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Rapid Tooling and the LOMOLD Process

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Study leader: Prof Dimitrov

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Declaration

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and has not previously in its entirety or in part been submitted at any university for a degree.

Ek, die ondergetekende verklaar hiermee dat die werk gedoen in hierdie tesis my eie oorspronklike werk is wat nog nie voorheen gedeeltelik of volledig by enige universiteit vir 'n graad aangebied is nie.

Signature: Date:

Synopsis

The LOMOLD process is a new plastic moulding process being researched at the University of Stellenbosch. The process essentially combines injection moulding and compression moulding. Molten plastic is forced into the mould cavity using a plunger. This plunger then forms part of the cavity wall. The plunger face must therefore follow the geometry of the part.

Rapid Tooling evolved from Rapid Prototyping. There are two categories of Rapid Tooling: indirect and direct rapid tools. Indirect rapid tools are manufactured by using a master pattern to form the mould cavity. The accuracy of the mould cavity depends heavily on the accuracy of the master pattern. The master pattern is usually produced using Rapid Prototyping technology. Direct rapid tools use Rapid Prototyping technology to build the mould through and additive, layer by layer process or a subtractive process.

This research investigates the use of Rapid Tools for the LOMOLD process. Aluminium Filled Epoxy Tooling (AFET) represents the indirect technology and CNC-machined tooling the direct technology. Both of these technologies are available at the University of Stellenbosch. Parts are manufactured on these tools using an experimental LOMOLD machine. These two technologies are compared in terms of part accuracy, tool lead time, tool cost and part cost.

The research concluded that the only advantage the AFET has over the CNC-machined tool is a shorter manufacturing lead-time. In terms of tool cost, tool life, part geometric accuracy, part cost and cycle time the CNC tool is superior. Therefore the application of AFET is limited to small volume, prototype or pre-production runs for tool design confirmation, part functional testing and part appearance testing. It is also demonstrated that a cooling system on the AFET tool has no significant influence on the tool performance and should therefore, especially for production runs less than 150 parts, not be included in the tool to save on tool cost.

Another conclusion is that the LOMOLD process is not consistent enough for a production process. This statement could be limited to the machine used for the research but to prove this statement wrong, the machine must be improved and more investigation is required.

Opsomming

Die LOMOLD proses is `n nuwe plastiek vorming proses wat ondersoek word deur die Universiteit van Stellenbosch. Die proses is basies `n kombinasie van spuit -en kompressie vormwerk. Gesmelte plastiek word in die vormholte ingeforseer deur n suier. Die suier vorm dan deel van die part se geometrie, daarom moet die suier dieselfde geometrie as die part oppervlak hê.

Snelle Gereedskap het ontstaan vanuit Snelle Prototipering. Daar is twee kategorieë van Snelle Gereedskap: direkte en indirekte snelle gereedskap. Indirekte snelle gereedskap word vervaardig deur `n meester model van die produk te gebuik om die vormholte te vorm. Die akkuraatheid van die vormholte steun swaar op die akkuraatheid van die meester model. Die meester model word meestal vervaardig met `n Snelle Prototipering tegnologie. Direkte snelle gereedskap gebruik Snelle Prototipering tegnologie om die gereedskap te vervaardig deur materiaal lagie vir lagie saam te smee of te verwyder.

Die navorsing gedoen ondersoek die gebruik van Snelle Gereedskap vir die LOMOLD proses. Aluminium Gevulde Epoksie Gereedskap (AFET) verteenwoordig die indirekte tegnologie en Rekenaar Numeries Beheerde (CNC) gemasjineerde gereedskap verteenwoordig die direkte tegnologie. Beide hierdie tegnologieë is beskikbaar by die Universiteit van Stellenbosch (US). Parte is vervaardig met beide gereedskap op die eksperimentele LOMOLD masjien wat by die US beskikbaar is. Die twee tegnologieë is vergelyk in terme van die akkuraatheid van die vervaardigde parte, gereedskap leityd, gereedskap koste en part produksie koste.

Die navorsing het bevind dat die enigste voordeel wat AFET het oor CNC-gemasjineerde gereedskap is `n korter vervaardiging leityd. In terme van gereedskapkoste, gereedskap leeftyd, die geometriese akkuraatheid van die vervaardigde parte, die part produksie koste en produksie siklus tyd is die CNC-gemasjineerde gereedskap beter. Dus is die toepaslikheid van AFET beperk tot klein prototipe of voor-produksie lotte om gereedskap ontwerp te verifieer of om parte se funksionele vermoëns en voorkoms te toets. Dit is ook bewys dat verkoeling op die AFET geen beduidende invloed op die vermoë van die gereedskap het nie. Daarom is verkoeling nie nodig nie veral as produksie lotte van 150 parte of minder met die greedskap geproduseer word om `n beduidende koste besparing in die vervaardiging van die gereedskap te hê.

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1. Introduction

The LOMOLD process is a new process for producing plastic products. It is essentially an injection moulding process but has some similarities with compression moulding as well. The process is currently being researched by three departments of the University of Stellenbosch: Polymer Science, Mechanical Engineering and Industrial Engineering.

