	25.05	6.43	112.71	3.47
Deviation %	*2.52*	*2.42*	*1.53*	*2.13*	*2.25*
4.11	24.79	25.07	6.46	112.75	3.45
Deviation %	*2.44*	*2.34*	*1.07*	*2.09*	*2.82*
4.12	24.75	25.03	6.45	112.74	3.45
Deviation %	*2.60*	*2.49*	*1.23*	*2.10*	*2.82*
4.13	24.75	25.01	6.42	112.76	3.46
Deviation %	*2.60*	*2.57*	*1.68*	*2.08*	*2.54*
4.14	24.77	25.06	6.44	112.7	3.45
Deviation %	*2.52*	*2.38*	*1.38*	*2.14*	*2.82*
4.15	24.75	25.03	6.43	112.76	3.46
Deviation %	*2.60*	*2.49*	*1.53*	*2.08*	*2.54*
4.16	24.78	25.03	6.45	112.7	3.44
Deviation %	*2.48*	*2.49*	*1.23*	*2.14*	*3.10*
4.17	24.77	25.01	6.44	112.72	3.47
Deviation %	*2.52*	*2.57*	*1.38*	*2.12*	*2.25*
4.18	24.77	25.03	6.43	112.74	3.46
Deviation %	*2.52*	*2.49*	*1.53*	*2.10*	*2.54*
4.19	24.78	25.03	6.43	112.75	3.47
Deviation %	*2.48*	*2.49*	*1.53*	*2.09*	*2.25*

Table 6.25 Continued

Number	Reading 1	Reading 2	Reading 3	Reading 4	Reading 5
Actual Dim	***25.41***	***25.67***	***6.53***	***115.16***	***3.55***
Right Part					
4.20	24.75	25.01	6.43	112.73	3.47
Deviation %	*2.60*	*2.57*	*1.53*	*2.11*	*2.25*
4.21	24.77	25.03	6.44	112.73	3.47
Deviation %	*2.52*	*2.49*	*1.38*	*2.11*	*2.25*
4.22	24.78	25.03	6.44	112.76	3.46
Deviation %	*2.48*	*2.49*	*1.38*	*2.08*	*2.54*
4.23	24.74	25	6.43	112.72	3.47
Deviation %	*2.64*	*2.61*	*1.53*	*2.12*	*2.25*
4.24	24.76	25.01	6.44	112.71	3.47
Deviation %	*2.56*	*2.57*	*1.38*	*2.13*	*2.25*
4.25	24.76	25	6.44	112.7	3.48
Deviation %	*2.56*	*2.61*	*1.38*	*2.14*	*1.97*
4.26	24.77	25	6.46	112.76	3.47
Deviation %	*2.52*	*2.61*	*1.07*	*2.08*	*2.25*
4.27	24.77	25.05	6.43	X	3.5
Deviation %	*2.52*	*2.42*	*1.53*	X	*1.41*
4.28	24.72	25.04	6.44	112.71	3.47
Deviation %	*2.72*	*2.45*	*1.38*	*2.13*	*2.25*
4.29	24.75	25.02	6.45	112.74	3.45
Deviation %	*2.60*	*2.53*	*1.23*	*2.10*	*2.82*
4.30	24.75	25.03	6.43	112.76	3.47
Deviation %	*2.60*	*2.49*	*1.53*	*2.08*	*2.25*

Table 6.26 Deviation in % of right parts

4.1 Deviation	2.36	2.38	1.23	2.08	2.54
4.2 Deviation	2.28	2.34	1.23	2.06	1.97
4.3 Deviation	2.20	2.30	1.38	2.02	1.41
4.4 Deviation	2.20	2.26	1.07	1.99	1.41
4.5 Deviation	2.48	2.38	1.53	2.12	2.82
4.6 Deviation	2.28	2.34	1.38	2.13	2.25
4.7 Deviation	2.24	2.30	1.23	2.10	2.25
4.8 Deviation	2.48	2.38	1.68	2.14	2.25
4.9 Deviation	2.48	2.53	1.23	2.14	2.54
4.10 Deviation	2.52	2.42	1.53	2.13	2.25
4.11 Deviation	2.44	2.34	1.07	2.09	2.82
4.12 Deviation	2.60	2.49	1.23	2.10	2.82
4.13 Deviation	2.60	2.57	1.68	2.08	2.54
4.14 Deviation	2.52	2.38	1.38	2.14	2.82
4.15 Deviation	2.60	2.49	1.53	2.08	2.54
4.16 Deviation	2.48	2.49	1.23	2.14	3.10
4.17 Deviation	2.52	2.57	1.38	2.12	2.25
4.18 Deviation	2.52	2.49	1.53	2.10	2.54
4.19 Deviation	2.48	2.49	1.53	2.09	2.25
4.20 Deviation	2.60	2.57	1.53	2.11	2.25
4.21 Deviation	2.52	2.49	1.38	2.11	2.25
4.22 Deviation	2.48	2.49	1.38	2.08	2.54
4.23 Deviation	2.64	2.61	1.53	2.12	2.25
4.24 Deviation	2.56	2.57	1.38	2.13	2.25
4.25 Deviation	2.56	2.61	1.38	2.14	1.97
4.26 Deviation	2.52	2.61	1.07	2.08	2.25
4.27 Deviation	2.52	2.42	1.53	X	1.41
4.28 Deviation	2.72	2.45	1.38	2.13	2.25
4.29 Deviation	2.60	2.53	1.23	2.10	2.82
4.30 Deviation	2.60	2.49	1.53	2.08	2.25
Average %	**2.49**	**2.46**	**1.38**	**2.10**	**2.33**

Table 6.27 Shrinkage in mm of left parts

Number	Reading 1	Reading 2	Reading 3	Reading 4	Reading 5
Actual Dim	***25.7***	***25.41***	***6.54***	***115.05***	***3.59***
Left Part					
4.1	25.18	24.83	6.48	112.71	3.54
Deviation	*0.52*	*0.58*	*0.06*	*2.34*	*0.05*
4.2	25.18	24.86	6.49	112.75	3.53
Deviation	*0.52*	*0.55*	*0.05*	*2.3*	*0.06*
4.3	25.18	24.87	6.49	112.87	3.53
Deviation	*0.52*	*0.54*	*0.05*	*2.18*	*0.06*
4.4	25.19	24.89	6.49	112.94	3.52
Deviation	*0.51*	*0.52*	*0.05*	*2.11*	*0.07*
4.5	25.1	24.83	6.49	X	3.53
Deviation	*0.6*	*0.58*	*0.05*	X	*0.06*
4.6	25.1	24.77	6.46	112.75	3.52
Deviation	*0.6*	*0.64*	*0.08*	*2.3*	*0.07*
4.7	25.11	24.8	6.49	112.77	3.51
Deviation	*0.59*	*0.61*	*0.05*	*2.28*	*0.08*
4.8	25.11	24.77	6.48	X	3.52
Deviation	*0.59*	*0.64*	*0.06*	X	*0.07*
4.9	25.07	24.78	6.46	X	3.52
Deviation	*0.63*	*0.63*	*0.08*	X	*0.07*
4.10	25.08	24.78	6.47	X	3.51
Deviation	*0.62*	*0.63*	*0.07*	X	*0.08*
4.11	25.07	24.78	6.49	X	3.53
Deviation	*0.63*	*0.63*	*0.05*	X	*0.06*
4.12	25.07	24.8	6.47	112.72	3.52
Deviation	*0.63*	*0.61*	*0.07*	*2.33*	*0.07*
4.13	25.09	24.79	6.47	112.7	3.52
Deviation	*0.61*	*0.62*	*0.07*	*2.35*	*0.07*
4.14	25.08	24.81	6.47	112.7	3.52
Deviation	*0.62*	*0.6*	*0.07*	*2.35*	*0.07*
4.15	25.09	24.83	6.48	112.71	3.53
Deviation	*0.61*	*0.58*	*0.06*	*2.34*	*0.06*
4.16	25.08	24.78	6.48	X	3.52
Deviation	*0.62*	*0.63*	*0.06*	X	*0.07*
4.17	25.07	24.78	6.47	112.72	3.54
Deviation	*0.63*	*0.63*	*0.07*	*2.33*	*0.05*
4.18	25.08	24.81	6.47	X	3.52
Deviation	*0.62*	*0.6*	*0.07*	X	*0.07*
4.19	25.07	24.8	6.47	X	3.51
Deviation	*0.63*	*0.61*	*0.07*	X	*0.08*

Table 6.27 Continued

Number	Reading 1	Reading 2	Reading 3	Reading 4	Reading 5
Actual Dim	***25.7***	***25.41***	***6.54***	***115.05***	***3.59***
Left Part					
4.20	25.06	24.79	6.46	112.7	3.53
Deviation	*0.64*	*0.62*	*0.08*	*2.35*	*0.06*
4.21	25.07	24.82	6.48	X	3.51
Deviation	*0.63*	*0.59*	*0.06*	X	*0.08*
4.22	25.1	24.81	6.49	112.72	3.53
Deviation	*0.6*	*0.6*	*0.05*	*2.33*	*0.06*
4.23	25.05	24.78	6.48	X	3.53
Deviation	*0.65*	*0.63*	*0.06*	X	*0.06*
4.24	25.07	24.83	6.49	X	3.51
Deviation	*0.63*	*0.58*	*0.05*	X	*0.08*
4.25	25.06	24.78	6.47	112.69	3.51
Deviation	*0.64*	*0.63*	*0.07*	*2.36*	*0.08*
4.26	25.1	24.77	6.48	112.75	3.53
Deviation	*0.6*	*0.64*	*0.06*	*2.3*	*0.06*
4.27	25.08	24.79	6.47	112.74	3.5
Deviation	*0.62*	*0.62*	*0.07*	*2.31*	*0.09*
4.28	25.07	24.81	6.48	X	3.53
Deviation	*0.63*	*0.6*	*0.06*	X	*0.06*
4.29	25.07	24.77	6.48	112.71	3.51
Deviation	*0.63*	*0.64*	*0.06*	*2.34*	*0.08*
4.30	25.08	24.76	6.47	112.73	3.52
Deviation	*0.62*	*0.65*	*0.07*	*2.32*	*0.07*

Table 6.28 Shrinkage in % of left parts

Number	Reading 1	Reading 2	Reading 3	Reading 4	Reading 5
Actual Dim	***25.7***	***25.41***	***6.54***	***115.05***	***3.59***
Left Part					
4.1	25.18	24.83	6.48	112.71	3.54
Deviation %	*2.02*	*2.28*	*0.92*	*2.03*	*1.39*
4.2	25.18	24.86	6.49	112.75	3.53
Deviation %	*2.02*	*2.16*	*0.76*	*2.00*	*1.67*
4.3	25.18	24.87	6.49	112.87	3.53
Deviation %	*2.02*	*2.13*	*0.76*	*1.89*	*1.67*
4.4	25.19	24.89	6.49	112.94	3.52
Deviation %	*1.98*	*2.05*	*0.76*	*1.83*	*1.95*
4.5	25.1	24.83	6.49	X	3.53
Deviation %	*2.33*	*2.28*	*0.76*	X	*1.67*
4.6	25.1	24.77	6.46	112.75	3.52
Deviation %	*2.33*	*2.52*	*1.22*	*2.00*	*1.95*
4.7	25.11	24.8	6.49	112.77	3.51
Deviation %	*2.30*	*2.40*	*0.76*	*1.98*	*2.23*
4.8	25.11	24.77	6.48	X	3.52
Deviation %	*2.30*	*2.52*	*0.92*	X	*1.95*
4.9	25.07	24.78	6.46	X	3.52
Deviation %	*2.45*	*2.48*	*1.22*	X	*1.95*
4.10	25.08	24.78	6.47	X	3.51
Deviation %	*2.41*	*2.48*	*1.07*	X	*2.23*
4.11	25.07	24.78	6.49	X	3.53
Deviation %	*2.45*	*2.48*	*0.76*	X	*1.67*
4.12	25.07	24.8	6.47	112.72	3.52
Deviation %	*2.45*	*2.40*	*1.07*	*2.03*	*1.95*
4.13	25.09	24.79	6.47	112.7	3.52
Deviation %	*2.37*	*2.44*	*1.07*	*2.04*	*1.95*
4.14	25.08	24.81	6.47	112.7	3.52
Deviation %	*2.41*	*2.36*	*1.07*	*2.04*	*1.95*
4.15	25.09	24.83	6.48	112.71	3.53
Deviation %	*2.37*	*2.28*	*0.92*	*2.03*	*1.67*
4.16	25.08	24.78	6.48	X	3.52
Deviation %	*2.41*	*2.48*	*0.92*	X	*1.95*
4.17	25.07	24.78	6.47	112.72	3.54
Deviation %	*2.45*	*2.48*	*1.07*	*2.03*	*1.39*
4.18	25.08	24.81	6.47	X	3.52
Deviation %	*2.41*	*2.36*	*1.07*	X	*1.95*
4.19	25.07	24.8	6.47	X	3.51
Deviation %	*2.45*	*2.40*	*1.07*	X	*2.23*

Table 6.28 Continued

Number	Reading 1	Reading 2	Reading 3	Reading 4	Reading 5
Actual Dim	***25.7***	***25.41***	***6.54***	***115.05***	***3.59***
Left Part					
4.20	25.06	24.79	6.46	112.7	3.53
Deviation %	*2.49*	*2.44*	*1.22*	*2.04*	*1.67*
4.21	25.07	24.82	6.48	X	3.51
Deviation %	*2.45*	*2.32*	*0.92*	X	*2.23*
4.22	25.1	24.81	6.49	112.72	3.53
Deviation %	*2.33*	*2.36*	*0.76*	*2.03*	*1.67*
4.23	25.05	24.78	6.48	X	3.53
Deviation %	*2.53*	*2.48*	*0.92*	X	*1.67*
4.24	25.07	24.83	6.49	X	3.51
Deviation %	*2.45*	*2.28*	*0.76*	X	*2.23*
4.25	25.06	24.78	6.47	112.69	3.51
Deviation %	*2.49*	*2.48*	*1.07*	*2.05*	*2.23*
4.26	25.1	24.77	6.48	112.75	3.53
Deviation %	*2.33*	*2.52*	*0.92*	*2.00*	*1.67*
4.27	25.08	24.79	6.47	112.74	3.5
Deviation %	*2.41*	*2.44*	*1.07*	*2.01*	*2.51*
4.28	25.07	24.81	6.48	X	3.53
Deviation %	*2.45*	*2.36*	*0.92*	X	*1.67*
4.29	25.07	24.77	6.48	112.71	3.51
Deviation %	*2.45*	*2.52*	*0.92*	*2.03*	*2.23*
4.30	25.08	24.76	6.47	112.73	3.52
Deviation %	*2.41*	*2.56*	*1.07*	*2.02*	*1.95*

Table 6.29 Deviation in % of left parts

4.1 Deviation	2.02	2.28	0.92	2.03	1.39
4.2 Deviation	2.02	2.16	0.76	2.00	1.67
4.3 Deviation	2.02	2.13	0.76	1.89	1.67
4.4 Deviation	1.98	2.05	0.76	1.83	1.95
4.5 Deviation	2.33	2.28	0.76	X	1.67
4.6 Deviation	2.33	2.52	1.22	2.00	1.95
4.7 Deviation	2.30	2.40	0.76	1.98	2.23
4.8 Deviation	2.30	2.52	0.92	X	1.95
4.9 Deviation	2.45	2.48	1.22	X	1.95
4.10 Deviation	2.41	2.48	1.07	X	2.23
4.11 Deviation	2.45	2.48	0.76	X	1.67
4.12 Deviation	2.45	2.40	1.07	2.03	1.95
4.13 Deviation	2.37	2.44	1.07	2.04	1.95
4.14 Deviation	2.41	2.36	1.07	2.04	1.95
4.15 Deviation	2.37	2.28	0.92	2.03	1.67
4.16 Deviation	2.41	2.48	0.92	X	1.95
4.17 Deviation	2.45	2.48	1.07	2.03	1.39
4.18 Deviation	2.41	2.36	1.07	X	1.95
4.19 Deviation	2.45	2.40	1.07	X	2.23
4.20 Deviation	2.49	2.44	1.22	2.04	1.67
4.21 Deviation	2.45	2.32	0.92	X	2.23
4.22 Deviation	2.33	2.36	0.76	2.03	1.67
4.23 Deviation	2.53	2.48	0.92	X	1.67
4.24 Deviation	2.45	2.28	0.76	X	2.23
4.25 Deviation	2.49	2.48	1.07	2.05	2.23
4.26 Deviation	2.33	2.52	0.92	2.00	1.67
4.27 Deviation	2.41	2.44	1.07	2.01	2.51
4.28 Deviation	2.45	2.36	0.92	X	1.67
4.29 Deviation	2.45	2.52	0.92	2.03	2.23
4.30 Deviation	2.41	2.56	1.07	2.02	1.95
Average %	**2.36**	**2.39**	**0.96**	**2.00**	**1.90**

LASERFORM™ A6 GROWN INSERT

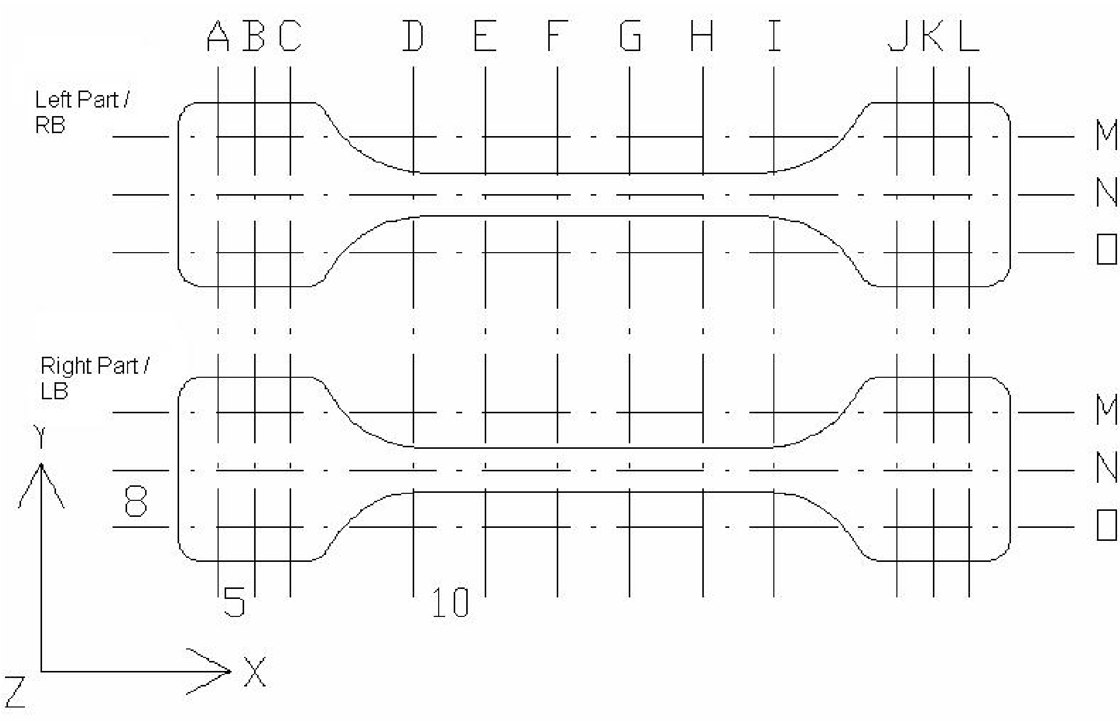


Figure 6.27 Schematic view of how the measurements were taken by the Renishaw scanner: LaserForm™ A6

The same procedure as mentioned on p.106 was followed for the LaserForm™ A6 grown insert. In other words, the A to O measurements were once again taken by using a Renishaw touch probe scanner, as shown in Figure 6.27. The actual grown dimensions and the design dimensions, are shown in Tables 6.31 and 6.32. The deviation from the design dimensions is indicated in Tables 6.33 and 6.34. In order to measure the parts produced during injection moulding, and draw a comparison between Alumide®, LaserForm™ A6 and LaserForm™ ST100, the inserts were again CNC machined as before. The insert was machined in the Z direction to ensure a good shut-off surface, whereafter the required depth (in Z direction) was machined into the insert. After the inserts were CNC machined, the A to O measurements were taken again, seen in Table 6.35, in order to compare them with the dimensions of the parts produced inside the cavity. Table 6.36 indicates the average readings of the CNC machined insert. This simplified the comparison between the dimensions of the injection moulded parts and the CNC machined insert. This is indicated in Tables 6.37 to 6.42.

Infiltration Efficiency of the LaserForm™ A6 Grown Insert

The following equations are used to determine the infiltration efficiency:

- Infiltration Efficiency = (Weight of infiltrated part / Weight of "green" part x 1.85) x 100 ***[E.3.]***
- (Weight of infiltrant) = (weight of part + weight of tabs) x 0.85 ***[E.4.]***

3D SYSTEMS (process developers) recommends that the infiltration efficiency of inserts has to be 95% or higher.