The LOMOLD process has some unique characteristics that can create new opportunities for the application of Rapid Tooling. Low injection and cavity pressures (see Table 1) will enable Rapid Tooling technologies to produce larger volumes of parts when used in conjunction with the LOMOLD process than with other moulding methods. The process is particularly suited to producing large parts therefore Rapid Tooling technologies that can produce moulds for large components economically will be investigated. The use of Rapid Tools as production tools may be possible with the LOMOLD process and has huge potential as an advantage in the demanding world markets today, where customized products are needed quickly and at low cost with excellent quality.

1.1 Problem statement

i. Investigate pre-production/prototype tooling solutions for the LOMOLD process

Pre-production/prototype tooling must be fast to produce therefore Rapid Tooling technologies offer ideal solutions. For the LOMOLD process, the Rapid Tooling technologies that will be used must posses certain capabilities. The technologies must be capable of producing tools for large parts. The tools must be abrasive resistant to produce parts with high fibre content. The technologies must be available locally to minimise the tool lead-time and it is preferred that the technologies must be substantially different in their approach to producing tools so that the research will cover a wider spectrum of Rapid Tooling technologies.

ii. Compare these identified technologies

A tool is produced from each technology and parts manufactured with each tool on the LOMOLD machine. The technologies are compared in terms of tool lead-time, tool cost, cycle time and geometric accuracy of the parts produced. Use a production part as benchmark to compare directly with parts produced during the research.

iii. Conclusions

Draw conclusions about the technologies. Identify the most suitable applications for each technology for use with the LOMOLD process. Recommend improvements to the LOMOLD machine and tooling process chains. Identify opportunities for future research.

1.2 Background on LOMOLD

1.2.1 The company

The company LOMOLD Ventures Ltd is situated in Paarl, Western Cape, South Africa. It was founded by entrepreneur, Pieter du Toit who is also the current owner.

1.2.2 The LOMOLD process

The LOMOLD process is a patented, low pressure moulding technology that combines the best features of compression moulding and injection moulding while avoiding the disadvantages of both (see Figure 1, [14]).

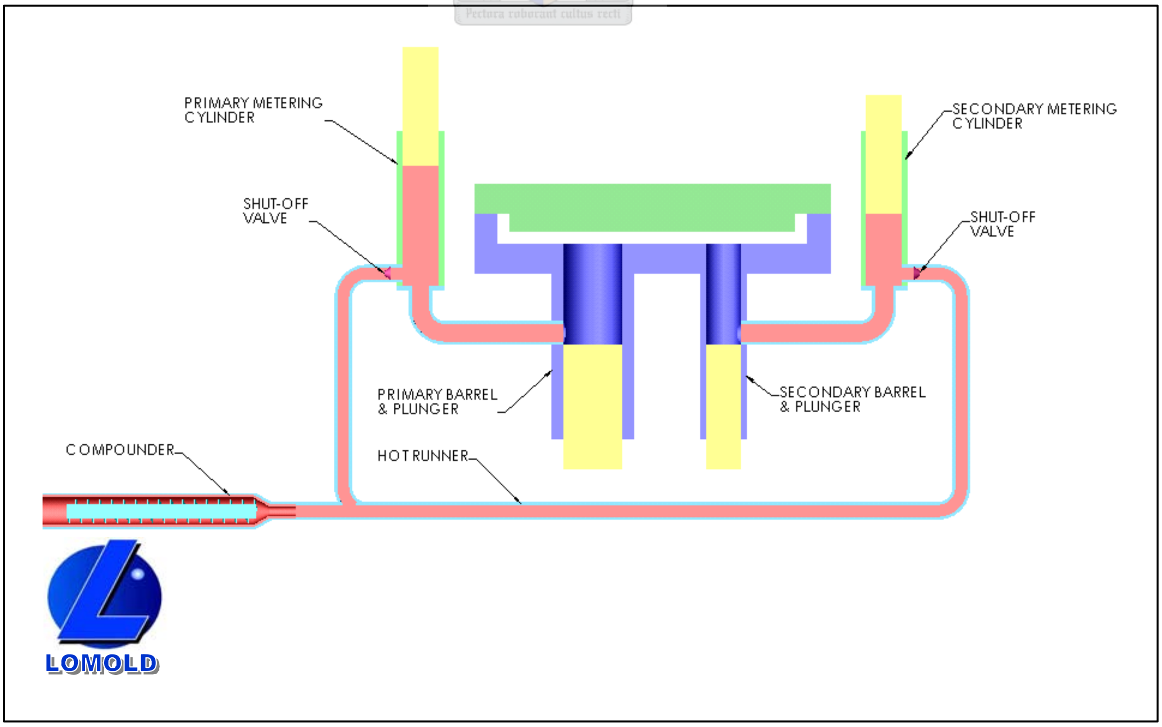


Figure 1: Basic concept of a LOMOLD machine

Some key characteristics of the process are the accurate metering of the melt before it enters the mould and a plunger pushing the melt into the mould cavity through a large gate. The plunger then becomes part of the wall of the mould.