Table 6.30 Infiltration efficiency of the LaserForm™ A6 grown insert

NAME	**WEIGHT OF "GREEN" PART**	**WEIGHT OF TABS**	**WEIGHT OF BRONZE**	**WEIGHT OF INFILTRATED PART**	**INFILTRATION EFFICIENCY**
LaserForm™ A6	2761 grams	0	2347 grams	5005 grams	97.986%

Table 6.31 CAD design dimensions of the insert

Section	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Left															
Y (mm)	25.4	25.4	25.4		6.3	6.3	6.3	6.3		25.4	25.4	25.4			
X (mm)													115	115	115
Z (mm)	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15			
Right															
Y (mm)	25.4	25.4	25.4		6.3	6.3	6.3	6.3		25.4	25.4	25.4			
X (mm)													115	115	115
Z (mm)	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15			

Table 6.32 LaserForm™ A6 grown insert dimensions

Section	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Left															
Y (mm)	25.61	25.56	25.61		6.35	6.41	6.37	6.38		25.52	25.57	25.61			
X (mm)													116.55	116.66	116.65
Z (mm)	2.63	2.63	2.61	2.60	2.61	2.62	2.64	2.63	2.64	2.65	2.64	2.65			
Right															
Y (mm)	25.51	25.53	25.61		6.41	6.40	6.37	6.40		25.52	25.52	25.51			
X (mm)													116.65	116.72	117.68
Z (mm)	3.09	3.03	3.01	2.89	2.85	2.79	2.75	2.70	2.65	2.60	2.56	2.54			
In the design, 0 mm stock was extruded on the surface of the mould in the Z direction, to surface grind after growing															

Table 6.33 Design dimensions minus LaserForm™ A6 grown insert dimensions in mm

Section	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**
Left															
Y (mm)	-0.21	-0.16	-0.21		-0.05	-0.11	-0.07	-0.08		-0.12	-0.17	-0.21			
X (mm)													-1.55	-1.66	-1.65
Z (mm)	0.52	0.52	0.54	0.55	0.54	0.53	0.52	0.52	0.51	0.51	0.51	0.51			
Right															
Y (mm)	-0.11	-0.13	-0.21		-0.11	-0.10	-0.07	-0.10		-0.12	-0.12	-0.11			
X (mm)													-1.65	-1.72	-2.68
Z (mm)	0.06	0.12	0.14	0.26	0.30	0.36	0.40	0.45	0.50	0.55	0.59	0.61			
In the design, 0 mm stock was extruded on the surface of the mould in the Z direction, to surface grind after growing															

Table 6.34 Design dimensions minus LaserForm™ A6 grown insert dimensions in %

Section	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**
Left															
Y (%)	-0.83	-0.63	-0.82		-0.83	-1.71	-1.08	-1.24		-0.46	-0.65	-0.81			
X (%)													-1.35	-1.44	-1.43
Z (%)	16.48	16.60	17.21	17.40	17.17	16.79	16.35	16.48	16.25	16.03	16.22	16.03			
Right															
Y (%)	-0.44	-0.52	-0.83		-1.70	-1.52	-1.17	-1.52		-0.48	-0.46	-0.43			
X (%)													-1.43	-1.50	-2.33
Z (%)	1.78	3.78	4.44	8.13	9.56	11.37	12.67	14.35	15.90	17.40	18.86	19.43			
In the design, 0 mm stock was extruded on the surface of the mould in the Z direction, to surface grind after growing															

Table 6.35 CNC machined LaserForm™ A6 grown insert dimensions

Section	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Left															
Y (mm)	25.76	25.81	25.83		6.49	6.51	6.50	6.51		25.82	25.80	25.82			
X (mm)													116.57	116.67	116.66
Z (mm)	3.14	3.14	3.14	3.14	3.14	3.15	3.15	3.15	3.15	3.16	3.16	3.17			
Right															
Y (mm)	25.82	25.85	25.85		6.64	6.66	6.67	6.66		25.88	25.85	25.75			
X (mm)													116.70	116.75	116.69
Z (mm)	3.15	3.14	3.14	3.14	3.14	3.15	3.15	3.15	3.16	3.16	3.16	3.18			

Table 6.36 CNC machined LaserForm™ A6 grown insert average dimensions

Section	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Left															
Y (mm)	25.80				6.50					25.81					
X (mm)													116.64		
Z (mm)	3.15														
Right															
Y (mm)	25.84				6.66					25.83					
X (mm)													116.71		
Z (mm)	3.15														

Table 6.37 Shrinkage in mm of right parts

Number	Reading 1	Reading 2	Reading 3	Reading 4	Reading 5
Actual Dim	***25.83***	***25.84***	***6.66***	***116.71***	***3.15***
Right Part					
6.1	25.41	25.49	6.51	114.78	3.1
Deviation	*0.42*	*0.35*	*0.15*	*1.93*	*0.05*
6.2	25.39	25.41	6.58	114.71	3.1
Deviation	*0.44*	*0.43*	*0.08*	*2*	*0.05*
6.3	25.43	25.48	6.57	114.75	3.09
Deviation	*0.4*	*0.36*	*0.09*	*1.96*	*0.06*
6.4	25.44	25.48	6.59	114.79	3.1
Deviation	*0.39*	*0.36*	*0.07*	*1.92*	*0.05*
6.5	25.43	25.46	6.59	114.7	3.07
Deviation	*0.4*	*0.38*	*0.07*	*2.01*	*0.08*
6.6	25.42	25.5	6.58	114.76	3.09
Deviation	*0.41*	*0.34*	*0.08*	*1.95*	*0.06*
6.7	25.49	25.42	6.58	114.73	3.11
Deviation	*0.34*	*0.42*	*0.08*	*1.98*	*0.04*
6.8	25.49	25.45	6.59	114.84	3.08
Deviation	*0.34*	*0.39*	*0.07*	*1.87*	*0.07*
6.9	25.43	25.47	6.58	114.72	3.1
Deviation	*0.4*	*0.37*	*0.08*	*1.99*	*0.05*
6.10	25.48	25.45	6.59	114.76	3.09
Deviation	*0.35*	*0.39*	*0.07*	*1.95*	*0.06*
6.11	25.44	25.43	6.58	114.67	3.1
Deviation	*0.39*	*0.41*	*0.08*	*2.04*	*0.05*
6.12	25.48	25.46	6.59	114.73	3.1
Deviation	*0.35*	*0.38*	*0.07*	*1.98*	*0.05*
6.13	25.44	25.46	6.57	114.86	3.09
Deviation	*0.39*	*0.38*	*0.09*	*1.85*	*0.06*
6.14	25.4	25.47	6.58	114.86	3.09
Deviation	*0.43*	*0.37*	*0.08*	*1.85*	*0.06*
6.15	25.48	25.5	6.59	114.75	3.11
Deviation	*0.35*	*0.34*	*0.07*	*1.96*	*0.04*
6.16	25.45	25.5	6.59	114.81	3.11
Deviation	*0.38*	*0.34*	*0.07*	*1.9*	*0.04*
6.17	25.42	25.49	6.59	114.78	3.09
Deviation	*0.41*	*0.35*	*0.07*	*1.93*	*0.06*
6.18	25.48	25.43	6.59	114.83	3.1
Deviation	*0.35*	*0.41*	*0.07*	*1.88*	*0.05*
6.19	25.49	25.42	6.58	114.84	3.1
Deviation	*0.34*	*0.42*	*0.08*	*1.87*	*0.05*

Table 6.37 Continued

Number	Reading 1	Reading 2	Reading 3	Reading 4	Reading 5
Actual Dim	***25.83***	***25.84***	***6.66***	***116.71***	***3.15***
Right Part					
6.20	25.46	25.43	6.57	114.8	3.09
Deviation	*0.37*	*0.41*	*0.09*	*1.91*	*0.06*
6.21	25.47	25.42	6.58	114.87	3.1
Deviation	*0.36*	*0.42*	*0.08*	*1.84*	*0.05*
6.22	25.5	25.45	6.57	114.95	3.09
Deviation	*0.33*	*0.39*	*0.09*	*1.76*	*0.06*
6.23	25.47	25.1	6.59	114.89	3.1
Deviation	*0.36*	*0.74*	*0.07*	*1.82*	*0.05*
6.24	25.46	25.42	6.59	114.98	3.11
Deviation	*0.37*	*0.42*	*0.07*	*1.73*	*0.04*
6.25	25.48	25.43	6.58	114.99	3.1
Deviation	*0.35*	*0.41*	*0.08*	*1.72*	*0.05*
6.26	25.41	25.43	6.56	114.86	3.08
Deviation	*0.42*	*0.41*	*0.1*	*1.85*	*0.07*
6.27	25.46	25.42	6.58	114.86	3.1
Deviation	*0.37*	*0.42*	*0.08*	*1.85*	*0.05*
6.28	25.42	25.47	6.57	114.83	3.1
Deviation	*0.41*	*0.37*	*0.09*	*1.88*	*0.05*
6.29	25.46	25.42	6.58	114.88	3.1
Deviation	*0.37*	*0.42*	*0.08*	*1.83*	*0.05*
6.30	25.46	25.48	6.58	114.9	3.1
Deviation	*0.37*	*0.36*	*0.08*	*1.81*	*0.05*
6.31	25.45	25.44	6.57	114.88	3.09
Deviation	*0.38*	*0.4*	*0.09*	*1.83*	*0.06*
6.32	25.46	25.41	6.56	114.82	3.1
Deviation	*0.37*	*0.43*	*0.1*	*1.89*	*0.05*
6.33	25.43	25.46	6.56	114.89	3.11
Deviation	*0.4*	*0.38*	*0.1*	*1.82*	*0.04*
6.34	25.46	25.47	6.58	114.9	3.1
Deviation	*0.37*	*0.37*	*0.08*	*1.81*	*0.05*
6.35	25.48	25.45	6.57	114.95	3.11
Deviation	*0.35*	*0.39*	*0.09*	*1.76*	*0.04*
6.36	25.43	25.44	6.58	114.82	3.1
Deviation	*0.4*	*0.4*	*0.08*	*1.89*	*0.05*

Table 6.38 Shrinkage in % of right parts

Number	Reading 1	Reading 2	Reading 3	Reading 4	Reading 5
Actual Dim	***25.83***	***25.84***	***6.66***	***116.71***	***3.15***
Right Part					
6.1	25.41	25.49	6.51	114.78	3.1
Deviation %	*1.63*	*1.35*	*2.25*	*1.65*	*1.59*
6.2	25.39	25.41	6.58	114.71	3.1
Deviation %	*1.70*	*1.66*	*1.20*	*1.71*	*1.59*
6.3	25.43	25.48	6.57	114.75	3.09
Deviation %	*1.55*	*1.39*	*1.35*	*1.68*	*1.90*
6.4	25.44	25.48	6.59	114.79	3.1
Deviation %	*1.51*	*1.39*	*1.05*	*1.65*	*1.59*
6.5	25.43	25.46	6.59	114.7	3.07
Deviation %	*1.55*	*1.47*	*1.05*	*1.72*	*2.54*
6.6	25.42	25.5	6.58	114.76	3.09
Deviation %	*1.59*	*1.32*	*1.20*	*1.67*	*1.90*
6.7	25.49	25.42	6.58	114.73	3.11
Deviation %	*1.32*	*1.63*	*1.20*	*1.70*	*1.27*
6.8	25.49	25.45	6.59	114.84	3.08
Deviation %	*1.32*	*1.51*	*1.05*	*1.60*	*2.22*
6.9	25.43	25.47	6.58	114.72	3.1
Deviation %	*1.55*	*1.43*	*1.20*	*1.71*	*1.59*
6.10	25.48	25.45	6.59	114.76	3.09
Deviation %	*1.36*	*1.51*	*1.05*	*1.67*	*1.90*
6.11	25.44	25.43	6.58	114.67	3.1
Deviation %	*1.51*	*1.59*	*1.20*	*1.75*	*1.59*
6.12	25.48	25.46	6.59	114.73	3.1
Deviation %	*1.36*	*1.47*	*1.05*	*1.70*	*1.59*
6.13	25.44	25.46	6.57	114.86	3.09
Deviation %	*1.51*	*1.47*	*1.35*	*1.59*	*1.90*
6.14	25.4	25.47	6.58	114.86	3.09
Deviation %	*1.66*	*1.43*	*1.20*	*1.59*	*1.90*
6.15	25.48	25.5	6.59	114.75	3.11
Deviation %	*1.36*	*1.32*	*1.05*	*1.68*	*1.27*
6.16	25.45	25.5	6.59	114.81	3.11
Deviation %	*1.47*	*1.32*	*1.05*	*1.63*	*1.27*
6.17	25.42	25.49	6.59	114.78	3.09
Deviation %	*1.59*	*1.35*	*1.05*	*1.65*	*1.90*
6.18	25.48	25.43	6.59	114.83	3.1
Deviation %	*1.36*	*1.59*	*1.05*	*1.61*	*1.59*
6.19	25.49	25.42	6.58	114.84	3.1
Deviation %	*1.32*	*1.63*	*1.20*	*1.60*	*1.59*

Table 6.38 Continued

Number	Reading 1	Reading 2	Reading 3	Reading 4	Reading 5
Actual Dim	***25.83***	***25.84***	***6.66***	***116.71***	***3.15***
Right Part					
6.20	25.46	25.43	6.57	114.8	3.09
Deviation %	*1.43*	*1.59*	*1.35*	*1.64*	*1.90*
6.21	25.47	25.42	6.58	114.87	3.1
Deviation %	*1.39*	*1.63*	*1.20*	*1.58*	*1.59*
6.22	25.5	25.45	6.57	114.95	3.09
Deviation %	*1.28*	*1.51*	*1.35*	*1.51*	*1.90*
6.23	25.47	25.1	6.59	114.89	3.1
Deviation %	*1.39*	*2.86*	*1.05*	*1.56*	*1.59*
6.24	25.46	25.42	6.59	114.98	3.11
Deviation %	*1.43*	*1.63*	*1.05*	*1.48*	*1.27*
6.25	25.48	25.43	6.58	114.99	3.1
Deviation %	*1.36*	*1.59*	*1.20*	*1.47*	*1.59*
6.26	25.41	25.43	6.56	114.86	3.08
Deviation %	*1.63*	*1.59*	*1.50*	*1.59*	*2.22*
6.27	25.46	25.42	6.58	114.86	3.1
Deviation %	*1.43*	*1.63*	*1.20*	*1.59*	*1.59*
6.28	25.42	25.47	6.57	114.83	3.1
Deviation %	*1.59*	*1.43*	*1.35*	*1.61*	*1.59*
6.29	25.46	25.42	6.58	114.88	3.1
Deviation %	*1.43*	*1.63*	*1.20*	*1.57*	*1.59*
6.30	25.46	25.48	6.58	114.9	3.1
Deviation %	*1.43*	*1.39*	*1.20*	*1.55*	*1.59*
6.31	25.45	25.44	6.57	114.88	3.09
Deviation %	*1.47*	*1.55*	*1.35*	*1.57*	*1.90*
6.32	25.46	25.41	6.56	114.82	3.1
Deviation %	*1.43*	*1.66*	*1.50*	*1.62*	*1.59*
6.33	25.43	25.46	6.56	114.89	3.11
Deviation %	*1.55*	*1.47*	*1.50*	*1.56*	*1.27*
6.34	25.46	25.47	6.58	114.9	3.1
Deviation %	*1.43*	*1.43*	*1.20*	*1.55*	*1.59*
6.35	25.48	25.45	6.57	114.95	3.11
Deviation %	*1.36*	*1.51*	*1.35*	*1.51*	*1.27*
6.36	25.43	25.44	6.58	114.82	3.1
Deviation %	*1.55*	*1.55*	*1.20*	*1.62*	*1.59*

Table 6.39 Deviation in % of right parts

6.1 Deviation	1.63	1.35	2.25	1.65	1.59
6.2 Deviation	1.70	1.66	1.20	1.71	1.59
6.3 Deviation	1.55	1.39	1.35	1.68	1.90
6.4 Deviation	1.51	1.39	1.05	1.65	1.59
6.5 Deviation	1.55	1.47	1.05	1.72	2.54
6.6 Deviation	1.59	1.32	1.20	1.67	1.90
6.7 Deviation	1.32	1.63	1.20	1.70	1.27
6.8 Deviation	1.32	1.51	1.05	1.60	2.22
6.9 Deviation	1.55	1.43	1.20	1.71	1.59
6.10 Deviation	1.36	1.51	1.05	1.67	1.90
6.11 Deviation	1.51	1.59	1.20	1.75	1.59
6.12 Deviation	1.36	1.47	1.05	1.70	1.59
6.13 Deviation	1.51	1.47	1.35	1.59	1.90
6.14 Deviation	1.66	1.43	1.20	1.59	1.90
6.15 Deviation	1.36	1.32	1.05	1.68	1.27
6.16 Deviation	1.47	1.32	1.05	1.63	1.27
6.17 Deviation	1.59	1.35	1.05	1.65	1.90
6.18 Deviation	1.36	1.59	1.05	1.61	1.59
6.19 Deviation	1.32	1.63	1.20	1.60	1.59
6.20 Deviation	1.43	1.59	1.35	1.64	1.90
6.21 Deviation	1.39	1.63	1.20	1.58	1.59
6.22 Deviation	1.28	1.51	1.35	1.51	1.90
6.23 Deviation	1.39	2.86	1.05	1.56	1.59
6.24 Deviation	1.43	1.63	1.05	1.48	1.27
6.25 Deviation	1.36	1.59	1.20	1.47	1.59
6.26 Deviation	1.63	1.59	1.50	1.59	2.22
6.27 Deviation	1.43	1.63	1.20	1.59	1.59
6.28 Deviation	1.59	1.43	1.35	1.61	1.59
6.29 Deviation	1.43	1.63	1.20	1.57	1.59
6.30 Deviation	1.43	1.39	1.20	1.55	1.59
6.31 Deviation	1.47	1.55	1.35	1.57	1.90
6.32 Deviation	1.43	1.66	1.50	1.62	1.59
6.33 Deviation	1.55	1.47	1.50	1.56	1.27
6.34 Deviation	1.43	1.43	1.20	1.55	1.59
6.35 Deviation	1.36	1.51	1.35	1.51	1.27
6.36 Deviation	1.55	1.55	1.20	1.62	1.59
Average %	**1.47**	**1.54**	**1.22**	**1.62**	**1.70**

Table 6.40 Shrinkage in mm of left parts

Number	Reading 1	Reading 2	Reading 3	Reading 4	Reading 5
Actual Dim	***25.81***	***25.8***	***6.5***	***116.64***	***3.15***
Left Part					
6.1	25.4	25.41	6.46	114.88	3.13
Deviation	*0.41*	*0.39*	*0.04*	*1.76*	*0.02*
6.2	25.33	25.3	6.47	114.73	3.12
Deviation	*0.48*	*0.5*	*0.03*	*1.91*	*0.03*
6.3	25.35	25.3	6.47	114.77	3.11
Deviation	*0.46*	*0.5*	*0.03*	*1.87*	*0.04*
6.4	25.38	25.32	6.48	114.78	3.12
Deviation	*0.43*	*0.48*	*0.02*	*1.86*	*0.03*
6.5	25.38	25.25	6.46	114.73	3.11
Deviation	*0.43*	*0.55*	*0.04*	*1.91*	*0.04*
6.6	25.39	25.33	6.48	114.78	3.11
Deviation	*0.42*	*0.47*	*0.02*	*1.86*	*0.04*
6.7	25.38	25.35	6.48	114.75	3.1
Deviation	*0.43*	*0.45*	*0.02*	*1.89*	*0.05*
6.8	25.36	25.31	6.47	114.87	3.1
Deviation	*0.45*	*0.49*	*0.03*	*1.77*	*0.05*
6.9	25.34	25.25	6.47	114.81	3.11
Deviation	*0.47*	*0.55*	*0.03*	*1.83*	*0.04*
6.10	25.37	25.32	6.47	114.76	3.12
Deviation	*0.44*	*0.48*	*0.03*	*1.88*	*0.03*
6.11	25.34	25.27	6.47	114.7	3.1
Deviation	*0.47*	*0.53*	*0.03*	*1.94*	*0.05*
6.12	25.34	25.29	6.46	114.83	3.12
Deviation	*0.47*	*0.51*	*0.04*	*1.81*	*0.03*
6.13	25.31	25.27	6.46	114.78	3.12
Deviation	*0.5*	*0.53*	*0.04*	*1.86*	*0.03*
6.14	25.34	25.28	6.47	114.81	3.11
Deviation	*0.47*	*0.52*	*0.03*	*1.83*	*0.04*
6.15	25.4	25.37	6.47	114.83	3.12
Deviation	*0.41*	*0.43*	*0.03*	*1.81*	*0.03*
6.16	25.34	25.31	6.46	114.84	3.13
Deviation	*0.47*	*0.49*	*0.04*	*1.8*	*0.02*
6.17	25.31	25.29	6.46	114.78	3.12
Deviation	*0.5*	*0.51*	*0.04*	*1.86*	*0.03*
6.18	25.33	25.32	6.47	114.84	3.13
Deviation	*0.48*	*0.48*	*0.03*	*1.8*	*0.02*
6.19	25.3	25.25	6.45	114.88	3.13
Deviation	*0.51*	*0.55*	*0.05*	*1.76*	*0.02*

Table 6.40 Continued

Number	Reading 1	Reading 2	Reading 3	Reading 4	Reading 5
Actual Dim	***25.81***	***25.8***	***6.5***	***116.64***	***3.15***
Left Part					
6.20	25.25	25.3	6.45	X	3.1
Deviation	*0.56*	*0.5*	*0.05*	X	*0.05*
6.21	25.31	25.27	6.45	114.86	3.12
Deviation	*0.5*	*0.53*	*0.05*	*1.78*	*0.03*
6.22	25.32	25.28	6.45	X	3.12
Deviation	*0.49*	*0.52*	*0.05*	X	*0.03*
6.23	25.32	25.28	6.46	114.83	3.13
Deviation	*0.49*	*0.52*	*0.04*	*1.81*	*0.02*
6.24	25.32	25.28	6.46	114.87	3.13
Deviation	*0.49*	*0.52*	*0.04*	*1.77*	*0.02*
6.25	25.32	25.25	6.46	114.94	3.13
Deviation	*0.49*	*0.55*	*0.04*	*1.7*	*0.02*
6.26	25.29	25.24	6.45	X	3.11
Deviation	*0.52*	*0.56*	*0.05*	X	*0.04*
6.27	25.3	25.26	6.46	114.8	3.12
Deviation	*0.51*	*0.54*	*0.04*	*1.84*	*0.03*
6.28	25.26	25.29	6.46	114.9	3.13
Deviation	*0.55*	*0.51*	*0.04*	*1.74*	*0.02*
6.29	25.26	25.25	6.45	X	3.1
Deviation	*0.55*	*0.55*	*0.05*	X	*0.05*
6.30	25.3	25.24	6.47	114.95	3.12
Deviation	*0.51*	*0.56*	*0.03*	*1.69*	*0.03*
6.31	25.3	25.23	6.46	X	3.1
Deviation	*0.51*	*0.57*	*0.04*	X	*0.05*
6.32	25.26	25.25	6.45	X	3.11
Deviation	*0.55*	*0.55*	*0.05*	X	*0.04*
6.33	25.28	25.21	6.46	X	3.1
Deviation	*0.53*	*0.59*	*0.04*	X	*0.05*
6.34	25.29	25.21	6.46	114.78	3.12
Deviation	*0.52*	*0.59*	*0.04*	*1.86*	*0.03*
6.35	25.31	25.26	6.47	114.86	3.12
Deviation	*0.5*	*0.54*	*0.03*	*1.78*	*0.03*
6.36	25.3	25.22	6.46	X	3.12
Deviation	*0.51*	*0.58*	*0.04*	X	*0.03*

Table 6.41 Shrinkage in % of left parts

Number	Reading 1	Reading 2	Reading 3	Reading 4	Reading 5
Actual Dim	***25.81***	***25.8***	***6.5***	***116.64***	***3.15***
Left Part					
6.1	25.4	25.41	6.46	114.88	3.13
Deviation %	*1.59*	*1.51*	*0.62*	*1.51*	*0.63*
6.2	25.33	25.3	6.47	114.73	3.12
Deviation %	*1.86*	*1.94*	*0.46*	*1.64*	*0.95*
6.3	25.35	25.3	6.47	114.77	3.11
Deviation %	*1.78*	*1.94*	*0.46*	*1.60*	*1.27*
6.4	25.38	25.32	6.48	114.78	3.12
Deviation %	*1.67*	*1.86*	*0.31*	*1.59*	*0.95*
6.5	25.38	25.25	6.46	114.73	3.11
Deviation %	*1.67*	*2.13*	*0.62*	*1.64*	*1.27*
6.6	25.39	25.33	6.48	114.78	3.11
Deviation %	*1.63*	*1.82*	*0.31*	*1.59*	*1.27*
6.7	25.38	25.35	6.48	114.75	3.1
Deviation %	*1.67*	*1.74*	*0.31*	*1.62*	*1.59*
6.8	25.36	25.31	6.47	114.87	3.1
Deviation %	*1.74*	*1.90*	*0.46*	*1.52*	*1.59*
6.9	25.34	25.25	6.47	114.81	3.11
Deviation %	*1.82*	*2.13*	*0.46*	*1.57*	*1.27*
6.10	25.37	25.32	6.47	114.76	3.12
Deviation %	*1.70*	*1.86*	*0.46*	*1.61*	*0.95*
6.11	25.34	25.27	6.47	114.7	3.1
Deviation %	*1.82*	*2.05*	*0.46*	*1.66*	*1.59*
6.12	25.34	25.29	6.46	114.83	3.12
Deviation %	*1.82*	*1.98*	*0.62*	*1.55*	*0.95*
6.13	25.31	25.27	6.46	114.78	3.12
Deviation %	*1.94*	*2.05*	*0.62*	*1.59*	*0.95*
6.14	25.34	25.28	6.47	114.81	3.11
Deviation %	*1.82*	*2.02*	*0.46*	*1.57*	*1.27*
6.15	25.4	25.37	6.47	114.83	3.12
Deviation %	*1.59*	*1.67*	*0.46*	*1.55*	*0.95*
6.16	25.34	25.31	6.46	114.84	3.13
Deviation %	*1.82*	*1.90*	*0.62*	*1.54*	*0.63*
6.17	25.31	25.29	6.46	114.78	3.12
Deviation %	*1.94*	*1.98*	*0.62*	*1.59*	*0.95*
6.18	25.33	25.32	6.47	114.84	3.13
Deviation %	*1.86*	*1.86*	*0.46*	*1.54*	*0.63*
6.19	25.3	25.25	6.45	114.88	3.13
Deviation %	*1.98*	*2.13*	*0.77*	*1.51*	*0.63*

Table 6.41 Continued

Number	Reading 1	Reading 2	Reading 3	Reading 4	Reading 5
Actual Dim	***25.81***	***25.8***	***6.5***	***116.64***	***3.15***
Left Part					
6.20	25.25	25.3	6.45	X	3.1
Deviation %	*2.17*	*1.94*	*0.77*	X	*1.59*
6.21	25.31	25.27	6.45	114.86	3.12
Deviation %	*1.94*	*2.05*	*0.77*	*1.53*	*0.95*
6.22	25.32	25.28	6.45	X	3.12
Deviation %	*1.90*	*2.02*	*0.77*	X	*0.95*
6.23	25.32	25.28	6.46	114.83	3.13
Deviation %	*1.90*	*2.02*	*0.62*	*1.55*	*0.63*
6.24	25.32	25.28	6.46	114.87	3.13
Deviation %	*1.90*	*2.02*	*0.62*	*1.52*	*0.63*
6.25	25.32	25.25	6.46	114.94	3.13
Deviation %	*1.90*	*2.13*	*0.62*	*1.46*	*0.63*
6.26	25.29	25.24	6.45	X	3.11
Deviation %	*2.01*	*2.17*	*0.77*	X	*1.27*
6.27	25.3	25.26	6.46	114.8	3.12
Deviation %	*1.98*	*2.09*	*0.62*	*1.58*	*0.95*
6.28	25.26	25.29	6.46	114.9	3.13
Deviation %	*2.13*	*1.98*	*0.62*	*1.49*	*0.63*
6.29	25.26	25.25	6.45	X	3.1
Deviation %	*2.13*	*2.13*	*0.77*	X	*1.59*
6.30	25.3	25.24	6.47	114.95	3.12
Deviation %	*1.98*	*2.17*	*0.46*	*1.45*	*0.95*
6.31	25.3	25.23	6.46	X	3.1
Deviation %	*1.98*	*2.21*	*0.62*	X	*1.59*
6.32	25.26	25.25	6.45	X	3.11
Deviation %	*2.13*	*2.13*	*0.77*	X	*1.27*
6.33	25.28	25.21	6.46	X	3.1
Deviation %	*2.05*	*2.29*	*0.62*	X	*1.59*
6.34	25.29	25.21	6.46	114.78	3.12
Deviation %	*2.01*	*2.29*	*0.62*	*1.59*	*0.95*
6.35	25.31	25.26	6.47	114.86	3.12
Deviation %	*1.94*	*2.09*	*0.46*	*1.53*	*0.95*
6.36	25.3	25.22	6.46	X	3.12
Deviation %	*1.98*	*2.25*	*0.62*	X	*0.95*

Table 6.42 Deviation in % of left parts

6.1 Deviation	1.59	1.51	0.62	1.51	0.63
6.2 Deviation	1.86	1.94	0.46	1.64	0.95
6.3 Deviation	1.78	1.94	0.46	1.60	1.27
6.4 Deviation	1.67	1.86	0.31	1.59	0.95
6.5 Deviation	1.67	2.13	0.62	1.64	1.27
6.6 Deviation	1.63	1.82	0.31	1.59	1.27
6.7 Deviation	1.67	1.74	0.31	1.62	1.59
6.8 Deviation	1.74	1.90	0.46	1.52	1.59
6.9 Deviation	1.82	2.13	0.46	1.57	1.27
6.10 Deviation	1.70	1.86	0.46	1.61	0.95
6.11 Deviation	1.82	2.05	0.46	1.66	1.59
6.12 Deviation	1.82	1.98	0.62	1.55	0.95
6.13 Deviation	1.94	2.05	0.62	1.59	0.95
6.14 Deviation	1.82	2.02	0.46	1.57	1.27
6.15 Deviation	1.59	1.67	0.46	1.55	0.95
6.16 Deviation	1.82	1.90	0.62	1.54	0.63
6.17 Deviation	1.94	1.98	0.62	1.59	0.95
6.18 Deviation	1.86	1.86	0.46	1.54	0.63
6.19 Deviation	1.98	2.13	0.77	1.51	0.63
6.20 Deviation	2.17	1.94	0.77	X	1.59
6.21 Deviation	1.94	2.05	0.77	1.53	0.95
6.22 Deviation	1.90	2.02	0.77	X	0.95
6.23 Deviation	1.90	2.02	0.62	1.55	0.63
6.24 Deviation	1.90	2.02	0.62	1.52	0.63
6.25 Deviation	1.90	2.13	0.62	1.46	0.63
6.26 Deviation	2.01	2.17	0.77	X	1.27
6.27 Deviation	1.98	2.09	0.62	1.58	0.95
6.28 Deviation	2.13	1.98	0.62	1.49	0.63
6.29 Deviation	2.13	2.13	0.77	X	1.59
6.30 Deviation	1.98	2.17	0.46	1.45	0.95
6.31 Deviation	1.98	2.21	0.62	X	1.59
6.32 Deviation	2.13	2.13	0.77	X	1.27
6.33 Deviation	2.05	2.29	0.62	X	1.59
6.34 Deviation	2.01	2.29	0.62	1.59	0.95
6.35 Deviation	1.94	2.09	0.46	1.53	0.95
6.36 Deviation	1.98	2.25	0.62	X	0.95
Average %	**1.85**	**1.97**	**0.56**	**1.56**	**1.04**

Figure 6.28 shows the 90 ton injection moulding machine used to conduct the shrinkage tests and Table 6.43 shows the injection moulding settings used. Table 6.44 shows comparative surface temperature (˚C) data between Alumide®, LaserForm™ ST 100 and LaserForm™ A6 inserts for 26 injection-moulding shots without any cooling.

Figure 6.28 90 Ton injection moulding machine used to conduct the shrinkage tests

Table 6.43 The injection moulding settings

Injection moulding temperature Stage 1 (at nozzle)	200 ˚C
Injection moulding temperature Stage 2	205˚C
Injection moulding temperature Stage 3	200˚C
Injection moulding temperature Stage 4	195˚C
Injection speed	25%
Injection pressure	35%
Holding pressure	15 bar

Cycle time	25 seconds
Cooling time	12 seconds

Table 6.44 Comparative surface temperature (˚C) data between Alumide®, LaserForm™ ST 100 and LaserForm™ A6

Alumide® Surface Temperature (˚C)	**LaserForm™ ST 100 Surface Temperature (˚C)**	**LaserForm™ A6 Surface Temperature (˚C)**
23	21	23.8
26	22	23.8
28	22	24.4
28	21.5	24.4
29	21	24.4
29	22	24.6
30	22	24.2
30	22	24.4
31	22.6	24.6
31	22.6	24.4
31	22.4	24.6
30	22.4	24.4
30	22.4	24.4
31	22.4	24.4
31	22.7	24.4
31	22.4	24.4
32	22.8	24.0
32	22.8	23.8
32	23	24.2
33	23	23.8
33	23.4	24.0
32	23.2	24.0
32	23.2	23.8
33	23.4	24.4
34	23.3	24.0
35	23.4	24.4

The data obtained from Table 6.44 was used to plot the following graph, as seen in Figure 6.29.

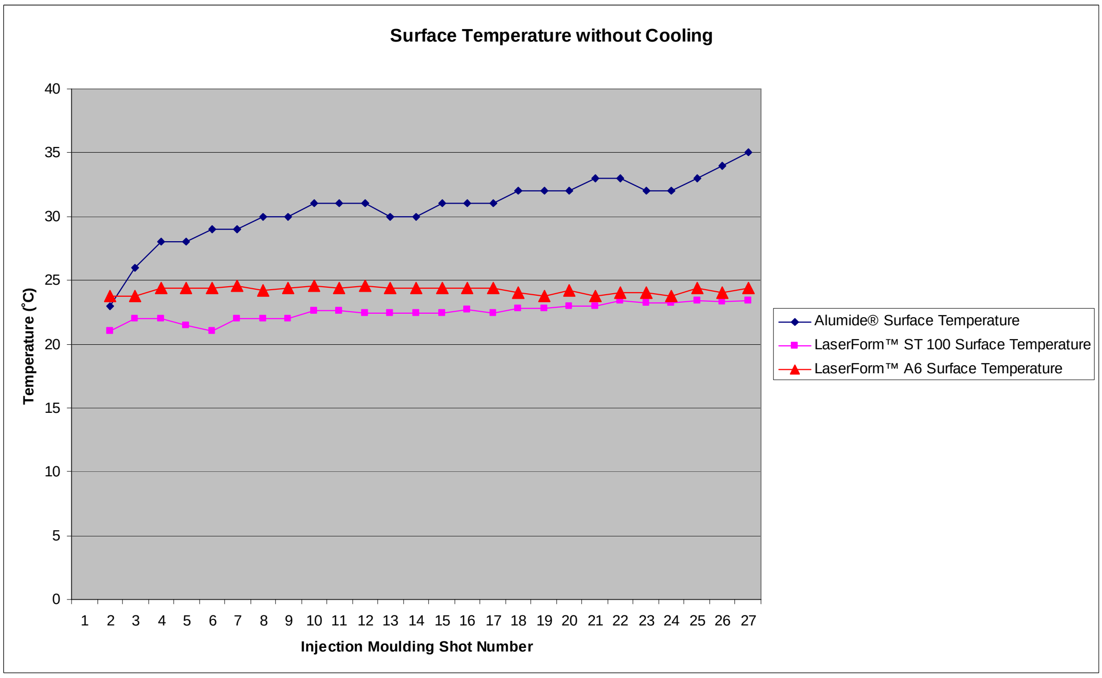
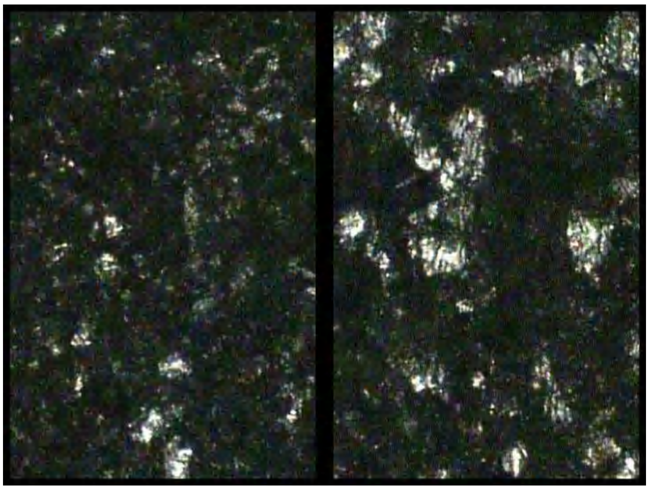


Figure 6.29 Comparative surface temperature data for 26 injection-moulding shots in Alumide®, compared to LaserForm™ ST 100 and LaserForm™ A6 inserts

Microscopic photos were taken of the Alumide® mould surfaces, and very little wear, around ten micron, could be observed (Figure 6.30). It was clear when studied under the microscope that the nylon on the surface was melted out to the next aluminium particle. Figure 6.30(a) was taken at 50 times magnification, and 6.30(b) at 100 times magnification.



(a) 50 times (b) 100 times

Figure 6.30 Microscopic images of the Alumide® Surfaces

Microscopic photos were taken, at 50 times magnification, of the LaserForm™ ST100 and the LaserForm™ A6 surfaces and are shown in Figures 6.31 and 6.32. No wear could be observed inside the cavities.

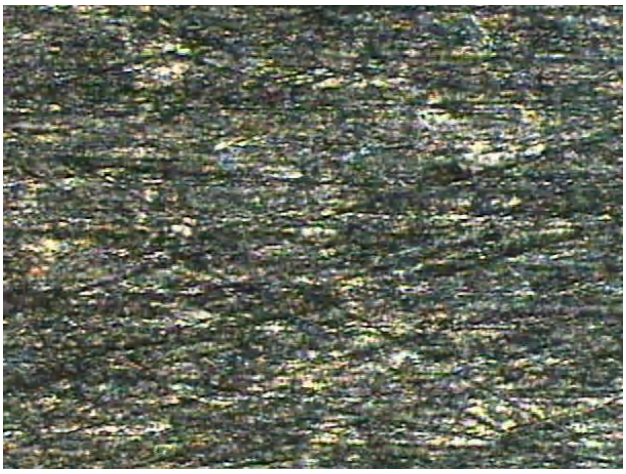


Figure 6.31 Microscopic image at 50 times magnification of the LaserForm™ ST100 Surface

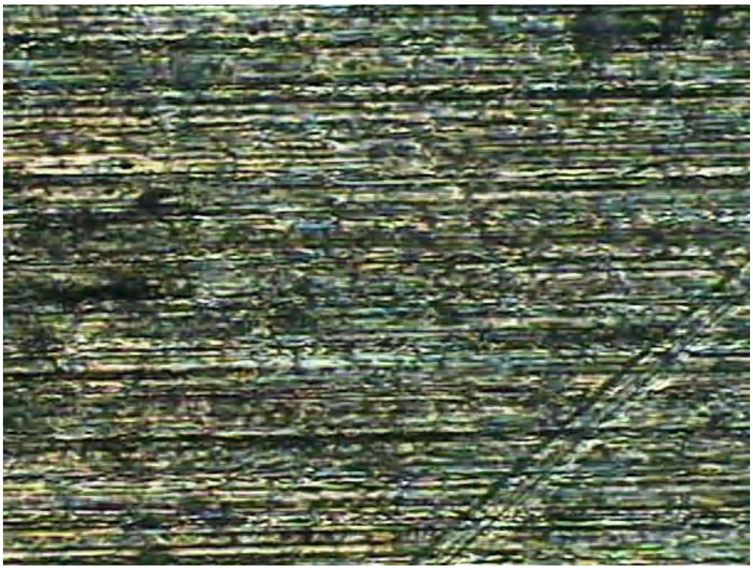


Figure 6.32 Microscopic image at 50 times magnification of the LaserForm™ A6 Surface

Summary

The accuracy of the inserts can be improved by growing more scaling parts, because the more the reiteration, the better the scaling values. The scaling values are obtained by growing scaling blocks that have known X, Y and Z readings. Scaling factors are necessary, because the process is exposed to high temperatures and shrinkages occur in the parts. These scaling blocks are also taken through the post-curing process, if necessary, because further shrinkages can occur. After the post-curing, the scaling blocks are measured and compared with actual measurements to obtain the scaling values.

Alumide® Insert

The largest deviation of the X and Y dimensions was 1.19%, and the smallest, around 0.01%. The Z accuracy was not good, with the largest deviation -5.94% and the smallest approximately -3.27%. The minus indicates that the grown dimensions were bigger than the design dimensions, because 0.3 mm stock was extruded on the surface of the mould in the Z direction. The extra stock was placed in the design to be able to grind the surface after growing to achieve a good shut-off. Taking the extra stock into account, the actual Z design dimension was 3.45 mm (3.15 +0.3 mm) and not 3.15 mm, as shown in the calculations. When using the 3.45 mm in the calculations the outcome will show the largest deviation value as 5.71% and the smallest value as 3.28%.

<u>LaserForm™ ST100 Insert</u>

When compared to the accuracy of the Alumide® grown insert, the accuracy of the X and Y design dimensions of the LaserForm™ ST100 produced insert was not as good. The largest deviation of the X and Y dimensions was a deviation of 3.59% and the smallest deviation, approximately 0.04%. The Z accuracy was not good, the largest deviation being -16.35% and the smallest deviation -12.6%. Once again, the minus shows that the grown dimensions were bigger than the design dimensions. This was required, because, 0.5 mm stock was extruded on the surface of the mould in the Z direction to be able to grind the surface after growing to achieve a good shut-off. Taking the extra stock into account, the actual Z design dimension was 3.65 mm (3.15 +0.5 mm) and not 3.15 mm as shown in the calculations. When using the 3.65 mm in the calculations the outcome will show the largest deviation value as 2.82% and the smallest value as 0.03%.

<u>LaserForm™ A6 Insert</u>

The LaserForm™ A6 produced insert showed better accuracy than the LaserForm™ ST100 insert in the X and Y direction, when compared to the design dimensions. The largest deviation for X and Y dimensions was a deviation of -2.33% and the smallest deviation -0.43%, where the minus shows that the grown dimensions were bigger than the design dimensions. The Z accuracy was poor with the largest deviation value of 19.43% and the smallest deviation of 1.78%. The distressing factor is that these two deviations were supposed to be a parallel surface to the shut-off surface. These deviations show that the part was distorted/ warped in the Z direction, which can be a result of the post-treatment done inside the oven cycle (Table 6.32).

6.5 CASE STUDY 5: DURABILITY TEST OF GROWN INSERTS

In this case study the objective was to test the durability of the Alumide®, LaserForm™ ST 100 and LaserForm™ A6 inserts. After injection, the surface as well as the internal temperatures of the inserts were taken in order to identify the heat distribution of the inserts. The surface temperatures were recorded by using a non-contact infra-red thermometer, capable of measuring -20˚C to 270˚C. The internal temperatures were recorded 9 mm below the surface, using standard thermocouples. Four Alumide® inserts were grown with the LS process of which one set was grown with the unsorted exposure parameter and the other set was grown using the mechanical exposure parameter (as explained in 5.3 of chapter 5). Four more inserts were grown using the SLS process, of which two inserts were grown in LaserForm™ ST 100 material and the other two inserts using LaserForm™ A6 material. The parts produced with these inserts are shown in Figure 6.33. The inserts were fitted into a bolster and fixed into a 90 ton injection moulder.

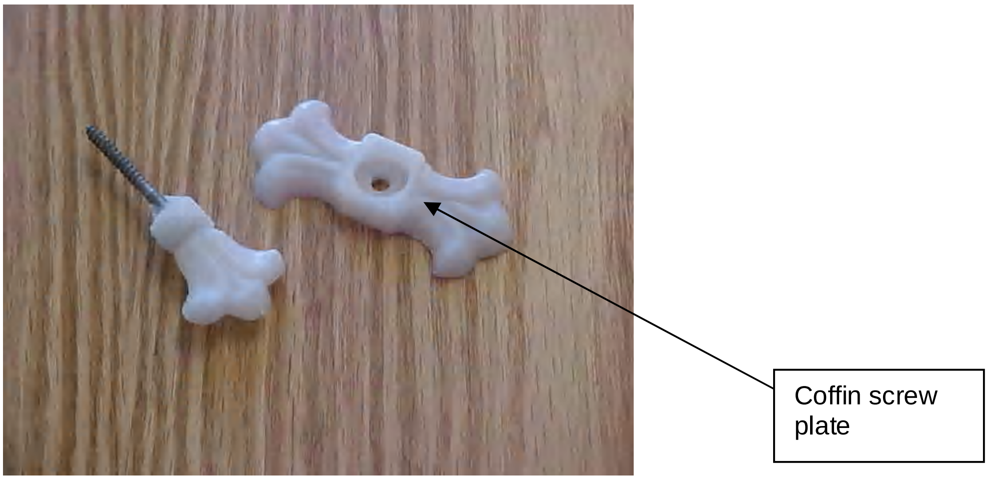


Figure 6.33 The coffin screw plate part which was manufactured in this case study

The injection specifications, as described below, were kept the same in this case study:

- Maximum shot weight of
  90 ton machine = 129 grams with a 32 diameter screw
- Injection pressure = 1914kg/cm^2 x 40 % = 765.6 kg/cm^2
- Injection speed = 69 cm^3/sec x 40 % = 27.6 cm^3/sec
- Holding pressure = 1914kg/cm^2 x 40 % = 765.6 kg/cm^2
- Holding speed = 69 cm^3/sec x 50 % = 34.5 cm^3/sec
- Holding time = 8 sec
- Maximum clamping force = 90 ton x 70 % = 63 ton
- Maximum injection temp = 205 ˚C
- Ejector force = 4.3 ton x 40 % = 2.8 ton

The goal of this study was to realize 1000 injection moulding shots into the Alumide® inserts, and 100 000 shots into the LaserForm™ ST100 and LaserForm™ A6 inserts. It was uncertain whether the Alumide® inserts could withstand the injection temperatures of 205˚C repeatedly, especially when taking into account that both the mechanical and unsorted inserts were sintered at ± 180 ˚C. Table 6.45 shows a cost and time comparison of the grown inserts.

Table 6.45 A cost and time comparison between Laserform™ ST100, Laserform™ A6, Alumide® - mechanical, Alumide® - unsorted and Conventional machining

MATERIAL	GROWING TIME	COST OF TWO INSERTS (excl VAT)
LaserForm™ ST100	22 hours 15 min	R 11 223
LaserForm™ A6	19 hours 30 min	R 10 585
Alumide® - mechanical	4 hours 6 min	R 4980
Alumide® - unsorted	2 hours 54 min	R 4505
Conventional machining	18 hours 32 min	R 8967

Alumide® Durability Test

Figure 6.34 shows pictures of the mould halves, with thermocouples connected to measure the internal temperature.

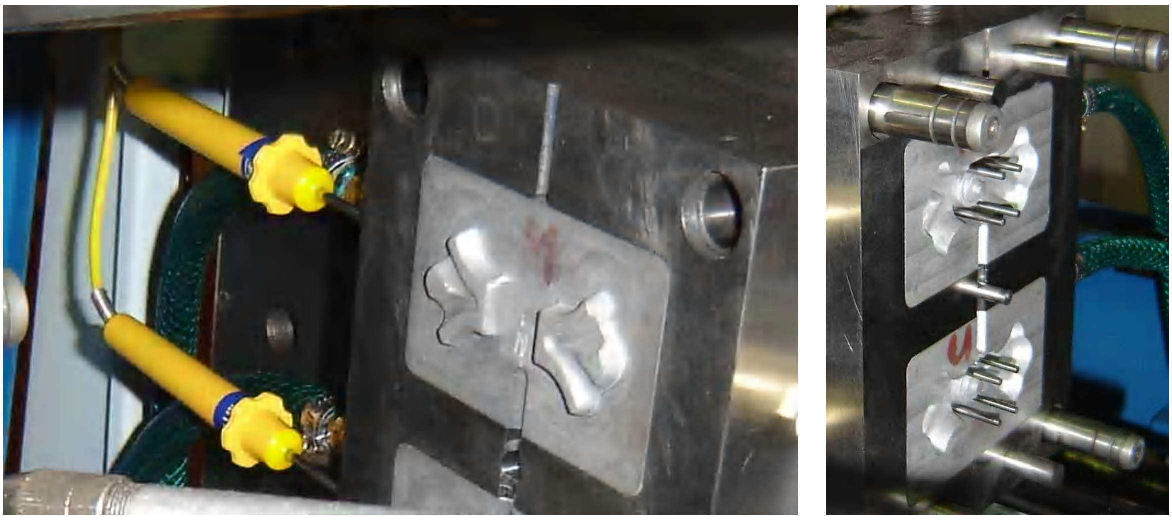


Figure 6.34 Pictures of the different mould halves, with thermocouples connected

The mechanically grown inserts were fitted on the top cavity of both the fixed and moving mould halves. The unsorted grown inserts were fitted on the bottom cavity of both the fixed and moving mould halves.

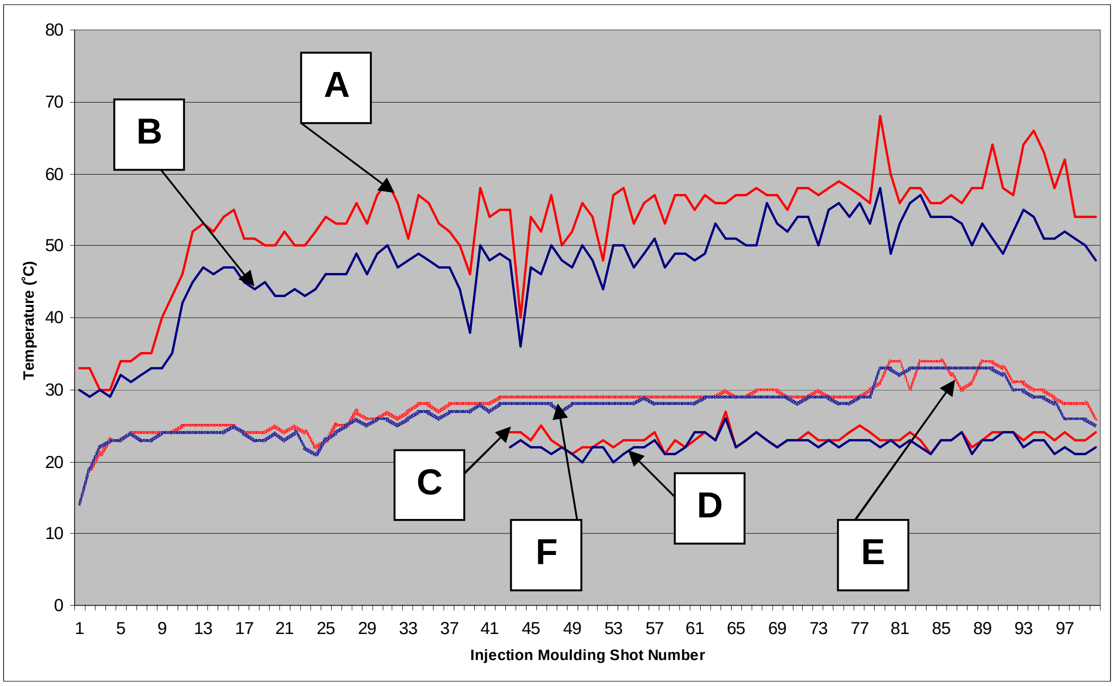
Cycle times: (the cycle time was 25 sec, excluding the air cooling)

1. for the first 235 of the 1004 injection moulding shots, the cycle time was:

   25 sec + 30 sec air cooling on each side of the mould = 25 + 30 + 30 = 85 sec

2. for the last 765 of the 1004 injection moulding shots, the cycle time was: 25 sec + 15 sec air cooling on each side of the mould = 25 + 15 + 15 = 55 sec
3. for the last 9 of the 1013 injection moulding shots, the cycle time was only: 25 sec as no cooling was applied.