Figure 1 will be used to demonstrate the basic principles of the LOMOLD idea. An inline compounder is used to plasticize the material. The material is fed through a hot runner system to the metering cylinder. Here the exact amount of material is accurately metered. When the correct amount of melt is in the metering cylinder, a shut of valve closes the metering cylinder from the hot runner. The piston in the metering cylinder forces the melt through another hot runner into the barrel in front of the plunger. The plunger forces the melt through a large gate into the cavity of the closed mould and forms part of the bounding wall of the mould. More than one plunger can be used to inject the melt into the mould cavity as illustrated in the Figure 1. In Figure 2, the melt is in the mould, the cooling phase is completed and the plungers are ready for next cycle [14].

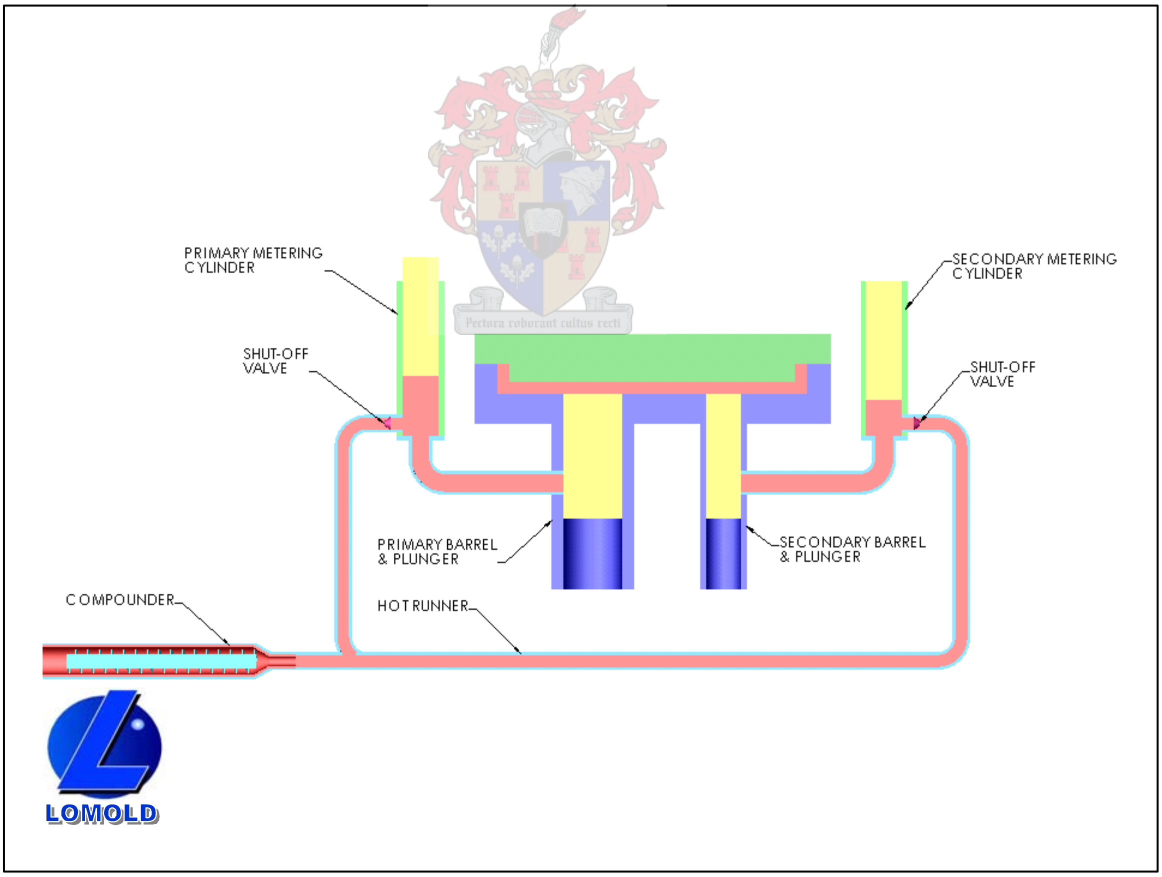


Figure 2: Part moulded with LOMOLD machine

1.2.3 Cycle of the LOMOLD process

The machine available for research work progresses sequentially through the process phases. A production version of the machine will complete some phases in parallel, thereby reducing the cycle time significantly. At the start of the cycle the mould is open and the piston is retracted in the barrel. A typical cycle on the current LOMOLD machine is:

1. The mould closes
2. Material is plasticized
3. The in feed valve to the metering cylinder opens
4. Material is pushed into the metering cylinder
5. The in feed valve closes
6. The out feed valve opens
7. The material is pushed out of the metering cylinder into the barrel in front of the piston
8. The out feed valve closes
9. The piston push the material into the mould cavity
10. The cooling time starts while the piston keeps pressurising the material
11. The mould opens
12. After 10 seconds the piston retracts into the barrel

The machine is now ready for the next cycle.

1.2.4 Characteristics comparison

As stated earlier, the LOMOLD process has features of both Compression Moulding (CM) and Injection Moulding (IM).