Both the mechanically and unsorted grown Alumide® inserts could withstand 1004 injection moulding shots, when using the abovementioned cycle times combined with the appropriate air cooling times. There was no visible wear on either sets of the grown inserts and it was decided to stop the air cooling to test the process without the cooling. Nine parts were produced without air cooling and the surface temperature went up to 78 ˚C on the mechanically grown inserts, whereafter the part started to bond to the insert. The different temperature measurements (as shown in Appendix A), taken directly after moulding, and again directly after cooling, are explained in Figure 6.35. Figures 6.35 to 6.42 show data captured on the heat distribution during injection moulding of the trial moulds.



A	Mould Temperature after Injection: Mechanical	**B**	Mould Temperature after Injection: Unsorted
C	Mould Temperature after Air Cooling: Mechanical	**D**	Mould Temperature after Air Cooling: Unsorted
E	Internal Mould Temperature: Mechanical	**F**	Internal Mould Temperature: Unsorted

Figure 6.35 Explanation of the measurement principles used

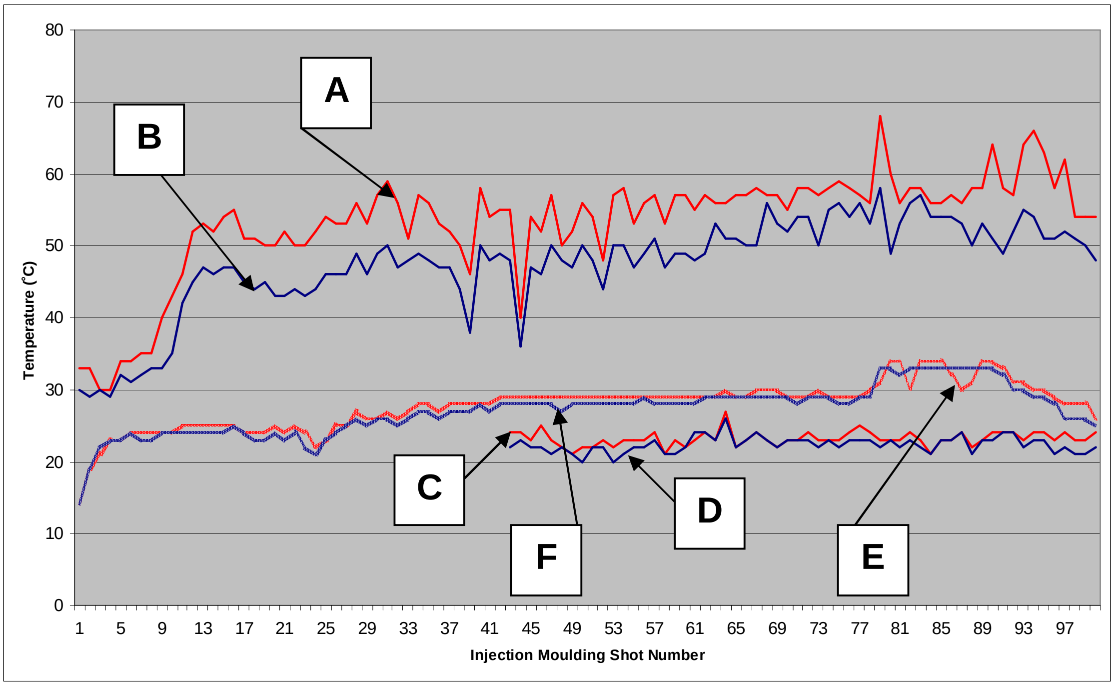


Figure 6.36: Durability Tests: Shot 1-100; 30 seconds cooling/side (85 sec cycle time) Injection temperature: 205˚C

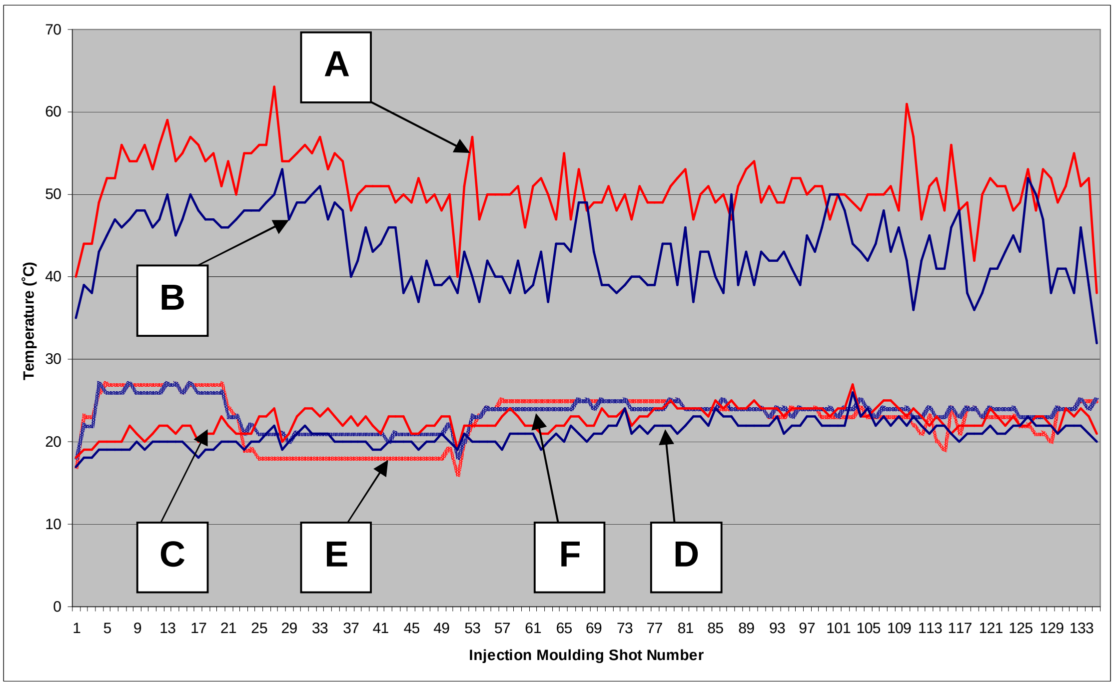


Figure 6.37: Durability Tests: Shot 101-235; 30 seconds cooling/side (85 sec cycle time) Injection temperature: 205˚C

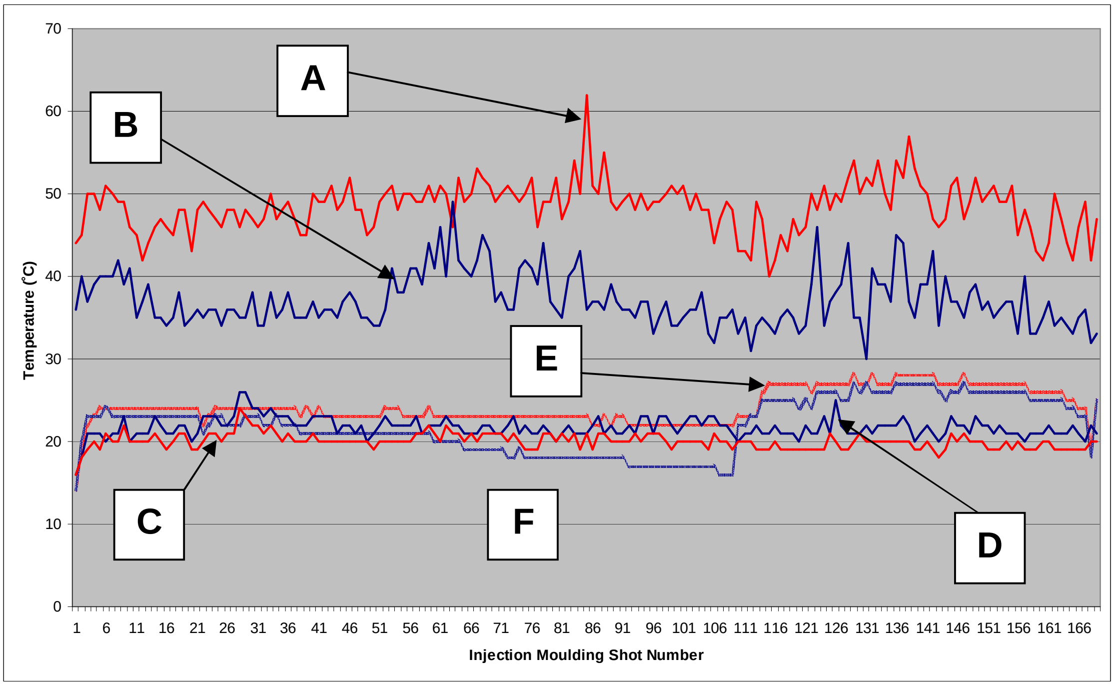


Figure 6.38: Durability Tests: Shot 236 - 404; 15 seconds cooling/side (55 sec cycle time) Injection temperature: 205˚C

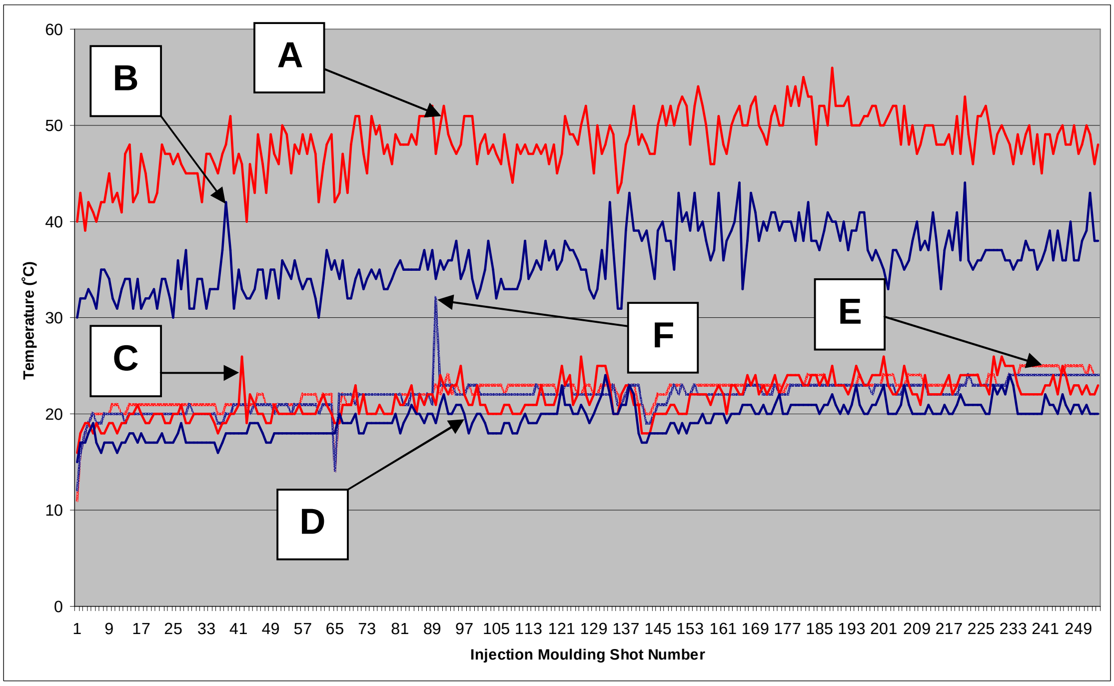


Figure 6.39: Durability Tests: Shot 405 - 658; 15 seconds cooling/side (55 sec cycle time) Injection temperature: 205˚C

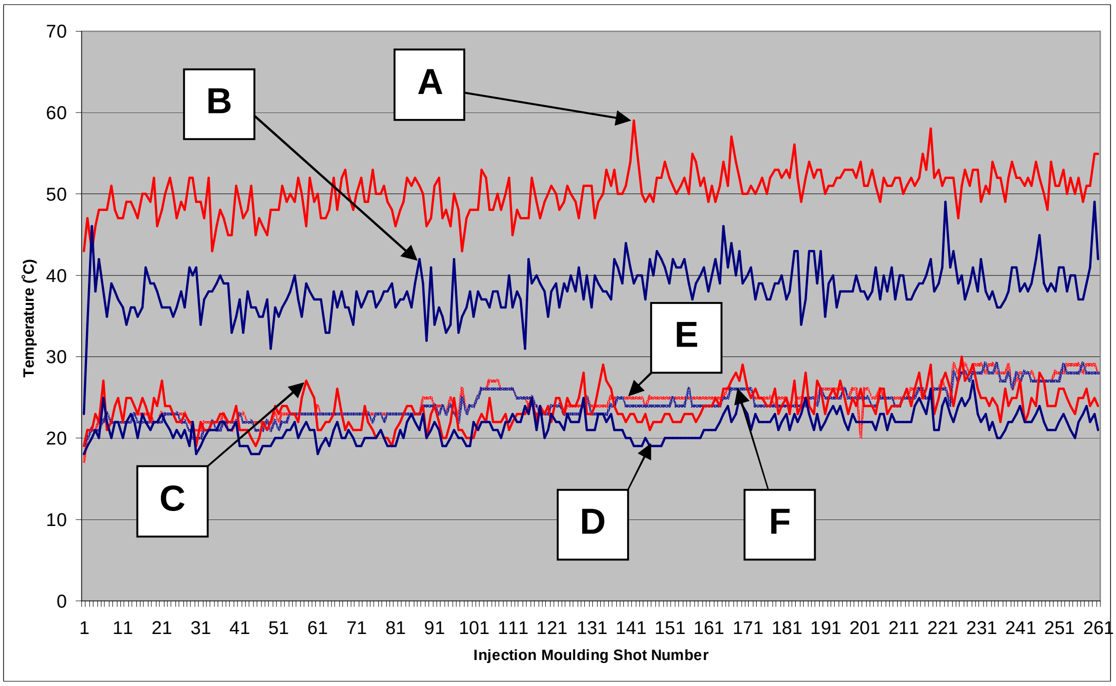


Figure 6.40: Durability Tests: Shot 659 - 919; 15 seconds cooling/side (55 sec cycle time) Injection temperature: 205˚C

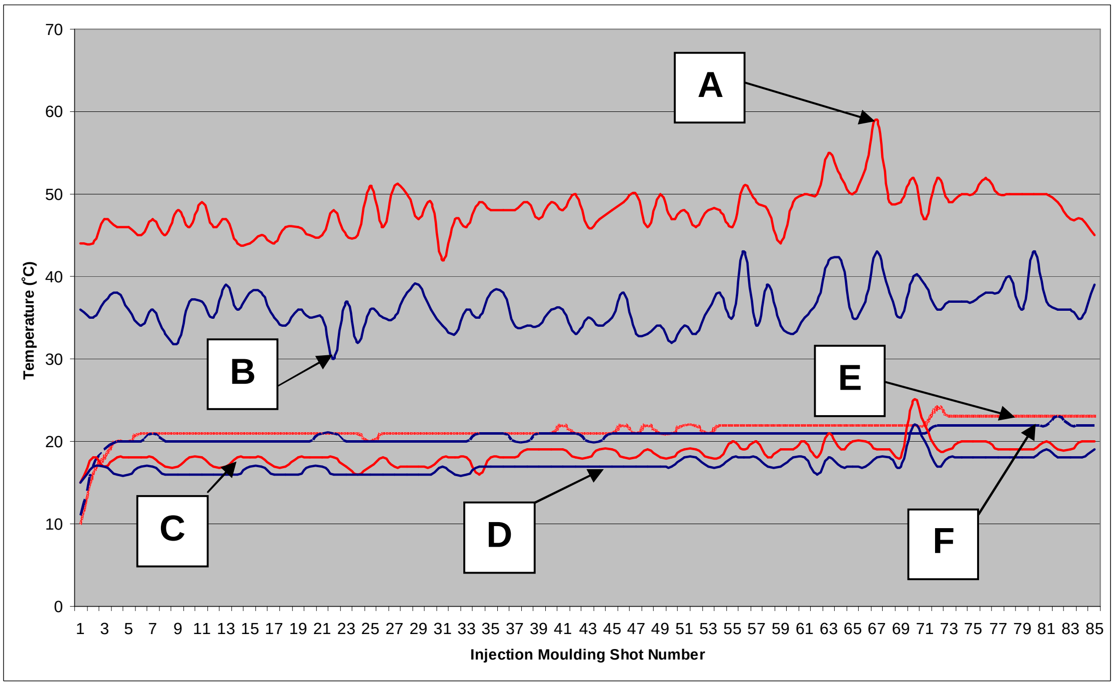
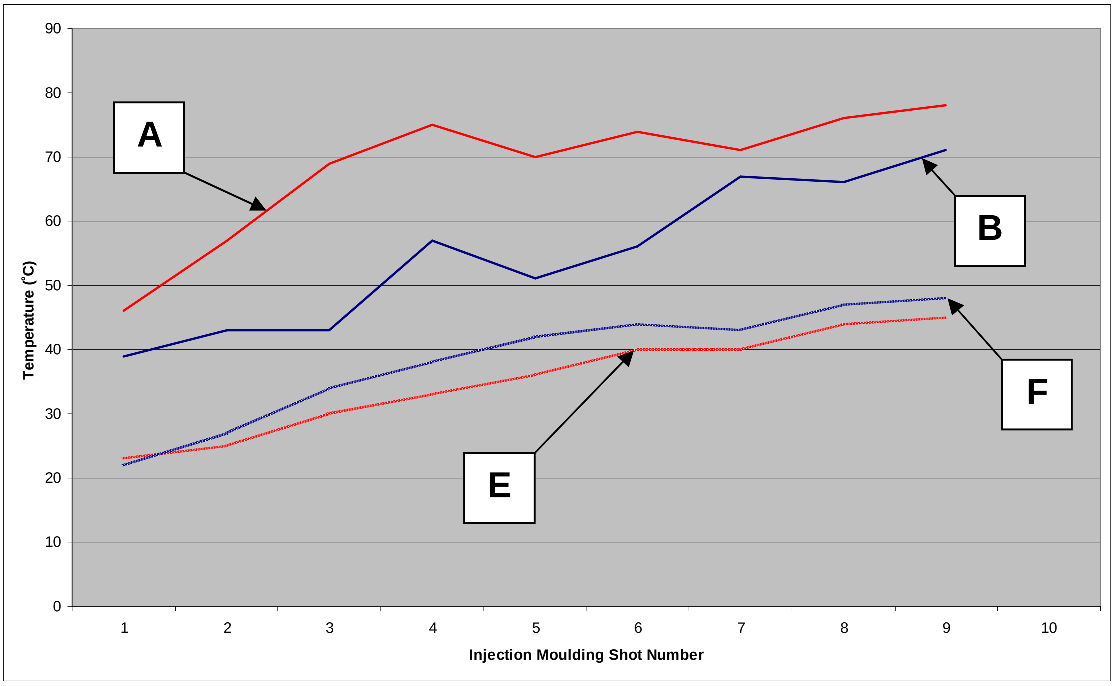


Figure 6.41: Durability Tests: Shot 920 - 1004; 15 seconds cooling/side (55 sec cycle time) Injection temperature: 205˚C



A	Mould Temperature after Injection: Mechanical	**B**	Mould Temperature after Injection: Unsorted
E	Internal Mould Temperature: Mechanical	**F**	Internal Mould Temperature: Unsorted

Figure 6.42: Durability Tests: Shot 1005 - 1013; No cooling (25 sec cycle time) Injection temperature: 205˚C

Summary

Alumide® Durability Test

From this case study it was seen that both the mechanically and unsorted grown inserts withstood the 205˚C injection temperatures and 1004 injection moulding shots (with sufficient air cooling) with no visible wear. It was interesting to note that the mechanically grown insert surface temperature was higher than that of the unsorted grown insert. This means that the insert that was grown with more energy, mechanically (slower scanning speed than the unsorted) had a slower heat distribution than the unsorted one.

LaserForm™ ST 100 and LaserForm™ A6 Durability Test

Figure 6.43 shows pictures of the grown inserts inside the DTM 2000 machine, as well as the inserts inside the bolster with the thermocouples connected to measure the internal temperature.

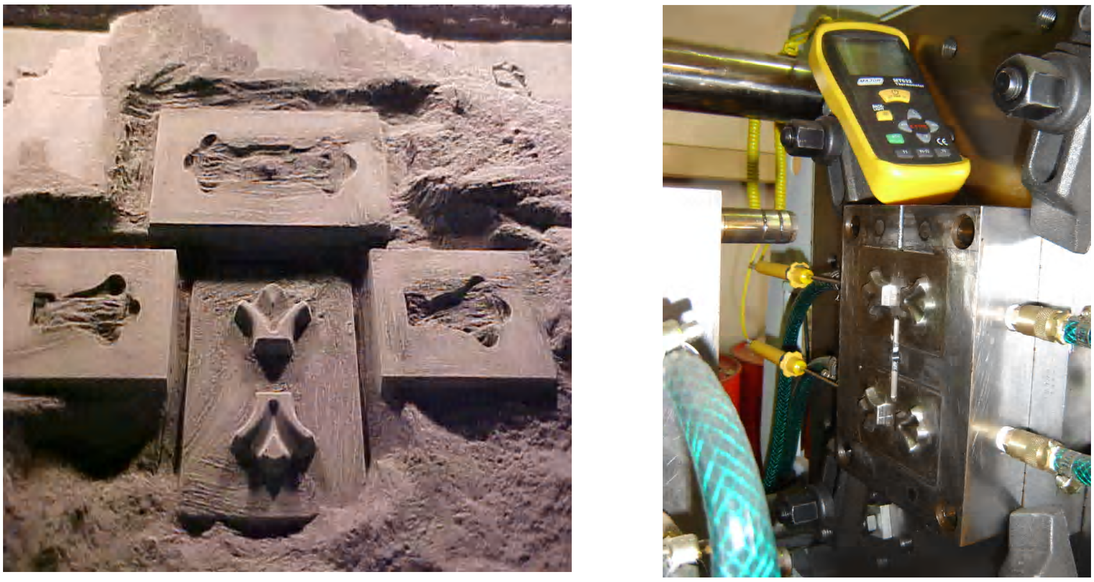


Figure 6.43: Pictures of the grown inserts inside the DTM 2000 machine as well as the inserts inside the bolster

The LaserForm™ A6 grown insert was fitted on the top cavity of both the fixed and moving mould halves. The LaserForm™ ST100 grown insert was fitted on the bottom cavity of both the fixed and moving mould halves. The same injection moulding settings for the machine were used for these trials. The only difference was that no air cooling was applied on the surfaces and the cycle time could be optimized to 17 seconds. The LaserForm™ ST100 and LaserForm™ A6 inserts withstood 100 000 injection moulding shots with no visible wear inside the cavities.

Infiltration Efficiency of the LaserForm™ ST100 Grown Inserts

The following equations are used to determine the infiltration efficiency:

- Infiltration Efficiency = (Weight of infiltrated part / Weight of “green” part x 1.72) x 100 ***[E.1.]***
- (Weight of infiltrant) = (weight of part + weight of tabs) x 0.72 ***[E.2.]***

3D SYSTEMS (process developers) recommends that the infiltration efficiency of inserts has to be 95% or higher. Table 6.46 shows the infiltration efficiency of the LaserForm™ ST100 grown inserts

Table 6.46 Infiltration efficiency of the LaserForm™ ST100 grown inserts

NAME	WEIGHT OF “GREEN” PART	WEIGHT OF TABS	WEIGHT OF BRONZE	WEIGHT OF INFILTRATED PART	INFILTRATION EFFICIENCY
LaserForm™ ST100 Top Cavity	450	0	324	767	99.096%
LaserForm™ ST100 Bottom Cavity	599	0	431	1024	98.625%

Infiltration Efficiency of the LaserForm™ A6 Grown Inserts

The following equations are used to determine the infiltration efficiency:

- Infiltration Efficiency = (Weight of infiltrated part / Weight of "green" part x 1.85) x 100 ***[E.3.]***
- (Weight of infiltrant) = (weight of part + weight of tabs) x 0.85 ***[E.4.]***

The infiltration efficiency of inserts has to be 95% or higher as recommended by the process developers. Table 6.47 shows the infiltration efficiency of the LaserForm™ A6 grown inserts

Table 6.47 Infiltration efficiency of the LaserForm™ A6 grown inserts

NAME	**WEIGHT OF "GREEN" PART**	**WEIGHT OF TABS**	**WEIGHT OF BRONZE**	**WEIGHT OF INFILTRATED PART**	**INFILTRATION EFFICIENCY**
LaserForm™ A6 Top Cavity	602	0	512	1095	98.294%
LaserForm™ A6 Bottom Cavity	759	0	645	1372	97.721%

The different temperature measurements, taken directly after moulding, are shown in Table 6.48.