Table 1: Characteristics comparison

Characteristics	Compression Moulding	Injection Moulding	LOMOLDING
Low injection pressure	●	■	▲
Low cavity pressure	●	■	▲
Long mould life	▲	■	●
Low mould cost	▲	■	●
Mould long fibres	▲	■	●
Fibre orientation	●	■	▲
Flashing/trimming	■	▲	●
Part Geometry	■	●	▲
Large components	▲	■	●
In-mould decoration	▲	■	●

Key:

■	Weak feature
▲	Strong feature
●	Very strong feature

The most important expected advantages from the LOMOLD process include:

- Lower injection pressures, cavity pressures and clamping force required
- Moulding of long fibres in components
- Moulding of large components
- Reduced material shear rates
- In-mould film decoration
- Significant cost reductions

Injection pressures are significantly less than those experienced in injection moulding. This is due to the big diameter plunger and large gate that force the melt into the mould cavity. It is expected that cavity pressure should also be less than in injection moulding. These lower pressures need less clamping force to keep the two mould halves closed. Therefore a cost reduction in the machine size is significant. The reduced cavity pressures will also influence cost savings in the tools used. Less expensive mould-making materials can be used without reducing the tool life. Rapid Tooling could be an option for production tooling with the added benefit of reduced lead-times making customized production and small runs viable.

The biggest cost savings will be achieved in producing large parts where cost reductions in terms of machine size and tool material will be most significant. Also the large gate and big diameter plunger combination is specifically well suited for producing large parts. Warpage in these large parts should be minimal due to the reduced material shear because of the large gate, improving the part quality.

The use of a compounder upstream of the LOMOLD machine enables a longer average fibre length in the melt. The large gate allows these longer fibres to enter the mould cavity without substantial shortening. The result is a stronger part with less fibre loading.

A lot of interest is shown internationally in whether the expected fibre lengths can be successfully moulded with the LOMOLD process. The reason for this is that long fibres are necessary to enhance the strength of the plastic part so that it can be considered for replacing other strong, expensive materials like steel. The long fibres will make the production of large parts easier and less expensive while improving the part mechanical properties. The longer the fibres the less the fibre content needs to be to get the required part strength. Also, the large gate gives the option of using “scrap” materials as filler material to also reduce the part cost.

The large gate reduces the shear rates in the material substantially. This leads to less part distortion. The long fibres in the melt are not aligned in one direction as in injection moulding. A more random orientation of the fibres is achieved. This will impact on the mechanical properties of the part.

These reduced shear rates together with the lower injection pressures make In-Mould Decoration (IMD) possible. This will have huge cost implications for applications where the part decoration is currently performed with a secondary process after the moulding process. Car manufacturers can save substantial amounts of money if they can mould decorative material found in car interiors during the moulding process and thereby eliminate expensive, labour intensive processes down stream from the moulding operation.

2. Rapid Tooling Overview

2.1 Rapid Tooling Technologies

2.1.1 History of Rapid Tooling

Rapid Tooling (RT) is a relatively new technology. It originated thanks to developments in the prototyping industry, therefore it is safe to say that Rapid Prototyping (RP) technology is driving RT.

Rapid Prototyping (RP) started in 1987 with the Stereolithography (SL) process from 3D Systems [1]. The process use a laser to solidify ultraviolet light-sensitive liquid polymer, thin layer by thin layer until the part is complete. In 1991 Fused Deposition Modelling (FDM), Solid Ground Curing (SGC) and Laminated Object Manufacturing (LOM) emerged as RP technologies. These are all layer manufacturing processes, building parts layer by layer from CAD data.

In 1996 3D Systems sold its first 3D Printer that uses an inkjet-like mechanism to deposit and bind a wax-like material to build the part layer by layer. Z-Corporation commercialized its 3D printer for concept modelling. The process uses technology developed at MIT to produce models from starch- and plaster-based powder materials and a water-based liquid binder. It is this technology that is available at the University of Stellenbosch. There have been many new developments in the field of RP since the nineties. The interested reader is referred to [1] for more detail especially on how the technology is used, where it is used and what for.

Rapid Prototyping (RP) is a special class of machine technology used for quickly creating physical models and functional prototypes directly from CAD data [1]. The manufacturing can be by removing material (like high speed milling) or adding material. An important point is that RP implies digital manufacturing i.e. using CAD data to produce the part [11]. Using a layer-by-layer approach, RP machines produce parts by joining liquid, powder or sheet material by breaking the 3D CAD model into successive horizontal cross sections.

This technology took the world by storm. In an ever increasing competitive market place, the development time for new products is becoming a great source of opportunity to get an edge over competitors. Prototypes of new products can be produced within hours, enabling fast design iterations for better quality parts and reduced time to get the product on the shelve.

A shortcoming of RP is the limited range of materials from which prototypes can be made. If the properties of the prototype material differ considerably from the final part material properties, functional testing of the prototype is not possible. Also, if a batch of parts must be produced, RP can be too costly. That is why RT originated. RT methods emerged using existing RP technology and 3D CAD modelling to produce prototypes in end product materials or materials representing the properties of the final product materials.

During the last few years, RT technologies were developed to directly produce tool cavities. This opened new opportunities for RT. RT is now applied not only for Prototype Tooling or Bridge Tooling but also for Production Tooling.

2.1.2 Definition of Rapid Tooling

Since the buzzword Rapid Tooling started making headlines, it is defined as the ability to create cavity and core inserts using a Rapid Prototyping technology. This definition had to evolve over recent years. Advances in 3D-CAD capabilities, CAM packages, machine tools and the use of the internet to transport data has made traditional tooling methods more competitive. The lead-time of traditionally manufactured tools is decreasing rapidly. Employers of these methods are starting to use “Rapid Tooling” to describe their tools.

There is no official definition for RT that satisfies the whole industry. Some say that it is any technology or method that produces tooling quickly. This includes processes like High Speed Machining (HSM). Other says that RT is “RP-driven” tooling. This definition gives credit to the technology that started RT, namely RP.

The fact is that using a cutting edge Rapid Tooling technology does not guarantee the delivery of tools faster. The RT technology is only an enabler, not a guarantee of reduced lead-times. Reducing lead-times is a combination of the tools used, the methods employed, the process used and the people involved [6].

The newest definition of RT follows in the wake of concepts like Rapid Manufacturing (RM). There seems to be more clarity in the industry where the boundaries of all these concepts are, therefore the new definition of RT is that the term Rapid Tooling aims only for long-term consistent tools capable of producing several thousands or even millions of parts [12]. This definition focuses on fast tools with long tool life. This gives insight into the maturity of the RT technology at present and the ultimate aim of Rapid Tooling technology: to replace traditionally machined production tools as the tool manufacturing technology of choice.

This is the definition of RT that will be used in this thesis, therefore only technologies that are covered by this definition will be considered.

There are two categories of Rapid Tooling. The one is indirect technologies that use RP master patterns to produce moulds. The second is direct technologies where RP machines build the actual tooling inserts [1]. Technologies from both categories will be discussed in the next pages.

2.1.3 Indirect methods of Rapid Tooling

A Rapid Tool is made indirectly if a pattern (normally created using a suitable Rapid Prototyping Technology) is used as a model for the mould making process [3].

These indirect methods allow tool validation in the product development cycle before changes become very costly. The aim of these RT methods is to fill the gap between RP and hard tooling by enabling the production of tools capable of short prototype runs.

The accuracy of all these processes is mainly dependent on the accuracy of the pattern used to create the tool cavity.

2.1.3.1 Metal Deposition Tools

A RP model is used to create these tools. The model must have a good surface finish, incorporate a draft angle and have an allowance for shrinkage of the moulding material. The pattern is embedded along its parting line into plasticine within a confined box. The sprue, gates and ejector pins are added. The exposed half of the mould is coated with a release agent and then a thin shell of 2-3 millimetres thick of low temperature molten metal is deposited onto it. The same process is repeated to form the other half of the tool. RP models can distort if subjected to high temperatures, so not all metal deposition techniques can be employed wit RP master patterns [3].

Spray metal tooling

This technique can be divided into two types: Gas Metal Spraying and Arc Metal Spraying.

Gas Metal Spraying uses a low melting point alloy that pass through a nozzle. The material is in the form of a metal wire (usually lead/tin) and is melted by a conical jet of burning gas. The material is atomised and propelled onto the RP pattern [3].

With Arc Metal Spraying, the surface of the mould is created using an arc spray process to deposit a thin layer of metal (low melting point alloys) on the pattern. This layer is typically 2 mm thick, depending on the part size and complexity. Different metals can be used including kirksite (a zinc-based alloy) and steel [1]. The surface is backfilled with an epoxy or a low-melt alloy to provide strength. The thin metal surface allows fast cooling times although the choice of backfill material influences the cooling rate of the tool significantly.

Spray metal tooling is good for producing large, accurate parts that is of low-to-medium complexity. The tools are relatively inexpensive, fast to produce and capable of handling abrasive materials. However, the mould has a limited life and complex geometries can increase the cost and lead-time considerably. Inserts must be used to create narrow slots or small diameter holes.

RSP tooling

Rapid Solidification Process is a spray deposition technology [1]. First a pattern of the tool is created from a CAD model. A negative of the pattern is then produced from ceramic. A 5 axis gripper holds this ceramic pattern while molten metal (almost any tooling alloy can be used) is sprayed onto the pattern from all angles. The metal is allowed to cool and can then be machined to fit into a mould base.

The steel deposition rate is about 227kg per hour, and very fine detail on the master pattern is replicated. The resultant tool insert can be used as an insert in the production processes.

Limitations are the insert size and deep slots or holes. The metal spray cannot sufficiently cover features with an aspect ratio greater than 2:1. These features are machined and then added to the insert. This adds to the cost and lead time of the tool insert.

It is possible to spray different materials onto the master pattern. Spray a thin layer of metal onto the pattern to capture the geometry and provide the strength and then spray a highly heat conductive material like copper onto the metal. This can significantly reduce cycle times on the tool.

Nickel electroforming

The RP model is painted with an electrically conductive paint and placed into an acid bath that contains nickel powder. A voltage is applied to the acid bath and nickel is attracted to the conductive paint by electrolyses. Nickel has better mechanical and thermal properties compared to the alloys used for metal spraying but the deposition rate is slow ($10\,\mu m/h$) and the deposition thickness depends on the geometry of the surface. Also, deep corners, sharp edges and narrow openings are difficult to plate and can wear faster [3].

Nickel Vapour Deposition (NVD)

This process is based on the growth of a metal from a gaseous vapour. The pattern is heated to between 110 and 190$^{\circ}C$. $Ni(CO)_4$ is passed over it. A layer of pure nickel is deposited on the surface of the part, replicating it. Deposition rates between 0.005 and 0.8 mm/h can be achieved so that a shell mould can be produced rapidly, regardless of its size and complexity.