Table 6.48 The surface and internal temperatures (˚C) of 100 000 shots inside the LaserForm™ ST 100 (T2) and LaserForm™ A6 (T1) inserts

Shot Nr:	T1 Surface A 6 (˚C)	T2 Surface ST 100 (˚C)	T1 Probe A 6 (˚C)	T2 Probe ST 100 (˚C)
1 000	17	17	14	14
2 000	17	17	15	15
3 000	17	17	16	16
4 000	17	16	16	16
5 000	17	16	17	17
6 000	17	16	17	17
7 000	17	17	17	17
8 000	17	17	17	17
9 000	17	17	17	17
10 000	17	17	17	17
11 000	18	18	17	17
12 000	18	18	16	16
13 000	18	18	14	15
14 000	18	18	16	16
15 000	17	17	13	13
16 000	22	21	17	18
17 000	20	19	17	17
18 000	20	20	18	17
19 000	21	21	20	20
20 000	21	20	17	17
21 000	22	22	23	22
22 000	22	22	22	22
23 000	23	23	23	23
24 000	20	19	20	21
25 000	22	22	21	22
26 000	22	22	22	22
27 000	22	22	22	22
28 000	19	19	19	20
29 000	20	20	21	20
30 000	21	21	17	18
31 000	24	24	23	24
32 000	22	22	22	22
33 000	22	22	19	19
34 000	21	21	19	19
35 000	24	24	24	24
36 000	25	26	25	25
37 000	23	23	23	23

38 000	25	24	21	21
39 000	28	28	29	29

Table 6.48 Continued

Shot Nr:	T1 Surface A 6	T2 Surface ST 100	T1 Probe A 6	T2 Probe ST 100
	(˚C)	(˚C)	(˚C)	(˚C)
40 000	24	24	25	25
41 000	25	25	25	25
42 000	20	20	19	19
43 000	23	22	20	20
44 000	22	22	21	21
45 000	25	25	24	24
46 000	24	24	24	24
47 000	21	21	18	18
48 000	23	23	22	22
49 000	22	23	22	22
50 000	25	24	24	24
51 000	27	26	25	25
52 000	22	21	19	19
53 000	22	22	21	21
54 000	24	23	22	22
55 000	25	24	24	25
56 000	23	23	21	21
57 000	21	20	17	18
58 000	22	22	18	19
59 000	23	23	22	22
60 000	23	23	22	22
61 000	23	23	23	23
62 000	23	22	20	20
63 000	23	23	23	23
64 000	26	25	26	27
65 000	23	23	21	21
66 000	26	26	24	23
67 000	25	25	27	28
68 000	23	23	24	25
69 000	23	23	19	20
70 000	22	22	21	21
71 000	24	24	23	23
72 000	25	25	30	30
73 000	24	23	24	25
74 000	24	24	22	23
75 000	23	23	24	25
76 000	27	26	29	28
77 000	26	26	25	26
78 000	23	23	20	21
79 000	23	24	20	21

80 000	26	26	27	27
81 000	25	25	28	29
82 000	26	26	31	32

Table 6.48 Continued

Shot Nr:	**T1 Surface A 6 (˚C)**	**T2 Surface ST 100 (˚C)**	**T1 Probe A 6 (˚C)**	**T2 Probe ST 100 (˚C)**
83 000	26	25	27	28
84 000	24	24	19	19
85 000	25	25	22	23
86 000	24	24	23	23
87 000	24	24	23	23
88 000	27	27	27	28
89 000	26	26	29	30
90 000	27	26	29	30
91 000	26	25	28	29
92 000	27	26	26	27
93 000	26	26	27	28
94 000	25	25	27	28
95 000	28	28	27	27
96 000	28	27	26	26
97 000	27	27	24	24
98 000	28	28	26	26
99 000	29	29	29	29
100 000	29	29	30	31
Average	**22.9 ˚C**	**22.6 ˚C**	**22 ˚C**	**22.3 ˚C**

The data from Table 6.48 was used to plot the following graphs:

- Figure 6.44 shows a graph of the LaserForm™ ST100 surface temperatures
- Figure 6.45 shows a graph of the LaserForm™ ST100 internal temperatures
- Figure 6.46 shows a graph of the LaserForm™ A6 surface temperatures
- Figure 6.47 shows a graph of the LaserForm™ A6 internal temperatures

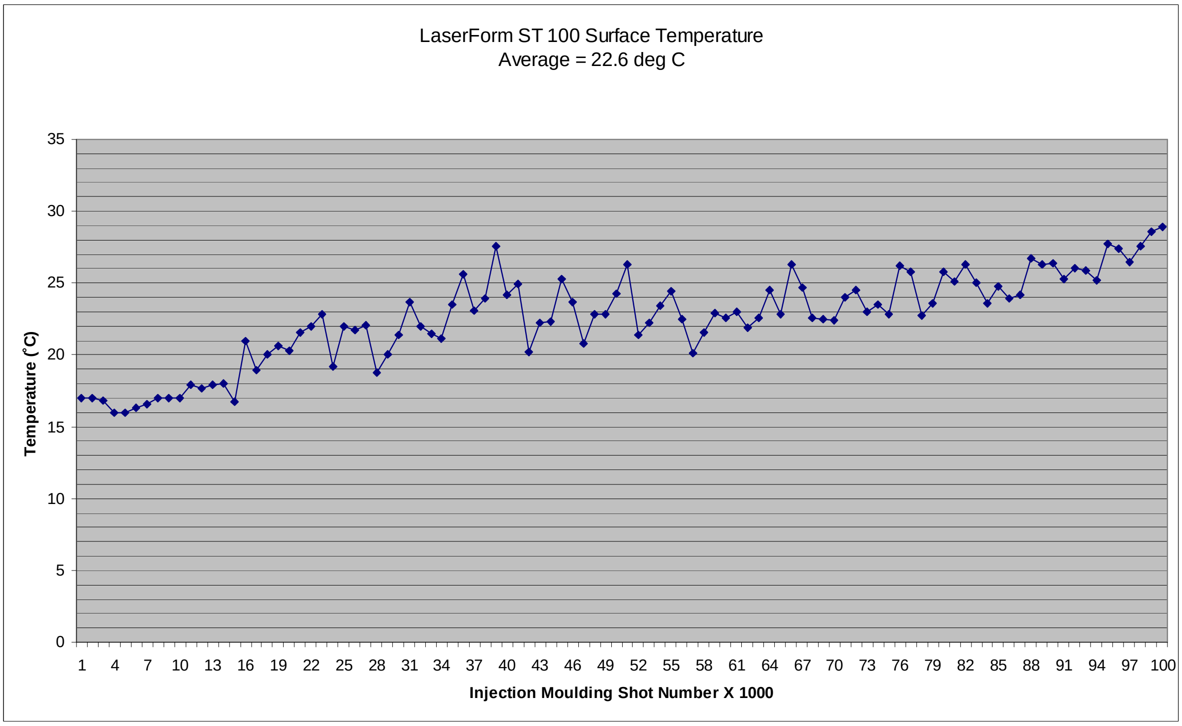


Figure 6.44 LaserForm™ ST100 surface temperatures

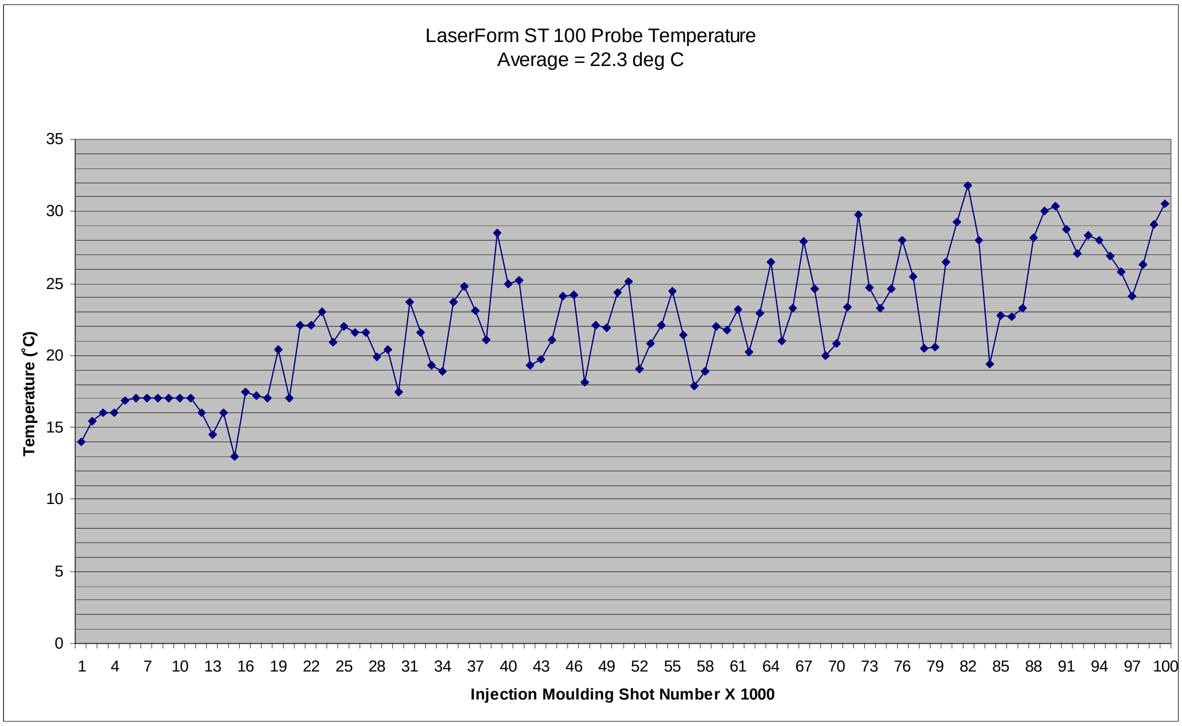


Figure 6.45 LaserForm™ ST100 internal temperatures

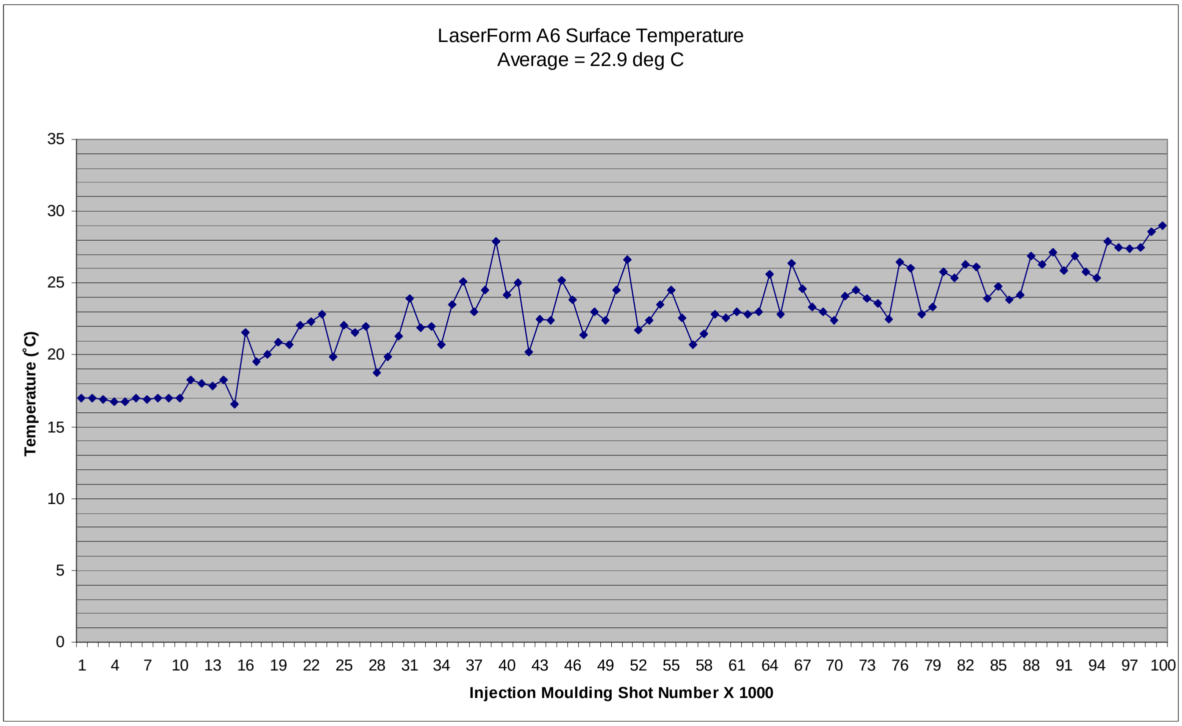


Figure 6.46 LaserForm™ A6 surface temperatures

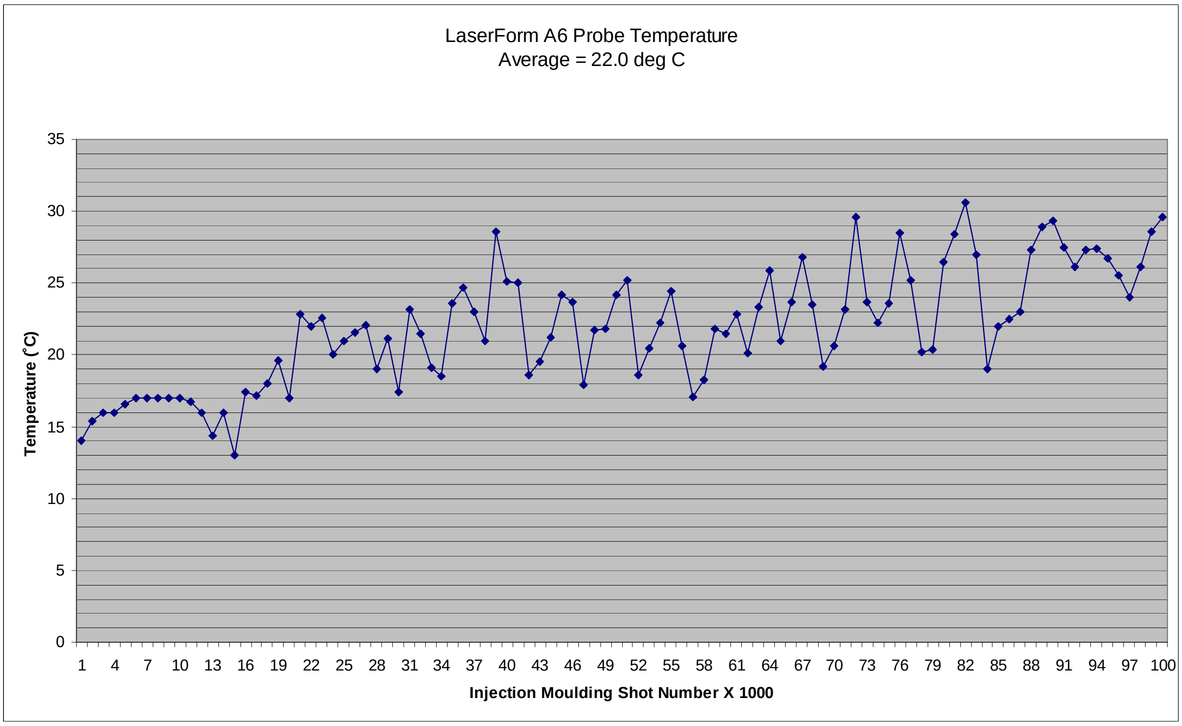


Figure 6.47 LaserForm™ A6 internal temperatures

Summary

LaserForm™ ST 100 and LaserForm™ A6 Durability Test

The SLS process developers stated that it was possible for the LaserForm™ grown inserts to withstand 100 000 injection moulding shots, and this statement was proved with this case study. The cycle time dropped from 25 seconds for the Alumide® inserts, to 17 seconds for the ST100 and A6 inserts without needing any air cooling. The decreasing cycle times and the heat distribution measurements (as shown in Table 6.48) proved that the ST100 and the A6 inserts react in the same way as normal steel and that a production run can be achieved with these inserts.

6.6 CASE STUDY 6: GYNAECOLOGICAL PRODUCT DEVELOPMENT

The CRPM of the Central University of Technology, Free State was asked to assist in the development of a new gynaecological cream applicator. Apart from the fact that the applicator needed a freeform fabrication system to give form, fit and function to the very complex design, the product also needed RT/Rapid Manufacturing.

Initially, only 50 parts were needed, which could have been achieved using vacuum casting/ silicon tooling, but it was necessary to develop a prototype tool for injection moulding, in order to support the following prototype testing and evaluation needs:

- Clinical tests would only be allowed if the product was manufactured in the final Food and Drug Administration (FDA) approved injection moulded rubber and this will eliminate the silicon tooling process.
- To ensure that the dosage would be exactly 6g, a prototype had to be manufactured from a flexible material to measure the delivered dosage with an electronic scale.

CAD Design

The design was done on CAD and evaluated by the customer and his patients, followed by a few minor aesthetic changes, which were applied to the design. The approximate internal volume could be calculated, using the CAD data, to ensure the 6g dosage. A prototype was grown to obtain better representation of the design. The complexity can be seen from Figure 6.48 which shows the completed design and Figure 6.49 shows the CAD of the core.

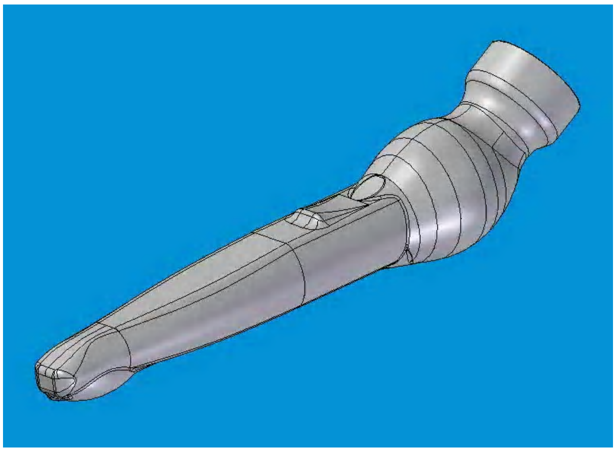


Figure 6.48: CAD design of cream applicator

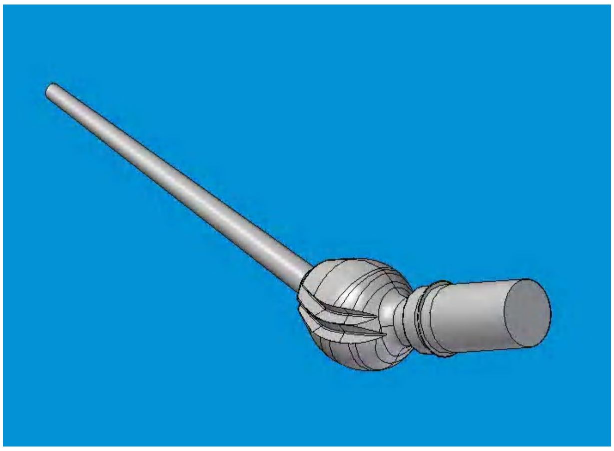


Figure 6.49: Design of the core

The bottom and top half of the tool were manufactured from aluminium by means of a three-axis CNC milling machine. The cost involved with CNC milling the inserts amounted to R 6 042 compared with the cost of growing the inserts on the SLS machine in LaserForm™ ST100 which was R10 630.50, as shown in Table 6.49. An existing bolster was used to accommodate the insert seeing that it was a prototype tool for limited production of parts.

Table 6.49 A cost and time comparison between CNC machining and SLS growing the top and bottom inserts

	Manufacturing time	Cost
CNC Machine aluminium inserts	24 hours	R 6 042.00
LaserForm™ ST100 grown inserts	16.25 hours (without 24 hour oven cycle)	R 10 630.50

It was decided to manufacture a hand-operated tool where the core would be manually pulled out of the product. Figure 6.50 shows the machined bottom half of the tool.

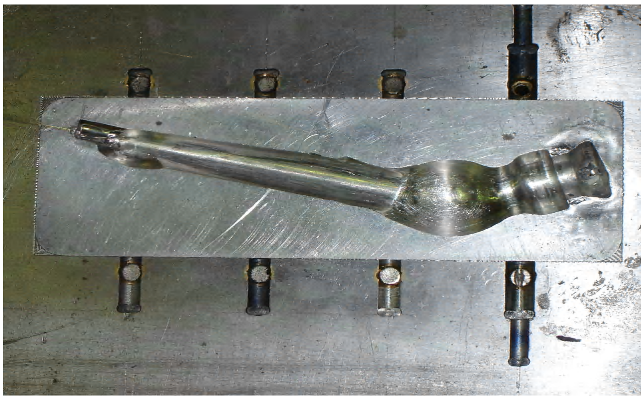


Figure 6.50: Machined bottom half of the tool

The shape of the product's corresponding core was very complex and needed five-axis CNC machining. Not having direct access to five-axis CNC machining, it was decided to grow a core with a DTM SLS 2000 machine, using LaserForm™ ST-100 steel. Table 6.50 shows the cost to produce the LaserForm™ ST100 core.

Table 6.50 The cost of producing the LaserForm™ ST100 grown core

	Manufacturing time	Cost
LaserForm™ ST100 grown core	4.75 hours (without 24 hour oven cycle)	R 2126.10

As seen in Figure 6.49, the design included a high level of complexity and detail, such as the ribs on the side of the ball, as well as a very thin and long shaft - all problematic for machining. By growing the core in LaserForm™ ST100, the product could be tested and the design (and corresponding core geometry) adjusted until the correct dosage was reached. Figure 6.51 shows the prototyped core in LaserForm™ ST100.

Figure 6.51: LaserForm™ ST100 grown core

Manufacturing of Functional Prototypes

Injection moulding was done by using a single-cavity tool. The moulded part (including the core) had to be removed from the tool by hand, following the hand-removal of the core from the product. After each cycle the core had to be placed back in the tool by hand, before a next cycle could start. The cycle time of 135 seconds/product was lengthy, but it was acceptable as only the 50 products needed to be manufactured for clinical tests. Figures 6.52 and 6.53 show the completed prototype tool, and the final part from the tool.

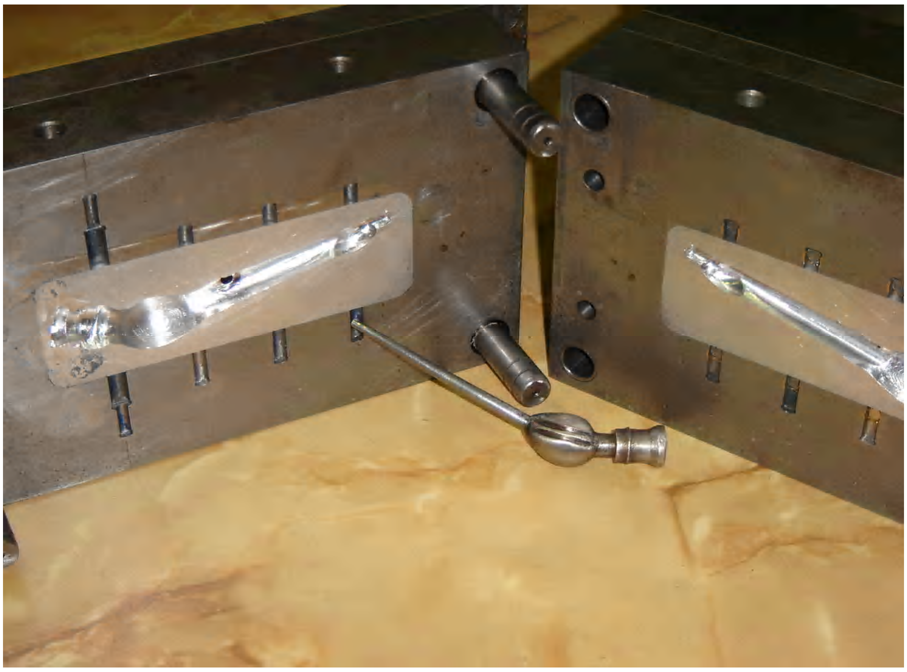


Figure 6.52: Prototype tool

Figure 6.53: Functional prototype

Summary

The gynaecologist was quoted R250 000 for a double cavity production tool. As the product was not yet proven (neither in terms of functionality, or accuracy of the dosage), the client could not consider manufacturing the moulds, and thus had no way of proving the product.