To improve the strength of the mould, it is backfilled using an epoxy resin or ceramic. These materials are used because their thermal expansion is close to that of the material the shells are made of. To improve the thermal conductivity of the backfilling material, aluminium powder is usually mixed in with it.

The shells produced are cost effective, have good dimensional accuracy, low mechanical strength and high porosity. The thermal conductivity of the mould can be improved by applying a layer of metal with a higher melting point but with better thermal properties over the shell [3].

Ford's Sprayform

The process uses twin wire metal arc guns to spray carbon steel onto the surface of a pattern. The pattern must be made of ceramic. A special freeze-casting process is used to ensure the stability and accuracy of the ceramic pattern. A robot controls the spray guns. The work envelope can hold parts of 760 x 1015 x 250 mm but pieces can be added together to create larger tools [9]. Conformal cooling can be incorporated in the mould by interrupting the spraying process, inserting cooling tubes and resuming the spray process to the required shell thickness. The pattern is destroyed when the metal is removed. The tool is squared and backfilled with an epoxy and critical surfaces machined.

Ford use Sprayform to produce production dies for sheet metal forming of non-visible parts. The process is being refined for applications such as injection-mould tooling and dies for visible metal-formed parts [1]. The process is also used to create sand cores, foam seat moulds and composite lay-up tooling [9].

2.1.3.2 Epoxy Tools

Producing an Epoxy Tool starts with a frame constructed around the RP pattern. The pattern is suspended in plasticine. A release agent is applied to the exposed surface of the pattern and the epoxy is poured over the pattern. Aluminium powder is usually added to the epoxy to increase the thermal conductivity of the mould. Once the epoxy is cured the assembly is inverted. The plasticine is removed leaving the pattern in the mould half just cast. The casting process is repeated to form the other side of the tool. After curing the two halves are parted and the pattern removed [3].

Epoxy curing is an exothermic reaction that can damage the RP pattern. Therefore it is not always possible to cast the epoxy directly onto the pattern. In such situations, a silicone RTV model must be made from the pattern. The resulting plastic part produced from this mould can be used as a pattern for epoxy casting. A loss of accuracy results from this extra step in the process.

Epoxy tools have a limited tool life, poor thermal transfer, depend on the master pattern for accuracy and aluminium filled epoxy has low tensile strength. The amount of parts that can be produced by plastic injection using epoxy tools for different final product materials are listed in Table 2 [3].

Advantages of epoxy tools are that production thermoplastics can be used. It works best with parts of low-to medium complexity. Relatively large moulds can be produced cheaper than conventional methods. However, the tool life is limited and long cycle times can be expected. Complex geometries may require many metal inserts that will increase the cost and lead-time. The epoxy is brittle and can easily be damaged [4].

Table 2: Approximate aluminium-epoxy tool life

MATERIAL	TOOL LIFE (SHOTS)
ABS	200-3000
Acetal	100-1000
Nylon	250-3000
Nylon (glass filled)	50-200
PBT	100-500
PC/ABS Blends	100-1000
Polycarbonate	100-1000
Polyethylene	500-5000
Polypropylene	500-5000
Polystyrene	500-5000

2.1.3.3 3D Keltool™ Process

This process is based on a metal sintering process. It converts a RP master pattern into a production tool insert with very good definition and surface finish. The following are the process steps:

1. Fabricate master patterns of the core and cavity.
2. Produce RTV silicone rubber moulds from the patterns.
3. Take a metal mixture of powdered steel, tungsten carbide and polymer binder and fill the moulds to replicate the patterns. The resulting parts are called “green parts” (powdered metal held together by the polymer binder)
4. Put the green parts in a furnace to remove the plastic binder and sinter the metal particles together. The sintered parts are now 70% dense.
5. Infiltrate these parts with copper in a furnace.
6. Finish the parts.

Tool inserts made using this process can be produced in two materials: Stellite or A-6 composite tool steel. More than 1000 000 moulding cycles can be completed with these inserts [3].

Advantages: Replicate details and features as small as 0.04 mm. Parts with complex shapes can be produced. The process is very accurate and the inserts can be polished to an excellent finish. Hundreds of thousands of parts can be injection moulded with these tools.

A disadvantage of the process is that the accuracy of the tool is dependent on the accuracy of the master pattern. Size is a limitation with the maximum size being 150 x 215 x 100 mm. It is possible to press fit two or more inserts together in a mould base to increase the tool size [1]. Thin geometries can also be broken while the part is in the “green” state, especially when de-moulding from the room temperature vulcanising (RTV) rubber.

It takes approximately 8 days to produce an insert with the two-step furnace process, depending on the complexity of the insert.

2.1.3.4 PolySteel

From a RP pattern, mould inserts are produced that consist of 90% steel by weight. These moulds produce prototype parts in glass-filled nylons, ABS, and wax for investment casting. No secondary machining or polishing is necessary [1]. The moulds have good thermal conductivity and conformal cooling channels can be incorporated in the mould. These moulds are stronger than conventional aluminium-filled epoxy tooling. A small to medium sized mould can be produced within two weeks.

PolySteel 2 is a more durable material and can be used for higher volume applications. The accuracy obtained with these tools can be compared to CNC-machined tools made from tooling steel [9]. PolySteel 2 has an expected tool life of 10 000 to 500 000 cycles, while PolySteel 2+ has an expected tool life of 500 000 to 1 000 000 cycles [4].

2.1.3.5 EcoTool

A RP pattern is created and placed on a parting line block. A metal powder/binder slurry is cast over the pattern to create the first halve of the mould. The process is repeated on a second pattern/parting line block to form the second halve of the mould. The slurry is allowed to harden at room temperature for two hours. This green part has sufficient tensile strength to be removed from the parting line block and be handled. The slurry can be poured over a wide range of materials used for RP pattern making because it hardens at room temperature [1].

A few options are available to increase the tensile strength of the green insert. A hot air treatment at $120^\circ C$ increases the tensile strength of the inserts to 10-20 MPa. If the insert is infiltrated with a copper alloy, the tensile strength increse to 300-400 MPa. Shrinkage occurs with copper alloy infiltration. The amount of shrinkage depends on the metal powder used and the powder particle size distribution.

EcoTool should be cheaper and faster than 3D Keltool because a less expensive nitrogen furnace is used instead of the hydrogen furnace used by the latter. Also, the part does not sinter before infiltration with the EcoTool process. The EcoTool binder has a high melting point allowing the part to be infiltrated directly. This has lead to no dimensional changes occurring during infiltration.

2.1.3.6 Express Tool

A graphite mandrel is CNC-machined and a 6 to 10 μm layer of nickel and copper is deposited on the mandrel by the electroforming process. The graphite acts as a natural release agent so that the shell can be easily removed from the mandrel. Conformal cooling channels can be put in place and the shell is backfilled with steel [1].

Graphite is used because it is an excellent conductor of electricity and it machines about five times faster than aluminium. Thermal conductivity is six to seven times better than standard tool steel, leading to reduce cooling times and improved productivity.

Disadvantages of the process are holes and narrow slots do not electroform well, therefore inserts must be machined and assembled into the shell. This increases the cost and lead-time of the mould.

Over 250 000 parts can be produced from unfilled material using these moulds.

Not really faster than conventional tool making processes but the material used increases heat conductivity resulting in reduced cycle times. The plating process deposits a 1-2 mm shell of nickel backed up by 3-4 mm of copper, and a backing support of a proprietary composite. Similar coefficients of thermal expansion keep the three layers from separating during use [4].

2.1.3.7 PHAST

Prototype Hard And Soft Tooling (PHAST) can create intricately detailed, multi-cavity tooling for injection moulding. The process starts with a pattern. From the pattern a plaster mould is created using a soft, accurate and reusable material [9]. Ceramic moulds are produced from this plaster mould. Wear resistant Metal Matrix Composite (MMC) mould inserts are produced from the ceramic moulds. The material consists of 30% tungsten and 70% bronze by volume.

PHAST is used for production tooling for injection moulding as well as prototype and bridge tooling for zinc die casting. The process is not as accurate as CNC machining but smaller features can be produced [9]. Also features with high aspect ratios are not a problem for this process.

2.1.4 Direct methods of Rapid Tooling

Indirect methods for tool production necessitates the use of at least one intermediate replication step in the process, resulting in a loss of accuracy and increased tool build time and cost. Direct methods produce tools capable of completing a few to thousands of moulding cycles. The life expectancy of these moulds differs depending on the material and RT method used. The limited range of materials available for producing these tools is the biggest drawback. A new approach is to use direct tooling methods in conjunction with traditional tooling methods, further increasing the application area of direct tooling methods [3].

Direct RT covers prototyping, pre-production and production tooling. There are two main groups of direct RT processes:

The first group are less expensive methods with shorter lead times. These tools are good for tool validation. These tools are also called “bridge tooling”. Bridge tooling fills the gap between “soft” and “hard” tooling. Bridge tooling produces tools for short prototype runs (50 – 100 parts) using the same material and manufacturing process as final production parts.

The second group are RT methods that can produce inserts for pre-production and production tooling. These tooling methods are called “hard tooling”. These methods revolve around the fabrication of sintered metal powder inserts infiltrated with bronze or copper [3].

The direct manufacture of metal tools (hard tools) can be divided into two categories: additive and subtractive processes. A subtractive process is High Speed Cutting (HSC). The additive category can be further divided into melting and non-melting systems (Figure 3). Each of these can be further divided into the form of the material used and further by the RP process underlying the tooling method [12].

2.1.4.1 SLS tooling

Selective Laser Sintering (SLS) fuses metal powder together using laser-sintering technology. The core, cavity and part CAD data is used with the SLS machine to create physical models. The material is A6 tool steel particles coated with a polymer binder. The produced part (called a green part) is fired in a furnace to remove the binder and to sinter the metal particles together in a porous structure. This is then infiltrated with bronze to produce a fully dense insert of about 55% steel and 45% bronze. The insets are then finished through conventional machining methods [1].

The newest material released is LaserForm A6. This material has a new binder resulting in stronger "green" parts so that finer detail and thinner walls can be produced. The A6 material also included tungsten carbide particles for increased wear resistance. Improved surface finish is another characteristic of the new material.