In order to market this idea to pharmaceutical companies, clinical trials are needed, which in turn requires products manufactured from FDA approved materials. Furthermore, products from this case study in the FDA material are required to test the dosage, and if not correct, to use the results for design iteration. This could lead to further redesigning and remanufacturing to reach the final proven stage.

Using the different technologies available and stages as discussed, the client invested/spent R32 000 on the development of the product. The technologies used resulted in a final product, which could be used to market the product to pharmaceutical companies without spending money on the production tool, prior to receiving orders. The size of the firm orders placed will determine which size production tool should be manufactured.

[2]

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

7.1.1 Case Study 1

As seen from the results of this case study, the three inserts' geometry was of such a nature that it was appropriate to manufacture it with normal CNC milling. Apart from the fact that it was easier/faster to manufacture the inserts with CNC milling, it was also more cost effective. The material cost of the SLS produced inserts alone (R 19 000), was higher than the total costs associated with the conventional tooling produced inserts (R 12 900). The higher cost of the SLS produced inserts is directly connected to the larger building volume of the inserts [see page 94]. The larger building volume takes up too much building time and associated material cost. Each project must be evaluated to find the most suitable manufacturing process.

A possible way to address this problem is to hollow out the geometry of the insert (5 mm wall thickness) as can be seen from Figures 7.1 and 7.2. The material cost of the proposed thin-shelled geometry will be R7514, which will save R11 486 on the material cost of the SLS produced inserts.

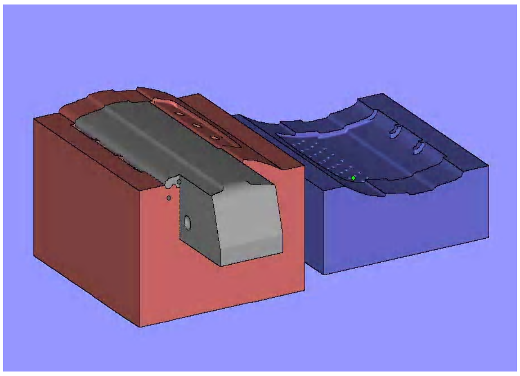


Figure 7.1: SLS produced inserts

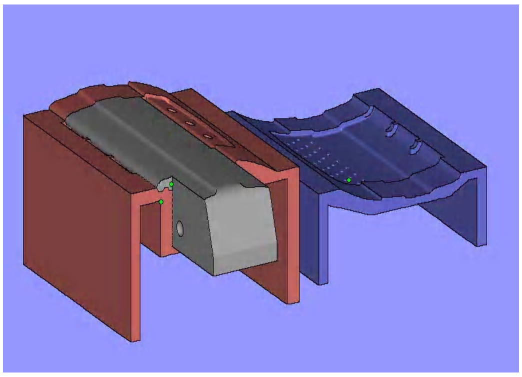


Figure 7.2: Proposed SLS thin-shelled geometry

The total cost of one set of inserts (1 cavity, 1 core and 1 slide) with the proposed thin-shelled geometry is detailed below:

<u>SLS Cost Analysis:</u>

Growing time on SLS machine	=	R 8492-00
Material cost – LaserForm™ ST 100 inserts (709 057 mm^3)	=	R 7514-00
Finishing of inserts	=	R 400-00
TOTAL	=	**R 16 406-00**

<u>SLS Growing Time Analysis:</u>

Growing time of three inserts on DTM 2000 machine	=	37 hours
Post-processing time of inserts inside the oven cycle	=	24 hours
Finishing time	=	4 hours
TOTAL	**=**	**65 hours**

Table 7.1 shows cost/time comparisons between the SLS and conventional tooling produced inserts.

Table 7.1 A cost/time comparison between the SLS and conventional tooling produced inserts

	SLS produced insert – original geometry (figure 7.1)	SLS produced insert – proposed geometry (figure 7.2)	Conventional Tooling produced insert
Insert cost	R 33 170.00	R 16 406.00	R 12 900.00
Production time of insert	88 hours	65 hours	37 hours

When comparisons are drawn between the original geometry and the proposed geometry, the SLS produced insert with the proposed thin-shelled geometry will save up to 50 % in cost and 26 % in time.

As the DMLS (EOS) M250 Xtended was purchased towards the completion of the research, the growing of the tools using on the DMLS process was also investigated. A theoretical analysis shows that the same thin-shelled geometry will take 43 hours to grow at an estimated price of R 28 750. It should, however, be kept in mind that the DMLS grows between 60 and 20µm layer thickness, for which the 60 µm was used in the calculation, opposed to the 80µm of the SLS process which was used in this research project.

The following conclusion can be drawn from this case study:

1. As seen from Table 7.1, the production of the conventional tooling inserts was faster than the SLS inserts, but if a thin-shelled geometry is be used, the cost and time margin will be reduced.
2. The Sintering process is better suited to smaller inserts with more detail that requires extensive EDM work.
3. Cooling channels need to be designed in a linear fashion for a two stage sintering process, to ensure that they can be cleared if they become blocked during the post cure process.
4. The parts must be grown in the correct axis, to achieve a better surface finish as well as better accuracy, to ensure good shut-offs on the sliding cores. Critical surfaces and holes need to be orientated in the direction (parallel) of the laser to minimise the stair-stepping effect through that surface
5. On the design files extra stock can be placed on critical surfaces which can then be cleaned off by CNC milling.

7.1.2 Case Study 2

A total of 3500 parts were produced in the inserts without any visible wear inside the tool. Figure 7.3 shows the surface that was extruded 0.5 mm in the design file to allow extra stock, which was surface-ground after the post-treatment phase. This principle worked very well to ensure good shut-off surfaces which are essential for plastic injection moulding.

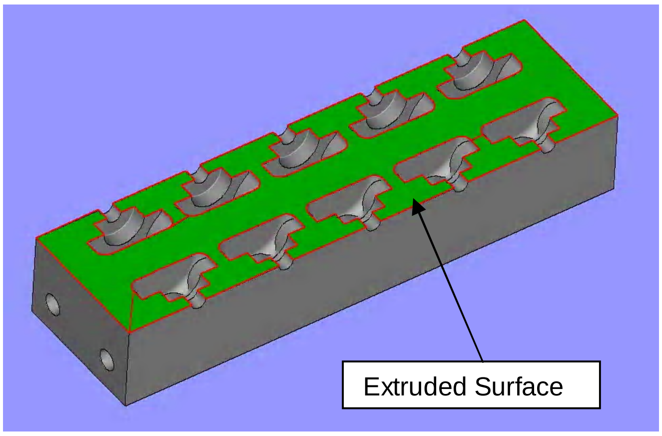


Figure 7.3: SLS produced insert with the extruded surface

To optimize the cost and time savings, it was decided to analyze the geometry to determine whether it is possible to remove some parts of the geometry to minimise the material cost of the SLS process. Figure 7.4 shows the original design geometry and Figure 7.5 shows the proposed thin-shelled geometry, which was hollowed out to a 5 mm wall thickness. The material cost of the proposed thin-shelled geometry will amount to R 4905, which will save R 2253 on material cost on the SLS produced inserts.

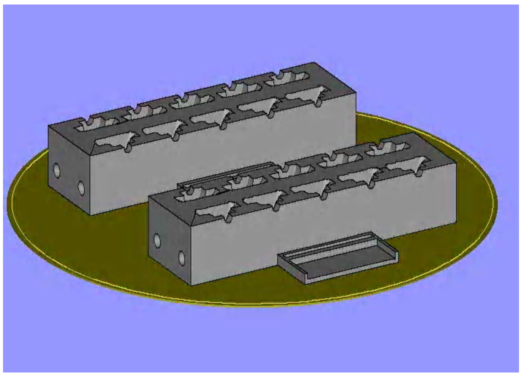


Figure 7.4: SLS produced inserts

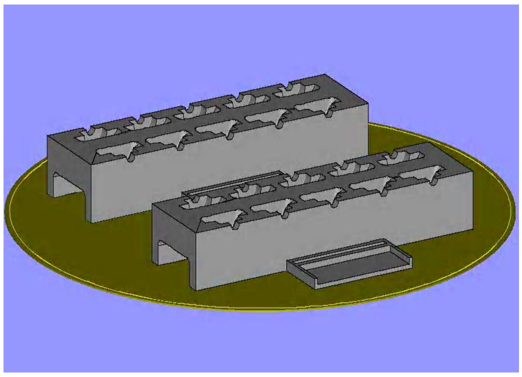


Figure 7.5: Proposed SLS thin-shelled geometry

The total cost of one set of inserts with the proposed thin-shelled geometry is detailed below:

<u>SLS Cost Analysis:</u>

Growing time on SLS machine	=	R 4131-00
Material cost – LaserForm™ ST 100 inserts (462 840 mm^3)	=	R 4905-00
Finishing of inserts	=	R 800-00
TOTAL	=	**R 9836-00**

<u>SLS Growing Time Analysis:</u>

Growing time of two inserts on DTM 2000 machine	=	18 hours
Post-processing time of inserts inside the oven cycle	=	24 hours
Finishing time	=	8 hours
TOTAL	**=**	**50 hours**

Table 7.2 shows cost/time comparisons between the SLS and conventional tooling produced insert.

Table 7.2 A cost/time comparison between the SLS and conventional tooling produced insert

	SLS produced insert – original geometry (figure 7.4)	SLS produced insert – proposed geometry (figure 7.5)	Conventional Tooling produced insert
Insert cost	R 13 466.00	R 9836.00	R 15 000.00
Production time of insert	56 hours	50 hours	38 hours

When comparing the SLS produced insert (Table 7.2) to the proposed SLS produced inserts, the thin-shelled geometry will save up to 27 % in cost and 11 % in time. A theoretical analysis, as described on p.188, was once again done on the DMLS process which shows that the same thin-shelled geometry will take 25 hours to grow at an estimated price of R 17 195. This analysis was done on a 60μm layer thickness, opposed to the 80μm which was used for the SLS process.

Because the SLS machine can run unattended for extended periods, the inserts can be produced in 2.5 days compared to almost a week's work (8 hours work day) to manufacture the inserts using the conventional tooling processes. This case study shows that if smaller geometry inserts are needed, they can be produced cheaper and faster by using the SLS process, rather than using the conventional approach. Optimization of the design is necessary to achieve this. The idea is to minimize the growing geometry to complex areas and to machine the larger areas using CNC machining.

7.1.3 Case Study 3

Initially only 30 trial samples were moulded inside the Alumide® inserts using a flame retardant ABS material. By using air cooling and prolonging the cycle time to four minutes, another 850 parts were moulded. The cycle time of Alumide® produced inserts is longer than conventionally produced inserts, but can still be used if a small production run is required. For example, when 500 parts are required, a cycle time of four minutes can still produce 120 parts in an 8 hour work day, or can even be increased with the introduction of shifts when urgent production is needed.

Extra stock of 0.3 mm was placed in the design file on the split line and shut-off surfaces to allow for growing tolerances. The growing accuracy was acceptable and the extra stock was not necessary. It was time-consuming to remove the extra material, which implies that in future extra stock will only be placed on critical areas, such as shut-off surfaces.

The moulds required 23 hours of prototyping (one build volume), with four days of finishing and fitting, which meant that the injection-moulding could start less than a week after finalizing the design. Approximate mould cost was R23 000, opposed to R90 000 (conservatively estimated).

7.1.4 Case Study 4

The aim of this case study was to test the shrinkages inside grown inserts during injection moulding. The materials used to grow the inserts are LaserForm™ ST100, LaserForm™ A6 Tool Steel and Alumide®. Around thirty six injection moulding shots were injected into the 2 cavity grown inserts. The injection moulding shots followed each other without any cooling. The test specimens were measured and Table 7.3 shows the average shrinkage values obtained in the Alumide®, LaserForm™ ST100 and LaserForm™ A6 inserts during the injection moulding process.

Table 7.3 The average shrinkage values

Material	**Reading 1**	**Reading 2**	**Reading 3**	**Reading 4**	**Reading 5**
Alumide®:					
Right part: Average Shrinkage	**1.54%**	**1.57%**	**0.43%**	**1.98%**	**1.30%**
Left part: Average Shrinkage	**1.60%**	**1.65%**	**0.55%**	**2.01%**	**0.15%**
LaserForm™ ST100:					
Right part: Average Shrinkage	**2.49%**	**2.46%**	**1.38%**	**2.10%**	**2.33%**
Left part: Average Shrinkage	**2.36%**	**2.39%**	**0.96%**	**2.00%**	**1.90%**
LaserForm™ A6:					
Right part: Average Shrinkage	**1.47%**	**1.54%**	**1.22%**	**1.62%**	**1.70%**
Left part: Average Shrinkage	**1.85%**	**1.97%**	**0.56%**	**1.56%**	**1.04%**

As can be seen from the abovementioned table, the shrinkages obtained inside the grown inserts are very close to the shrinkages of polypropylene inside normal tool steel (1 to 2.5 % shrinkage) [19 p 172].

7.1.5 Case Study 5

The objective of this case study was to test the durability of the Alumide®, LaserForm™ ST 100 and LaserForm™ A6 inserts. After injection, the surface as well as the internal temperatures of the inserts were taken in order to identify the heat distribution of the inserts. The goal of this study was to realize 1000 injection moulding shots into the Alumide® inserts, and 100 000 shots into the LaserForm™ ST100 and LaserForm™ A6 inserts.

a) Alumide®

This case study proved that the Alumide® inserts could withstand the injection temperatures of 205˚C repeatedly and 1004 injection moulding shots were made into these inserts. This was a unexpected achievement, especially when taking into account that both the mechanically and unsorted grown inserts were sintered at ± 180 ˚C.

Table 7.4 clearly indicates a significant difference in surface temperatures measured on the "mechanical" and "unsorted" inserts. The latter only reached 51 ˚C after 1013 injection moulding shots, whilst the "mechanical" inserts raised up to 78 ˚C after the same number of shots. Referring back to the definitions for "unsorted" and "mechanical", it was expected that the mechanical-grown insert would be better (stronger) for injection moulding tooling. The results however proved that both parameters are suited for injection moulding and that the unsorted grown parts functioned at lower surface temperatures.

Therefore, if 1000 shots are needed, it is better to grow the inserts (depending on the geometry) using the unsorted exposure parameter, because the unsorted insert has a lower surface temperature and will take longer for the parts to bond to the surface. If the air cooling is optimized, the cycle times can also be decreased.

Table 7.4 The last nine temperature measurements after no air cooling was applied to the surface and the part bonded to the mechanically grown insert on shot 1013

Shot Nr:	T1 Probe/ mechanically	T2 Probe/ unsorted	T1 Surface/mechanical After Shot	T2 Surface/unsorted After Shot
Average	35.1	38.3	68.4	52.6
1005	23	22	46	39
1006	25	27	57	43
1007	30	34	69	43
1008	33	38	75	57
1009	36	42	70	51
1010	40	44	74	56
1011	40	43	71	67
1012	44	47	76	66
1013	45	48	78	51

The surface cooling (compressed air) that was applied to these inserts worked well, but it prolonged the injection moulding cycle time. In-depth research needs to be done in heat transfer within the Alumide® inserts, as well as appropriate conformal cooling close to the surface of the insert, because the water cooling that was implemented in these tests was in the bolsters only and too far away from the surface which had no effect on the cooling of the insert.

b) LaserForm™ ST100 and LaserForm™ A6

The LaserForm™ ST 100 as well as the LaserForm™ A6 grown inserts withstood 100 000 injection moulding shots. The maximum surfaces as well as the probe temperatures were recorded as follows:

- Highest surface temperature LaserForm™ A6 = 29˚C
- Highest surface temperature LaserForm™ ST100 = 29˚C
- Highest probe temperature LaserForm™ A6 = 32˚C
- Highest probe temperature LaserForm™ ST100 = 34˚C

The cycle time dropped from 25 seconds for the Alumide® inserts, to 17 seconds for the ST100 and A6 inserts without the necessity for any air cooling. The decreased cycle times and the heat distribution measurements (as shown in Table 6.48) proved that the ST100 and the A6 inserts react in the same way as normal steel and that typical production quantities can be produced with these inserts.

As can been seen from Table 7.5, the Alumide® grown inserts are 50% cheaper and are produced in almost 25% of the time necessary for the LaserForm™ produced inserts. The growing time is much faster than the LaserForm™ inserts and no post-curing (oven cycle) is needed afterwards, as it can affect the accuracy of the inserts.

Furthermore, Alumide® enables the smaller inserts to be grown over night, which will then be ready for fitment in the bolster the next day. The only drawback is that the surface quality of the Alumide® produced inserts are not as good as the LaserForm™ inserts. The Alumide® inserts are produced with a layer thickness of 0.15 mm and the LaserForm™ inserts are produced using 0.08 mm. LaserForm™ inserts can still be used if larger production runs (50 000 parts and above) are needed, as well as if a very good surface finish is necessary.

Table 7.5 A cost and time comparison between Laserform™ ST100, Laserform™ A6, Alumide® - mechanical, Alumide® - unsorted and Conventional machining

MATERIAL	GROWING TIME	COST OF TWO INSERTS (excl VAT)
LaserForm™ ST100	22 hours 15 min	R 11 223
LaserForm™ A6	19 hours 30 min	R 10 585
Alumide® - mechanical	4 hours 6 min	R 4980
Alumide® - unsorted	2 hours 54 min	R 4505
Conventional machining	18 hours 32 min	R 8967

A theoretical analysis was done on the DMLS process, as described on p.188, and this shows that the same geometry will take 14 hours to grow on the M250 Xtended machine at an estimated price of R 9040. This analysis was done on a

60μm layer thickness, opposed to the 80μm which was used for the SLS (LaserForm™) process.

7.1.6 Case Study 6

As can be seen from Tables 7.6 and 7.7, to find the most economical and appropriate manufacturing solution, it is advisable to combine conventional mould making techniques with RT techniques to develop “hybrid” moulds, where certain parts of the tooling can be grown, and inserted into/onto parts machined with conventional techniques. This approach will be lead by the tool-geometry.

Table 7.6 A cost and time comparison between CNC machining and SLS growing the top and bottom inserts

	Manufacturing time	Cost
CNC Machine aluminium inserts	24 hours	R 6 042.00
LaserForm™ ST100 grown inserts	16.25 hours (without 24 hour oven cycle)	R 10 630.50

Table 7.7 The cost of producing the LaserForm™ ST100 grown core

	Manufacturing time	Cost
LaserForm™ ST100 grown core (80μm layer thickness)	4.75 hours (without 24 hour oven cycle)	R 2 126.10

As described on p.188, a theoretical estimate was done on the DMLS process, which shows that the core geometry (60µm layer thickness) will take 3 hours 20 min to grow on the M250 Xtended machine at an estimated price of R 2140.

7.2 RECOMMENDATIONS

7.2.1 Insert Geometry

Larger, less complex inserts are better suited to normal CNC milling. To attain fine features inside a complex insert, like thread or fine writing, conventionally required the EDM process. However, the disadvantage of EDM is that it is a time-consuming process and such inserts will be better suited to grow on the SLS or LS process. Each injection moulding tool must be evaluated to see whether it has large areas that can be CNC-machined or fine thread or detail that can be grown directly on the SLS/LS machine. If surface finish is not the primary concern (such as a spark-eroded surface finish), Alumide® grown inserts can be a more economical option to the SLS process, but the limitation is a mould life of ±1000 parts. A combination of these processes will give a better solution, but the process selection will be determined by the geometry of the tools. Further research will have to be done to find methods to align these grown/machined inserts with each other in such a way that no marks are visible on the moulded products and to ensure good shut-off surfaces. The time/cost calculations done on the thin-shelled inserts also proved that the material cost as well as growing time (which both translate to cost savings) can be reduced. The thin-shelling can also help with the reduction in distortion of the parts during the post treatment of the SLS process, because the internal stresses are reduced in parts that have a thinner wall thickness.

7.2.2 Accuracy

To improve the accuracy of the SLS process, it is necessary to have a direct laser sintering process with no post-cure treatment, for example oven cycle. Out of the study it was seen that the warp-age through the oven cycle (LaserForm ™ A6) caused the largest deviation in Z-direction of 19.43% and the smallest deviation of 1.78%. The distressing factor is that these two deviations were supposed to be a parallel surface to the shut-off surface. It is difficult to control the shrinkages through two processes (sintering and oven cycle) and it was also seen that some parts distorted during the oven cycle. It is almost impossible to use these distorted parts, as cores and good shut-off surfaces cannot be achieved.

To improve the accuracy of the LS process using the Alumide® material, more test parts, with known geometry, must be grown and measured, to build a user-database. As the process is repeated, the accuracy of the parts will improve. The LS process is a one stage process and no post-curing/oven cycle is necessary.

7.2.3 Durability and Shrinkages

The case studies proved that the Alumide® inserts can be subjected to more than 1000 injection moulding shots. The LaserForm™ ST100 and the LaserForm™ A6 inserts proved to be durable for more than 100 000 injection moulding shots. The abovementioned results are dependant on tool geometry as these moulds were normal open and close moulds without any sliding cores. It is thus recommended that metal sintered core or inserts are used to replace detail areas, which will be time-consuming to machine. During the injection moulding process, the shrinkages in the grown inserts were approximately the same as the shrinkages of normal tool steel.

7.2.4 Feasibility of RT in South Africa

During the last two years, the CRPM has experienced a rapid increase in demand for limited run production in an injection moulding material. Excellent results have been achieved through this study, which proved the applicability of the technology. The goals/objectives which were set initially are:

- determine the cost effectiveness of grown inserts,
- determine the durability of grown inserts,
- determine the accuracy of grown inserts,
- determine the shrinkages obtained inside the grown inserts during injection moulding,
- determine the manufacturing time of the grown inserts.

The abovementioned goals/objectives were all achieved and through a number of successful case studies which has set the stage for the use of RT in SA.

7.3 FUTURE WORK

Currently, there are various uncertainties regarding RT in SA, which necessitates further research in this regard, namely:

- The impact of the Direct Metal Laser Sintering System (EOSINT M250 Xtended) which was introduced into SA after completion of the experimental work;
- Surface finishing of sintered parts (Alumide® and Metal);
- Further case studies to guide potential RT users in the selection of either Alumide® and DMLS inserts, especially taking geometry, surface finish, cycle time and costs into account;
- An investigation into surface-finishing techniques that will not affect accuracy, but will enhance the resultant product so as to be comparable to that available from conventional processes;
- The possibility to use internal cooling, and the enhancement thereof through conformal cooling, which for the first time will really be possible;
- The design/development of hybrid tooling design and development techniques.

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Appendix A

ALUMIDE® DURABILITY TEST

Table A1: Surface and Internal temperatures when 30 seconds air cooling was applied on the left and then 30 seconds on the right side of the mould (first 100 shots)

Shot Nr:	T1 Probe/ mechanical	T2 Probe/ unsorted	T1 Surface/mechanical		T2 Surface/unsorted	
			After Shot	After Cooling	After Shot	After Cooling
Average	**27.8**	**27.2**	**53.3**	**23.2**	**47.4**	**22.4**
1	14	14	33	X	30	X
2	19	19	33	X	29	X
3	21	22	30	X	30	X
4	23	23	30	X	29	X
5	23	23	34	X	32	X
6	24	24	34	X	31	X
7	24	23	35	X	32	X
8	24	23	35	X	33	X
9	24	24	40	X	33	X
10	24	24	43	X	35	X
11	25	24	46	X	42	X
12	25	24	52	X	45	X
13	25	24	53	X	47	X
14	25	24	52	X	46	X
15	25	24	54	X	47	X
16	25	25	55	X	47	X
17	24	24	51	X	45	X
18	24	23	51	X	44	X
19	24	23	50	X	45	X

20	25	24	50	X	43	X
21	24	23	52	X	43	X
22	25	24	50	X	44	X
23	24	22	50	X	43	X
24	22	21	52	X	44	X
25	23	23	54	X	46	X
26	25	24	53	X	46	X
27	25	25	53	X	46	X
28	27	26	56	X	49	X
29	26	25	53	X	46	X

Table A1: Continued

Shot Nr:	**T1 Probe/ mechanical**	**T2 Probe/ unsorted**	**T1 Surface/mechanical**		**T2 Surface/unsorted**	
			After Shot	**After Cooling**	**After Shot**	**After Cooling**
Average	**27.8**	**27.2**	**53.3**	**23.2**	**47.4**	**22.4**
30	26	26	57	X	49	X
31	27	26	59	X	50	X
32	26	25	56	X	47	X
33	27	26	51	X	48	X
34	28	27	57	X	49	X
35	28	27	56	X	48	X
36	27	26	53	X	47	X
37	28	27	52	X	47	X
38	28	27	50	X	44	X
39	28	27	46	X	38	X
40	28	28	58	X	50	X
41	28	27	54	X	48	X
42	29	28	55	X	49	X
43	29	28	55	24	48	22
44	29	28	40	24	36	23
45	29	28	54	23	47	22
46	29	28	52	25	46	22
47	29	28	57	23	50	21
48	29	27	50	22	48	22
49	29	28	52	21	47	21
50	29	28	56	22	50	20
51	29	28	54	22	48	22
52	29	28	48	23	44	22
53	29	28	57	22	50	20
54	29	28	58	23	50	21
55	29	28	53	23	47	22
56	29	29	56	23	49	22
57	29	28	57	24	51	23

58	29	28	53	21	47	21
59	29	28	57	23	49	21
60	29	28	57	22	49	22
61	29	28	55	23	48	24
62	29	29	57	24	49	24
63	29	29	56	23	53	23
64	30	29	56	27	51	26
65	29	29	57	22	51	22
66	29	29	57	23	50	23

Table A1: Continued

Shot Nr:	**T1 Probe/ mechanical**	**T2 Probe/ unsorted**	**T1 Surface/mechanical**		**T2 Surface/unsorted**	
			After Shot	**After Cooling**	**After Shot**	**After Cooling**
Average	**27.8**	**27.2**	**53.3**	**23.2**	**47.4**	**22.4**
67	30	29	58	24	50	24
68	30	29	57	23	56	23
69	30	29	57	22	53	22
70	29	29	55	23	52	23
71	29	28	58	23	54	23
72	29	29	58	24	54	23
73	30	29	57	23	50	22
74	29	29	58	23	55	23
75	29	28	59	23	56	22
76	29	28	58	24	54	23
77	29	29	57	25	56	23
78	30	29	56	24	53	23
79	31	33	68	23	58	22
80	34	33	60	23	49	23
81	34	32	56	23	53	22
82	30	33	58	24	56	23
83	34	33	58	23	57	22
84	34	33	56	21	54	21
85	34	33	56	23	54	23
86	32	33	57	23	54	23
87	30	33	56	24	53	24
88	31	33	58	22	50	21
89	34	33	58	23	53	23
90	34	33	64	24	51	23
91	33	32	58	24	49	24
92	31	30	57	24	52	24
93	31	30	64	23	55	22
94	30	29	66	24	54	23

95	30	29	63	24	51	23
96	29	28	58	23	51	21
97	28	26	62	24	52	22
98	28	26	54	23	51	21
99	28	26	54	23	50	21
100	26	25	54	24	48	22

Table A2: Surface and Internal temperatures when 30 seconds air cooling was applied on the left and then 30 seconds on the right side of the mould (remainder of shots)

Shot Nr:	**T1 Probe/ mechanical**	**T2 Probe/ unsorted**	**T1 Surface/mechanical**		**T2 Surface/unsorted**	
			After Shot	**After Cooling**	**After Shot**	**After Cooling**
Average	**22.8**	**23.5**	**51.0**	**22.6**	**43.3**	**21.0**
101	17	18	40	18	35	17
102	23	22	44	19	39	18
103	23	22	44	19	38	18
104	26	27	49	20	43	19
105	27	26	52	20	45	19
106	27	26	52	20	47	19
107	27	26	56	20	46	19
108	27	27	54	22	47	19
109	27	26	54	21	48	20
110	27	26	56	20	48	19
111	27	26	53	21	46	20
112	27	26	56	22	47	20
113	27	27	59	22	50	20
114	27	27	54	21	45	20
115	26	26	55	22	47	20
116	27	27	57	22	50	19
117	27	26	56	20	48	18
118	27	26	54	21	47	19
119	27	26	55	21	47	19
120	27	26	51	23	46	20
121	24	23	54	22	46	20

122	23	23	50	21	47	20
123	19	21	55	21	48	19
124	19	22	55	21	48	20
125	18	21	56	23	48	20
126	18	21	56	23	49	21
127	18	21	63	24	50	22
128	18	21	54	20	53	19
129	18	20	54	21	47	20

Table A2: Continued

Shot Nr:	T1 Probe/ mechanical	T2 Probe/ unsorted	T1 Surface/mechanical		T2 Surface/unsorted	
			After Shot	After Cooling	After Shot	After Cooling
Average	**22.8**	**23.5**	**51.0**	**22.6**	**43.3**	**21.0**
130	18	21	55	23	49	21
131	18	21	56	24	49	22
132	18	21	55	24	50	21
133	18	21	57	23	51	21
134	18	21	53	24	47	21
135	18	21	55	23	49	20
136	18	21	54	22	48	20
137	18	21	48	23	40	20
138	18	21	50	22	42	20
139	18	21	51	23	46	20
140	18	21	51	22	43	19
141	18	21	51	21	44	19
142	18	20	51	23	46	20
143	18	21	49	23	46	20
144	18	21	50	23	38	20
145	18	21	49	21	40	20
146	18	21	52	21	37	19
147	18	21	49	22	42	20
148	18	21	50	22	39	20
149	18	21	48	23	39	21
150	19	22	50	23	40	20
151	16	18	40	19	38	19
152	20	20	51	22	43	21

153	22	23	57	22	40	20
154	23	23	47	22	37	20
155	24	24	50	22	42	20
156	24	24	50	22	40	20
157	25	24	50	23	40	19
158	25	24	50	24	38	21
159	25	24	51	23	42	21
160	25	24	46	22	38	21
161	25	24	51	22	39	21

Table A2: Continued

Shot Nr:	**T1 Probe/ mechanical**	**T2 Probe/ unsorted**	**T1 Surface/mechanical**		**T2 Surface/unsorted**	
			After Shot	**After Cooling**	**After Shot**	**After Cooling**
Average	**22.8**	**23.5**	**51.0**	**22.6**	**43.3**	**21.0**
162	25	24	52	21	43	19
163	25	24	50	21	37	20
164	25	24	47	22	44	21
165	25	24	55	22	44	20
166	25	24	47	23	43	22
167	25	25	53	23	49	21
168	25	25	48	22	49	20
169	25	24	49	22	43	21
170	25	25	49	24	39	21
171	25	25	51	23	39	22
172	25	25	48	23	38	22
173	25	25	50	24	39	24
174	25	24	47	22	40	21
175	25	24	51	23	40	22
176	25	24	49	23	39	21
177	25	24	49	24	39	22
178	25	24	49	24	44	22
179	25	25	51	25	44	22
180	25	25	52	24	39	21
181	24	24	53	24	46	22
182	24	24	47	24	37	23
183	24	24	50	24	43	23
184	24	24	51	23	43	22

185	24	24	49	25	40	24
186	24	25	50	24	38	23
187	24	24	47	25	50	23
188	24	24	51	24	39	22
189	24	24	53	24	43	22
190	24	24	54	25	39	22
191	24	24	49	24	43	22
192	23	23	51	24	42	22

Table A2: Continued

Shot Nr:	**T1 Probe/ mechanical**	**T2 Probe/ unsorted**	**T1 Surface/mechanical**		**T2 Surface/unsorted**	
			After Shot	**After Cooling**	**After Shot**	**After Cooling**
Average	**22.8**	**23.5**	**51.0**	**22.6**	**43.3**	**21.0**
193	23	24	49	24	42	23
194	23	24	49	23	43	21
195	24	23	52	24	41	22
196	24	24	52	24	39	22
197	24	24	50	24	45	23
198	24	24	51	24	43	23
199	23	24	51	24	46	22
200	23	24	47	23	50	22
201	23	23	50	24	50	22
202	23	24	50	24	48	22
203	23	24	49	27	44	26
204	24	25	48	23	43	23
205	23	24	50	23	42	24
206	23	23	50	24	44	22
207	23	24	50	25	48	23
208	23	24	51	25	43	22
209	23	24	48	24	46	23
210	23	24	61	23	42	22
211	22	23	57	24	36	23
212	21	23	47	23	42	22
213	23	24	51	22	45	21
214	20	23	52	23	41	22
215	19	23	48	22	41	22

216	24	24	56	21	46	21
217	21	23	48	22	48	20
218	24	24	49	22	38	21
219	24	24	42	22	36	21
220	23	23	50	22	38	21
221	23	24	52	24	41	22
222	23	24	51	23	41	21
223	23	24	51	22	43	21

Table A2: Continued

Shot Nr:	**T1 Probe/ mechanical**	**T2 Probe/ unsorted**	**T1 Surface/mechanical**		**T2 Surface/unsorted**	
			After Shot	**After Cooling**	**After Shot**	**After Cooling**
Average	**22.8**	**23.5**	**51.0**	**22.6**	**43.3**	**21.0**
224	23	24	48	23	45	22
225	22	23	49	22	43	22
226	22	23	53	22	52	23
227	21	23	48	23	50	22
228	21	23	53	23	47	22
229	20	23	52	22	38	22
230	24	24	49	21	41	21
231	24	24	51	24	41	22
232	24	24	55	23	38	22
233	25	25	51	24	46	22
234	25	24	52	23	39	21
235	25	25	38	21	32	20

Table A3: Surface and Internal temperatures when 15 seconds air cooling was applied on the left and then 15 seconds on the right side of the mould

Shot Nr:	**T1 Probe/ mechanical**	**T2 Probe/ unsorted**	**T1 Surface/mechanical**		**T2 Surface/unsorted**	
			After Shot	**After Cooling**	**After Shot**	**After Cooling**
Average	**23.7**	**21.1**	**48.5**	**21.8**	**37.3**	**20.2**
236	14	14	44	16	36	16
237	19	20	45	18	40	18
238	22	23	50	21	37	19
239	23	23	50	21	39	20
240	24	23	48	21	40	19
241	24	24	51	20	40	21
242	24	23	50	21	40	20
243	24	23	49	21	42	20
244	24	23	49	23	39	22
245	24	23	46	20	41	20
246	24	23	45	21	35	20
247	24	23	42	21	37	20
248	24	23	44	21	39	20
249	24	23	46	23	35	21
250	24	23	47	22	35	20
251	24	23	46	21	34	19
252	24	23	45	21	35	20
253	24	23	48	22	38	21
254	24	23	48	22	34	21
255	24	23	43	20	35	19
256	24	23	48	21	36	19
257	22	21	49	23	35	20
258	23	22	48	23	36	21
259	24	23	47	23	36	21
260	24	23	46	22	34	20

261	24	22	48	22	36	21
262	24	22	48	23	36	21
263	24	22	46	26	35	24
264	24	23	48	26	35	23
265	24	23	47	24	38	22
266	24	23	46	24	34	22
267	24	22	47	23	34	21
268	24	22	50	24	38	22
269	24	23	47	23	35	21

Table A3: Continued

Shot Nr:	**T1 Probe/ mechanical**	**T2 Probe/ unsorted**	**T1 Surface/mechanical**		**T2 Surface/unsorted**	
			After Shot	**After Cooling**	**After Shot**	**After Cooling**
Average	**23.7**	**21.1**	**48.5**	**21.8**	**37.3**	**20.2**
270	24	22	48	23	36	20
271	24	22	49	23	38	21
272	24	22	47	22	35	20
273	23	21	45	22	35	20
274	24	21	45	22	35	20
275	23	21	50	23	37	21
276	24	21	49	23	35	20
277	23	21	49	23	36	20
278	23	21	51	23	36	20
279	23	21	48	21	35	20
280	23	21	49	22	37	20
281	23	21	52	22	38	20
282	23	21	48	21	37	20
283	23	21	48	22	35	20
284	23	21	45	20	35	20
285	23	21	46	21	34	19
286	23	21	49	22	34	20
287	24	21	50	23	36	20
288	24	21	51	22	41	20
289	24	21	48	22	38	20
290	23	21	50	22	38	20
291	23	21	50	22	41	20
292	23	21	49	23	41	21
293	23	21	49	21	39	21
294	24	21	51	22	44	22
295	23	20	49	22	41	21
296	23	20	51	22	46	20

297	23	20	50	23	40	22
298	23	20	46	22	49	21
299	23	20	52	22	42	21
300	23	19	49	21	41	20
301	23	19	50	21	40	21
302	23	19	53	21	42	20
303	23	19	52	22	45	21
304	23	19	51	22	43	21
305	23	19	49	21	37	21
306	23	19	50	21	38	21

Table A3: Continued

Shot Nr:	**T1 Probe/ mechanical**	**T2 Probe/ unsorted**	**T1 Surface/mechanical**		**T2 Surface/unsorted**	
			After Shot	**After Cooling**	**After Shot**	**After Cooling**
Average	**23.7**	**21.1**	**48.5**	**21.8**	**37.3**	**20.2**
307	23	18	51	22	36	20
308	23	18	50	23	36	21
309	23	19	49	21	41	20
310	23	18	50	22	42	19
311	23	18	52	21	41	19
312	23	18	46	21	39	19
313	23	18	49	22	44	21
314	23	18	49	21	37	21
315	23	18	52	20	36	20
316	23	18	47	21	35	21
317	23	18	49	22	40	20
318	23	18	54	21	41	21
319	23	18	50	21	43	19
320	23	18	62	21	36	21
321	22	18	51	22	37	19
322	22	18	50	23	37	21
323	23	18	55	21	36	21
324	22	18	49	22	39	20
325	23	18	48	21	37	20
326	23	18	49	21	36	20
327	22	17	50	22	36	20
328	22	17	48	21	35	21
329	22	17	50	23	37	20
330	22	17	48	23	37	21
331	22	17	49	21	33	21
332	22	17	49	23	35	21
333	22	17	50	23	37	20

334	22	17	51	22	34	19
335	22	17	50	21	34	20
336	22	17	51	22	35	20
337	22	17	48	23	36	20
338	22	17	50	23	36	20
339	22	17	48	22	38	20
340	22	17	48	23	33	19
341	22	17	44	23	32	21
342	22	16	47	22	35	20
343	22	16	49	22	35	20

Table A3: Continued

Shot Nr:	**T1 Probe/ mechanical**	**T2 Probe/ unsorted**	**T1 Surface/mechanical**		**T2 Surface/unsorted**	
			After Shot	**After Cooling**	**After Shot**	**After Cooling**
Average	**23.7**	**21.1**	**48.5**	**21.8**	**37.3**	**20.2**
344	22	16	48	21	36	19
345	23	22	43	20	33	20
346	23	22	43	21	35	20
347	23	23	42	21	31	20
348	23	23	49	22	34	19
349	26	25	47	21	35	19
350	27	25	40	21	34	19
351	27	25	42	22	33	20
352	27	25	45	21	35	19
353	27	25	43	21	36	19
354	27	25	47	21	35	19
355	27	24	45	20	33	19
356	27	25	46	22	34	19
357	26	24	50	21	39	19
358	27	26	48	21	46	19
359	27	26	51	23	34	19
360	27	26	48	21	37	21
361	27	26	50	25	38	20
362	27	25	49	22	39	19
363	27	25	52	21	44	19
364	28	27	54	21	35	20
365	27	26	50	21	35	21
366	27	27	52	22	30	20
367	28	26	51	21	41	20
368	27	26	54	22	39	20
369	27	26	50	22	39	20
370	27	26	48	22	37	20

371	28	27	54	22	45	20
372	28	27	52	23	44	20
373	28	27	57	22	37	20
374	28	27	53	20	35	19
375	28	27	51	21	39	19
376	28	27	50	22	39	20
377	28	27	47	21	43	19
378	27	26	46	20	34	18
379	27	25	47	21	40	19
380	27	26	51	23	37	21

Table A3: Continued

Shot Nr:	**T1 Probe/ mechanical**	**T2 Probe/ unsorted**	**T1 Surface/mechanical**		**T2 Surface/unsorted**	
			After Shot	**After Cooling**	**After Shot**	**After Cooling**
Average	**23.7**	**21.1**	**48.5**	**21.8**	**37.3**	**20.2**
381	27	26	52	22	37	20
382	28	27	47	22	35	21
383	27	26	49	21	38	20
384	27	26	52	23	39	20
385	27	26	49	22	36	20
386	27	26	50	22	37	19
387	27	26	51	21	35	19
388	27	26	49	22	36	19
389	27	26	49	21	37	20
390	27	26	51	21	37	19
391	27	26	45	21	33	20
392	27	26	48	20	40	19
393	26	25	46	21	33	19
394	26	25	43	21	33	19
395	26	25	42	21	35	20
396	26	25	44	22	37	20
397	26	25	50	21	34	19
398	26	25	47	21	35	19
399	25	24	44	21	34	19
400	25	24	42	22	33	19
401	24	23	46	21	35	19
402	24	23	49	20	36	19
403	19	18	42	22	32	20
404	25	25	47	21	33	20

Table A3: Continued

Shot Nr:	T1 Probe/ mechanical	T2 Probe/ unsorted	T1 Surface/mechanical		T2 Surface/unsorted	
			After Shot	After Cooling	After Shot	After Cooling
Average	**21.5**	**21.1**	**46.7**	**20.7**	**34.0**	**18.7**
405	11	12	40	16	30	15
406	16	16	43	18	32	17
407	18	18	39	19	32	17
408	19	19	42	19	33	18
409	20	20	41	18	32	19
410	20	19	40	19	31	17
411	20	19	42	18	35	16
412	20	20	42	18	35	17
413	20	20	45	19	34	17
414	21	20	42	19	32	17
415	21	20	43	18	31	16
416	20	20	41	19	33	17
417	20	19	47	19	34	17
418	21	20	48	20	34	18
419	21	20	42	20	31	18
420	21	20	43	21	34	17
421	21	20	47	20	31	18
422	21	20	45	19	32	17
423	21	20	42	19	32	17
424	21	20	42	20	33	17
425	21	20	43	20	31	17
426	21	20	48	20	34	18
427	21	20	47	19	34	17
428	21	20	47	19	32	17
429	21	20	46	20	30	17
430	21	20	47	20	36	18
431	21	20	46	21	33	19

432	21	20	45	19	37	17
433	21	21	45	19	31	17
434	21	20	45	20	31	17
435	21	20	45	20	34	17
436	21	20	42	20	34	17
437	21	20	47	20	31	17
438	21	20	47	20	33	17
439	21	20	46	19	33	17
440	20	19	45	18	33	16

Table A3: Continued

Shot Nr:	**T1 Probe/ mechanical**	**T2 Probe/ unsorted**	**T1 Surface/mechanical**		**T2 Surface/unsorted**	
			After Shot	**After Cooling**	**After Shot**	**After Cooling**
Average	**21.5**	**21.1**	**46.7**	**20.7**	**34.0**	**18.7**
441	20	19	47	19	37	17
442	21	20	48	19	42	18
443	21	20	51	20	37	18
444	21	21	45	20	31	18
445	21	21	47	21	35	18
446	21	21	46	26	33	18
447	21	21	40	19	32	18
448	21	20	46	22	32	19
449	21	21	43	21	33	19
450	22	21	49	20	35	19
451	22	21	46	20	35	18
452	21	21	43	19	32	17
453	21	21	49	19	35	17
454	21	20	47	21	35	18
455	21	21	46	20	32	18
456	21	21	50	20	36	18
457	21	21	49	20	35	18
458	21	20	45	20	34	18
459	21	21	48	20	36	18
460	21	21	47	21	34	18
461	22	21	49	20	33	18
462	22	21	47	20	34	18
463	22	21	49	20	34	18
464	22	21	47	20	32	18
465	21	20	42	21	30	18
466	22	21	46	22	34	18
467	22	21	48	21	37	18

468	22	21	49	20	35	18
469	14	14	42	19	36	18
470	21	22	43	19	34	20
471	22	22	47	21	36	19
472	21	22	43	21	32	19
473	21	22	48	21	32	19
474	22	21	51	23	34	20
475	22	22	51	20	35	18
476	22	22	47	22	33	18
477	22	22	45	20	34	19

Table A3: Continued

Shot Nr:	**T1 Probe/ mechanical**	**T2 Probe/ unsorted**	**T1 Surface/mechanical**		**T2 Surface/unsorted**	
			After Shot	**After Cooling**	**After Shot**	**After Cooling**
Average	**21.5**	**21.1**	**46.7**	**20.7**	**34.0**	**18.7**
478	22	22	51	20	35	19
479	22	22	49	20	34	19
480	22	22	50	21	35	19
481	22	22	47	20	3	19
482	22	22	48	20	33	19
483	22	22	46	20	34	19
484	22	22	49	22	35	20
485	22	22	48	21	36	18
486	22	21	48	21	35	19
487	22	21	48	22	35	20
488	22	22	49	23	35	21
489	22	22	48	20	35	20
490	22	22	51	22	35	20
491	22	21	51	21	37	19
492	22	22	51	22	35	20
493	22	21	52	22	37	20
494	23	32	47	21	34	19
495	22	23	50	24	36	21
496	23	23	52	23	35	22
497	24	23	49	22	36	20
498	22	23	48	23	36	20
499	23	22	47	23	38	21
500	22	22	48	25	34	21
501	22	22	51	22	35	20
502	23	23	51	21	37	18
503	22	23	51	21	34	19
504	22	23	46	23	32	20

505	23	22	48	21	33	20
506	23	22	49	21	35	19
507	23	22	47	20	38	18
508	23	22	48	20	35	18
509	23	22	47	20	32	18
510	23	22	46	20	34	18
511	22	22	49	21	33	19
512	23	22	46	21	33	19
513	23	22	44	20	33	18
514	23	22	48	20	33	18

Table A3: Continued

Shot Nr:	**T1 Probe/ mechanical**	**T2 Probe/ unsorted**	**T1 Surface/mechanical**		**T2 Surface/unsorted**	
			After Shot	**After Cooling**	**After Shot**	**After Cooling**
Average	**21.5**	**21.1**	**46.7**	**20.7**	**34.0**	**18.7**
515	23	22	47	20	34	19
516	23	22	48	21	38	20
517	23	22	47	21	34	19
518	23	22	47	21	35	19
519	23	23	48	21	36	19
520	23	22	47	23	35	20
521	23	22	48	21	38	20
522	23	22	46	21	36	20
523	23	22	48	21	37	20
524	22	22	45	22	35	20
525	22	22	47	25	36	23
526	23	23	51	23	38	21
527	23	23	49	24	37	21
528	23	22	49	21	37	20
529	22	22	48	22	36	20
530	22	22	50	26	35	21
531	23	22	52	22	35	20
532	23	22	49	21	33	19
533	22	22	45	22	32	20
534	22	22	50	25	33	21
535	23	22	47	25	37	22
536	23	22	48	25	34	24
537	23	22	50	23	42	22
538	23	23	49	20	37	20
539	22	21	43	20	31	20
540	21	21	44	22	31	21
541	22	22	48	23	39	21
542	23	23	49	23	43	23

543	23	23	52	21	39	22
544	21	23	48	21	39	18
545	21	21	49	18	38	17
546	20	19	48	18	39	17
547	20	19	47	18	37	18
548	21	20	47	20	34	18
549	22	21	50	20	39	18
550	22	21	52	20	40	18
551	22	21	50	20	38	18
552	23	22	52	21	38	19

Table A3: Continued

Shot Nr:	**T1 Probe/ mechanical**	**T2 Probe/ unsorted**	**T1 Surface/mechanical**		**T2 Surface/unsorted**	
			After Shot	**After Cooling**	**After Shot**	**After Cooling**
Average	**21.5**	**21.1**	**46.7**	**20.7**	**34.0**	**18.7**
553	23	23	50	21	35	19
554	23	22	52	20	43	18
555	23	23	53	20	40	19
556	22	22	52	20	41	18
557	22	22	48	22	39	19
558	23	23	52	22	43	19
559	23	22	54	22	39	19
560	23	22	52	22	40	20
561	23	22	50	22	38	19
562	23	22	46	21	36	19
563	23	22	46	22	37	20
564	23	22	51	23	43	20
565	23	22	48	22	36	20
566	23	22	47	20	38	19
567	23	22	50	23	39	20
568	23	22	51	23	40	20
569	23	22	52	22	44	20
570	23	22	50	22	33	21
571	23	23	50	24	38	21
572	23	23	52	23	43	21
573	23	23	53	24	41	20
574	23	23	50	22	38	20
575	23	22	49	23	40	21
576	23	22	48	22	39	20
577	23	22	51	23	41	20
578	23	23	52	24	41	21
579	23	22	50	22	39	22

580	22	22	50	23	40	20
581	23	22	54	24	40	20
582	23	23	52	24	40	21
583	23	23	54	24	38	21
584	23	23	52	24	41	21
585	23	23	55	23	38	21
586	24	23	53	23	42	21
587	24	23	53	24	38	21
588	24	23	48	24	38	21
589	24	23	52	23	37	20

Table A3: Continued

Shot Nr:	**T1 Probe/ mechanical**	**T2 Probe/ unsorted**	**T1 Surface/mechanical**		**T2 Surface/unsorted**	
			After Shot	**After Cooling**	**After Shot**	**After Cooling**
Average	**21.5**	**21.1**	**46.7**	**20.7**	**34.0**	**18.7**
590	24	23	52	24	39	21
591	23	23	50	23	41	21
592	23	23	56	25	40	22
593	23	23	52	23	40	21
594	23	23	52	23	38	20
595	23	23	52	23	40	21
596	23	23	53	22	37	20
597	23	23	50	23	39	21
598	23	23	50	25	39	23
599	24	23	50	24	41	21
600	23	23	51	23	41	20
601	23	23	51	23	37	20
602	23	22	52	24	36	21
603	23	23	52	24	37	21
604	23	23	50	24	36	22
605	24	23	50	26	35	23
606	24	23	51	23	33	20
607	24	23	52	22	37	20
608	23	22	52	22	37	20
609	23	22	48	23	36	21
610	23	23	52	25	35	23
611	24	23	48	23	36	21
612	24	23	50	22	38	20
613	24	23	47	22	40	20
614	24	23	48	21	37	20
615	23	23	50	24	38	20
616	23	22	50	22	37	21

617	23	22	50	22	41	20
618	23	22	48	22	38	20
619	23	22	48	22	33	20
620	23	22	48	23	37	21
621	23	22	49	24	39	20
622	23	22	47	22	37	20
623	23	22	51	23	41	21
624	23	23	47	24	36	22
625	23	23	53	24	44	21
626	24	24	49	24	36	21

Table A3: Continued

Shot Nr:	**T1 Probe/ mechanical**	**T2 Probe/ unsorted**	**T1 Surface/mechanical**		**T2 Surface/unsorted**	
			After Shot	**After Cooling**	**After Shot**	**After Cooling**
Average	**21.5**	**21.1**	**46.7**	**20.7**	**34.0**	**18.7**
627	24	23	46	24	35	21
628	24	23	51	24	36	21
629	23	23	51	23	36	21
630	23	23	52	23	37	20
631	24	23	50	22	37	20
632	24	23	47	26	37	23
633	23	23	49	24	37	22
634	23	23	50	26	37	23
635	23	23	49	25	36	22
636	24	24	48	25	36	24
637	24	24	46	25	35	23
638	24	24	49	23	36	20
639	25	24	47	22	36	20
640	25	24	49	22	38	20
641	25	24	50	22	37	20
642	25	24	46	22	37	20
643	25	24	49	22	35	20
644	25	24	45	22	36	20
645	25	24	49	23	37	22
646	25	24	49	23	39	21
647	25	24	47	24	36	21
648	25	24	49	22	39	20
649	24	24	50	25	36	22
650	25	24	48	24	36	21
651	25	24	48	22	40	20
652	25	24	50	23	36	21
653	25	24	47	23	36	21

654	25	24	48	22	38	20
655	24	24	50	23	39	21
656	25	24	49	22	43	20
657	24	24	46	22	38	20
658	24	24	48	23	38	20
659	17	19	43	19	23	18
660	20	20	47	21	34	19
661	21	21	43	21	46	20
662	21	21	46	23	38	21
663	22	21	48	22	42	20

Table A3: Continued

Shot Nr:	**T1 Probe/ mechanical**	**T2 Probe/ unsorted**	**T1 Surface/mechanical**		**T2 Surface/unsorted**	
			After Shot	**After Cooling**	**After Shot**	**After Cooling**
Average	**23.2**	**22.9**	**48.8**	**22.8**	**36.8**	**20.8**
664	22	22	48	27	38	25
665	23	23	48	21	35	22
666	22	22	51	22	39	20
667	22	22	48	24	38	22
668	22	22	47	25	37	22
669	22	22	47	22	36	20
670	22	22	49	25	34	22
671	22	22	49	25	36	23
672	23	23	48	24	36	22
673	23	22	47	23	35	20
674	23	22	50	25	36	23
675	23	22	50	24	41	22
676	23	22	49	22	39	21
677	22	22	52	25	39	22
678	22	22	46	24	38	22
679	23	22	48	27	36	23
680	23	23	50	24	6	22
681	23	23	52	24	36	21
682	23	23	50	23	35	20
683	23	23	47	22	36	21
684	23	22	49	22	38	20
685	23	22	48	23	36	21
686	22	21	52	22	41	19
687	21	20	52	22	40	22
688	21	20	49	19	41	18
689	21	20	49	22	34	19

690	22	21	47	21	37	20
691	22	21	52	21	38	21
692	22	22	43	22	38	21
693	22	21	46	22	39	21
694	22	21	48	23	40	22
695	23	22	47	23	39	22
696	21	22	45	22	39	21
697	21	22	45	22	33	21
698	22	22	51	24	35	22
699	23	23	49	21	37	19

Table A3: Continued

Shot Nr:	**T1 Probe/ mechanical**	**T2 Probe/ unsorted**	**T1 Surface/mechanical**		**T2 Surface/unsorted**	
			After Shot	**After Cooling**	**After Shot**	**After Cooling**
Average	**23.2**	**22.9**	**48.8**	**22.8**	**36.8**	**20.8**
700	23	22	47	21	33	19
701	22	22	48	21	38	19
702	22	22	51	20	36	18
703	22	21	45	19	36	18
704	22	21	47	20	35	18
705	22	21	46	22	35	19
706	22	22	45	21	37	19
707	22	21	48	22	31	19
708	23	22	48	24	36	20
709	22	21	48	23	35	20
710	23	22	51	24	36	20
711	23	22	49	24	37	21
712	23	23	50	23	38	21
713	23	23	49	23	40	22
714	23	23	52	22	37	20
715	23	23	50	25	35	21
716	23	23	46	27	39	22
717	23	23	52	26	38	21
718	23	23	49	25	37	21
719	24	23	50	21	37	18
720	23	23	47	21	37	19
721	23	23	47	22	33	20
722	23	23	48	22	33	19
723	23	23	52	23	38	21
724	23	23	48	26	36	22

725	23	23	52	23	38	20
726	23	23	53	21	36	20
727	23	23	50	22	36	21
728	23	23	48	21	34	20
729	23	23	50	21	38	19
730	23	23	52	21	36	19
731	23	23	49	24	37	20
732	23	23	49	22	38	20
733	23	22	53	21	38	20

Table A3: Continued

Shot Nr:	**T1 Probe/ mechanical**	**T2 Probe/ unsorted**	**T1 Surface/mechanical**		**T2 Surface/unsorted**	
			After Shot	**After Cooling**	**After Shot**	**After Cooling**
Average	**23.2**	**22.9**	**48.8**	**22.8**	**36.8**	**20.8**
734	23	23	50	20	36	20
735	23	23	50	21	37	21
736	23	22	51	20	38	20
737	23	23	49	20	38	19
738	23	23	48	19	39	19
739	23	23	46	21	36	19
740	23	23	48	22	37	21
741	23	23	49	23	37	20
742	23	23	52	24	38	22
743	23	23	51	24	36	23
744	23	23	52	23	39	22
745	23	23	51	23	42	21
746	25	24	50	24	39	23
747	25	24	46	20	32	20
748	25	24	47	23	41	21
749	24	24	51	24	34	22
750	24	23	52	22	36	21
751	24	24	47	20	35	19
752	23	23	48	20	33	19
753	25	24	46	22	34	20
754	24	23	50	25	42	21
755	23	22	48	21	33	20
756	26	25	43	21	35	20
757	23	23	47	20	36	19
758	24	24	48	20	38	19

759	24	24	48	20	35	22
760	25	25	48	22	38	21
761	26	26	53	23	37	22
762	26	26	52	22	37	22
763	27	26	48	25	36	22
764	27	26	48	22	38	21
765	27	26	50	22	38	21
766	26	26	48	22	36	20
767	26	26	50	23	36	22
768	26	26	52	21	40	22
769	26	26	45	22	36	23
770	25	25	48	23	38	22

Table A3: Continued

Shot Nr:	**T1 Probe/ mechanical**	**T2 Probe/ unsorted**	**T1 Surface/mechanical**		**T2 Surface/unsorted**	
			After Shot	**After Cooling**	**After Shot**	**After Cooling**
Average	**23.2**	**22.9**	**48.8**	**22.8**	**36.8**	**20.8**
771	25	25	47	23	37	22
772	25	25	47	23	31	24
773	24	25	47	24	42	23
774	24	25	52	25	39	25
775	23	24	49	22	40	21
776	23	23	47	24	39	24
777	23	23	49	23	38	20
778	23	23	50	24	35	21
779	24	24	51	22	38	23
780	24	24	50	25	39	22
781	24	24	48	25	36	22
782	23	23	49	23	39	21
783	24	23	51	25	38	23
784	24	23	50	24	40	22
785	24	23	49	24	38	22
786	24	23	47	25	41	22
787	24	24	51	28	37	25
788	25	25	51	23	40	21
789	24	23	51	23	36	21
790	24	23	47	24	40	21
791	24	23	49	26	39	23
792	24	23	50	29	38	23
793	24	23	53	27	38	22
794	25	24	51	26	37	23
795	25	24	53	24	42	21

796	25	25	50	23	41	21
797	25	25	51	23	39	21
798	25	24	51	22	44	20
799	25	24	54	23	41	20
800	25	24	59	23	39	19
801	25	24	55	22	40	19
802	25	24	50	22	40	19
803	24	24	49	23	37	20
804	25	24	50	21	42	19
805	25	24	49	22	40	19
806	25	24	52	22	43	19

Table A3: Continued

Shot Nr:	**T1 Probe/ mechanical**	**T2 Probe/ unsorted**	**T1 Surface/mechanical**		**T2 Surface/unsorted**	
			After Shot	**After Cooling**	**After Shot**	**After Cooling**
Average	**23.2**	**22.9**	**48.8**	**22.8**	**36.8**	**20.8**
807	25	24	52	22	42	19
808	25	24	54	23	41	20
809	25	24	52	23	39	20
810	25	25	51	22	42	20
811	25	24	50	22	41	20
812	25	24	51	22	41	20
813	25	24	52	23	42	20
814	25	26	50	23	39	20
815	25	24	55	23	37	20
816	25	24	54	22	39	20
817	25	24	51	23	40	20
818	25	24	52	24	41	21
819	25	24	49	24	38	21
820	25	24	51	24	40	21
821	25	24	49	25	42	21
822	25	24	51	24	39	22
823	25	25	54	26	46	23
824	26	25	51	26	41	24
825	26	26	57	27	44	22
826	26	26	54	28	40	23
827	26	26	52	27	43	25
828	26	26	50	29	39	24
829	26	26	50	26	40	23
830	26	26	51	25	41	21
831	25	24	50	26	37	23

832	25	24	51	25	39	22
833	25	24	52	25	39	22
834	25	24	50	24	37	22
835	25	24	52	24	37	22
836	24	24	53	26	39	23
837	25	24	53	23	39	21
838	25	24	52	24	40	22
839	25	24	53	25	37	23
840	24	24	52	23	38	21
841	24	24	56	27	43	23
842	25	24	52	23	43	22
843	25	24	49	24	34	23

Table A3: Continued

Shot Nr:	**T1 Probe/ mechanical**	**T2 Probe/ unsorted**	**T1 Surface/mechanical**		**T2 Surface/unsorted**	
			After Shot	**After Cooling**	**After Shot**	**After Cooling**
Average	**23.2**	**22.9**	**48.8**	**22.8**	**36.8**	**20.8**
844	25	24	52	28	37	25
845	25	25	54	24	43	23
846	25	25	52	23	43	21
847	25	24	53	27	39	23
848	26	26	53	26	43	21
849	26	25	50	23	35	22
850	26	25	51	25	39	23
851	26	25	51	26	40	24
852	26	25	52	25	36	23
853	26	25	52	27	38	24
854	26	26	53	25	38	22
855	25	25	53	23	38	21
856	26	25	53	25	38	23
857	26	25	52	24	40	22
858	20	25	54	26	38	22
859	26	25	51	24	38	22
860	26	25	51	24	37	22
861	25	24	53	24	38	22
862	25	24	51	23	41	21
863	26	25	49	26	37	23
864	25	25	52	26	40	23
865	25	25	51	23	38	21
866	25	25	51	24	41	23
867	25	24	52	24	37	22
868	25	24	52	24	40	22

869	25	25	50	25	40	22
870	25	25	51	26	37	22
871	26	25	52	24	37	22
872	26	25	51	26	38	24
873	26	26	52	28	39	25
874	25	26	55	25	39	24
875	25	25	53	26	40	23
876	25	25	58	29	42	26
877	26	26	52	23	38	21
878	26	26	53	25	39	21
879	27	26	51	27	41	24
880	26	26	52	28	49	25

Table A3: Continued

Shot Nr:	**T1 Probe/ mechanical**	**T2 Probe/ unsorted**	**T1 Surface/mechanical**		**T2 Surface/unsorted**	
			After Shot	**After Cooling**	**After Shot**	**After Cooling**
Average	**23.2**	**22.9**	**48.8**	**22.8**	**36.8**	**20.8**
881	25	24	52	26	41	23
882	29	28	52	24	43	22
883	28	27	47	27	39	24
884	29	28	51	30	40	25
885	29	28	53	27	37	24
886	28	27	51	28	39	25
887	29	28	53	29	41	27
888	29	28	53	26	38	23
889	29	28	49	25	42	22
890	28	29	51	25	38	23
891	29	28	50	24	37	21
892	29	28	54	25	38	22
893	28	29	52	24	36	20
894	28	27	52	22	36	20
895	28	27	49	26	37	21
896	29	28	52	24	38	22
897	26	26	54	25	41	22
898	27	28	52	25	41	23
899	28	27	52	27	38	24
900	28	28	51	22	39	22
901	28	28	52	23	38	22
902	28	27	51	25	39	22
903	27	27	54	24	42	23
904	27	27	52	28	45	24
905	27	27	50	27	39	22

906	27	27	48	24	38	21
907	27	27	54	24	39	21
908	28	27	51	24	38	21
909	28	27	51	26	41	22
910	28	29	53	26	41	23
911	29	28	50	25	38	22
912	29	28	52	24	40	21
913	29	28	50	23	40	20
914	29	28	52	25	37	22
915	28	29	49	25	37	23
916	29	28	51	26	39	24
917	29	28	51	24	41	22

Table A3: Continued

Shot Nr:	**T1 Probe/ mechanical**	**T2 Probe/ unsorted**	**T1 Surface/mechanical**		**T2 Surface/unsorted**	
			After Shot	**After Cooling**	**After Shot**	**After Cooling**
Average	**21.4**	**20.6**	**48.0**	**18.5**	**36.1**	**17.1**
918	29	28	55	25	49	23
919	28	28	55	24	42	21
920	10	11	44	15	36	15
921	16	17	44	18	35	17
922	18	19	47	17	37	17
923	20	20	46	18	38	16
924	20	20	46	18	36	16
925	21	20	45	18	34	17
926	21	21	47	18	36	17
927	21	20	45	17	33	16
928	21	20	48	17	32	16
929	21	20	46	18	37	16
930	21	20	49	18	37	16
931	21	20	46	17	35	16
932	21	20	47	17	39	16
933	21	20	44	18	36	16
934	21	20	44	18	38	17
935	21	20	45	18	38	17
936	21	20	44	17	35	16
937	21	20	46	17	34	16
938	21	20	46	18	36	16
939	21	20	45	18	35	17
940	21	21	45	18	35	17
941	21	21	48	18	30	16

942	21	20	45	17	37	16
943	21	20	45	16	32	16
944	20	20	51	17	36	16
945	21	20	46	18	35	16
946	21	20	51	17	35	16
947	21	20	50	17	38	16
948	21	20	47	17	39	16
949	21	20	49	17	36	16
950	21	20	42	18	34	17
951	21	20	47	18	33	16
952	21	20	46	18	36	16
953	21	21	49	16	35	17

Table A3: Continued

Shot Nr:	**T1 Probe/ mechanical**	**T2 Probe/ unsorted**	**T1 Surface/mechanical**		**T2 Surface/unsorted**	
			After Shot	**After Cooling**	**After Shot**	**After Cooling**
Average	**21.4**	**20.6**	**48.0**	**18.5**	**36.1**	**17.1**
954	21	21	48	18	38	17
955	21	21	48	18	38	17
956	21	20	48	18	34	17
957	21	20	49	19	34	17
958	21	21	47	19	34	17
959	21	21	49	19	36	17
960	22	21	48	19	36	17
961	21	21	50	18	33	17
962	21	20	46	18	35	17
963	21	20	47	19	34	17
964	21	21	48	19	35	17
965	22	21	49	18	38	17
966	21	21	50	18	33	17
967	22	21	46	19	33	17
968	21	21	50	18	34	17
969	21	21	47	18	32	17
970	22	21	48	19	34	18
971	22	21	46	19	33	18
972	21	21	48	18	36	17
973	22	21	48	18	38	17
974	22	21	46	20	35	18
975	22	21	51	19	43	18
976	22	21	49	20	34	18
977	22	21	48	18	39	17

978	22	21	44	19	34	17
979	22	21	49	19	33	18
980	22	21	50	20	35	18
981	22	21	50	18	37	16
982	22	21	55	21	42	18
983	22	21	52	19	42	17
984	22	21	50	20	35	17
985	22	21	53	20	37	17
986	22	21	59	19	43	18
987	22	21	49	19	38	18
988	22	21	49	18	35	17
989	22	21	52	25	40	22
990	22	21	47	22	39	20

Table A3: Continued

Shot Nr:	**T1 Probe/ mechanical**	**T2 Probe/ unsorted**	**T1 Surface/mechanical**		**T2 Surface/unsorted**	
			After Shot	**After Cooling**	**After Shot**	**After Cooling**
Average	**21.4**	**20.6**	**48.0**	**18.5**	**36.1**	**17.1**
991	24	22	52	19	36	17
992	23	22	49	19	37	18
993	23	22	50	20	37	18
994	23	22	50	20	37	18
995	23	22	52	20	38	18
996	23	22	50	19	38	18
997	23	22	50	19	40	18
998	23	22	50	19	36	18
999	23	22	50	19	43	18
1000	23	22	50	20	37	19
1001	23	23	49	19	36	18
1002	23	22	47	19	36	18
1003	23	22	47	20	35	18
1004	23	22	45	20	39	19

Table A4: Surface and Internal temperatures with no air cooling applied to the moulds after 9 shots the part bonded to the mechanically grown insert

Shot Nr:	**T1 Probe/ mechanical**	**T2 Probe/ unsorted**	**T1 Surface/mechanical**		**T2 Surface/unsorted**	
			After Shot	**After Cooling**	**After Shot**	**After Cooling**

Average	**35.1**	**38.3**	**68.4**		**52.6**	
1005	23	22	46		39	
1006	25	27	57		43	
1007	30	34	69		43	
1008	33	38	75		57	
1009	36	42	70		51	
1010	40	44	74		56	
1011	40	43	71		67	
1012	44	47	76		66	
1013	45	48	78		51	

Appendix B

ALUMIDE® DATA SHEET (Information supplied by EOS)

General Material Properties:

Table 1: General Material Properties for Alumide®

Property	**Standard Used**	**Quantity**	**Unit**
Average grain size	Laser diffraction	60	µm
Bulk density	DIN 53466	0.64 ± 0.04	g/cm³
Density of laser-sintered part	EOS-method	1.36 ± 0.05	g/cm³

Thermal Properties:

Table 2: Thermal Properties for Alumide®

Property	**Standard Used**	**Quantity**	**Unit**
Melting Point	DIN 53736	172 – 180	°C
Heat Deflection Temperature	ASTMD648 (0,45 Mpa)	177.1	°C
Vicat Softening Temperature B/50	DIN EN ISO 306	169	°C
Heat Conductivity (170 ° C)	Hot Wire Method	0.5 – 0.8	$W(mK)^{-1}$

Mechanical Properties:

Table 3: Mechanical Properties for Alumide®

Property	**Standard Used**	**Quantity**	**Unit**
Tensile Modulus	DIN EN ISO 527	3800 ± 150	N/mm²
Tensile Strength	DIN EN ISO 527	46 ± 3	N/mm²
Elongation at Break	DIN EN ISO 527	3.5 ± 1	%
Flexural Modulus	DIN EN ISO 178	3000 ± 150	N/mm²
Flexural Strength	DIN EN ISO 178	74 ± 2	N/mm²
Charpy - Impact Strength	DIN EN ISO 179	29 ± 2	kJ/m²
Charpy - Notched Impact	DIN EN ISO 179	4.6 ± 0.3	kJ/m²

Strength			
Shore D - hardness	DIN 53505	76 ± 2	

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

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Appendix C

LASERFORM™ ST 100 DATA SHEET (Information supplied by 3D SYSTEMS)

LaserForm™ ST-100 Material Properties for the SLS systems			
Powder Properties	**Units**	**Test Method**	
Density 23°C	g/cm³	ASTM D792	7.7
Thermal Properties	**Units**	**Test Method**	(1)
Thermal conductivity 100°C 200°C	 W/m/°K W/m/°K	 ASTM E457 ASTM E457	 49 56
Coefficient Thermal Expansion $x10^{(-6)}$ 51 – 150°C	m/m/°C	ASTM E831	12.4
Mechanical Properties	**Units**	**Test Method**	
Tensile - Yield strength (0.2%)	MPa	ASTM E8	305
Strength	MPa	ASTM E8	510
Elongation	%	ASTM E8	10
Young Modulus	GPa	ASTM E8	137
Compression - Yield Strength (0.2%)	MPa	ASTM E9	317
Hardness - Rockwell "B" as infiltrated as machined		 ASTM E18 ASTM E18	 87 79

Data was generated from the testing of parts produced with the LaserForm™ ST-100 powder under typical processing conditions. (New materials processed at 35 watts laser power, 380 cm/sec scan speed, 0.075 mm scan spacing, 0.075 mm layer thickness on a Sinterstation® 2500 *plus* system and then debinded, sintered and bronze infiltrated in an oven). Final composition is approximately 40% bronze and 60% 420 stainless steel. Warranty/Disclaimer: The performance characteristics of these products may vary according to product application, operating conditions, material combined with, or with end use. 3D Systems makes no warranties of any type, express or implied, including, but not limited to, the warranties of merchantability or fitness for a particular use.

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Appendix D

LASERFORM™ A6 DATA SHEET (Information supplied by 3D SYSTEMS)

LaserForm™ A6 Material Properties for the SLS systems			
Powder Properties	**Units**	**Test Method**	
Density	g/cm^3	ASTM D792	7.8
Thermal Properties	**Units**	**Test Method**	
Thermal conductivity 215°C	W/m/°C	ASTM E457	39
Thermal Expansion Coefficient	µm/m/°C	ASTM E831	7.45
Mechanical Properties	**Units**	**Test Method**	
Tensile - Yield strength (0.2%)	MPa	ASTM E8	470
Strength	MPa	ASTM E8	610
Elongation	%	ASTM E8	2 – 4
Young Modulus	GPa	ASTM E8	138
Compression - Yield Strength	MPa	ASTM E8	480
Hardness - Rockwell "C" as polished as heat treated		ASTM E18 ASTM E18	HRc:10 - 20 HRc:39

Data was generated from testing of infiltrated parts produced with LaserForm™ A6 steel material and a Vanguard HS SLS system using 3D Systems defined parameters. Material properties may vary and are dependant upon part geometry and other factors. Warranty/Disclaimer: The performance characteristics of these products may vary according to product application, operating conditions, material combined with, or with end use. 3D Systems makes no warranties of any type, express or implied, including, but not limited to, the warranties of merchantability or fitness for a particular use.

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