Small to medium sized complex metal inserts can be produced fast and combining this technology with traditional machining technologies further increases the usefulness of this technology.

2.1.4.2 DMLS

Direct Metal Laser Sintering (DMLS) is a process developed by EOS (Electrical Optical Systems) that produces fully sintered parts in one step. A blend of powdered metal that contains a low and high melting point binder is fused layer-by-layer with a laser. The low melting point binder is fused to keep the remaining powder in form.

EOS currently offers two materials: DirectMetal relates closely to bronze and DirectSteel relates closely to steel. The bronze-based material produces parts that are 60% dense. DirectSteel can produce almost 100% dense parts. The layer thickness of the latter is 50 μm that means finishing of the part is required [4].

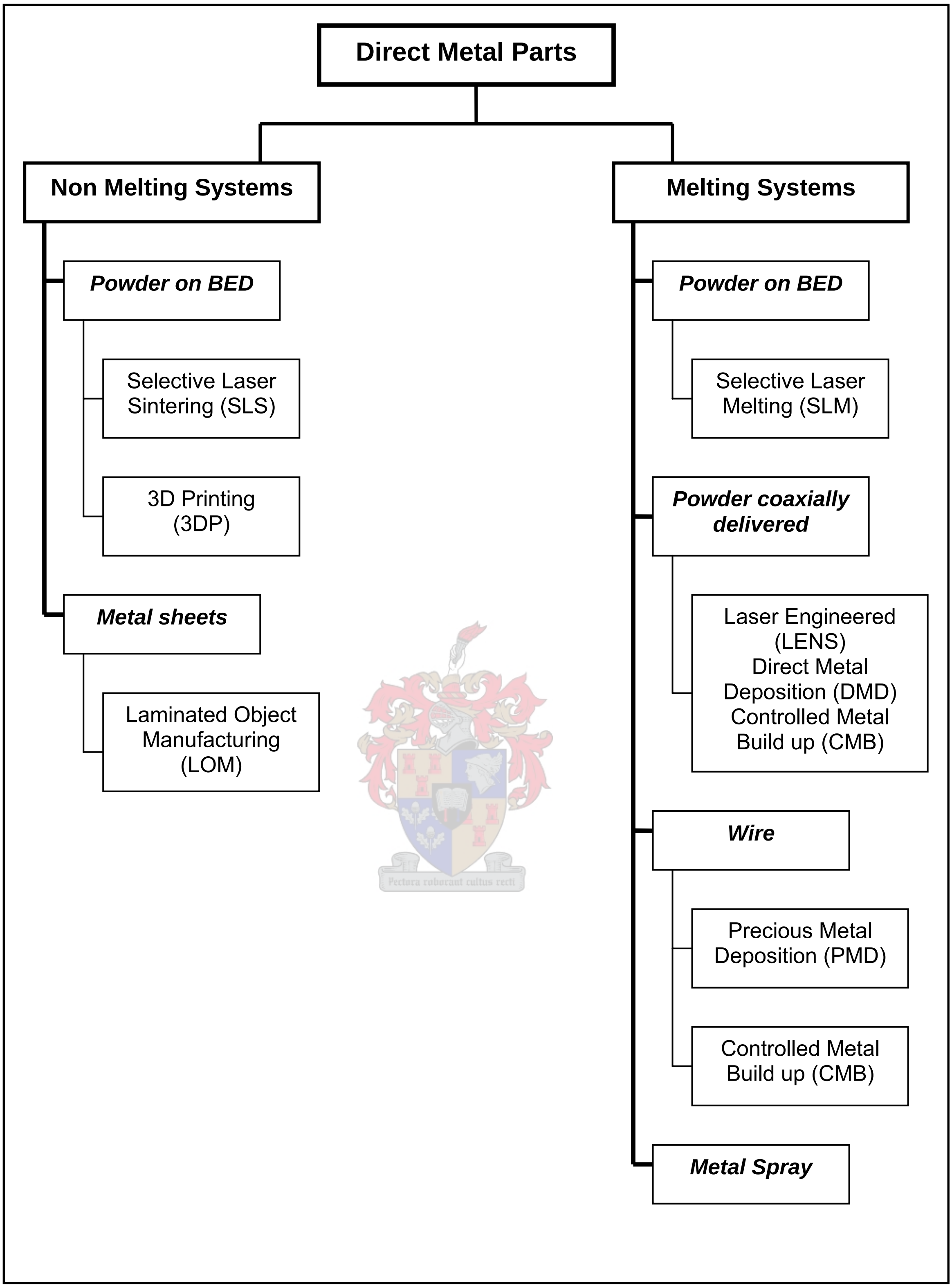


Figure 3: Classification of Direct Metal Parts, additive systems [12]

2.1.4.3 Solidica

Solidica patented a process called Ultrasonic Consolidation™ (UC). It is a direct metal fabrication process that produces parts in aluminium. The process uses aluminium tape, a layer-by-layer approach together with CNC-machining. No lasers or powder is used. UC uses sound to bond layers of metal together. Other metals will be available for use with this process in the future [1].

2.1.4.4 ProMetal

The process is called MoldFusion. It is essentially a 3DP (developed at MIT) process for manufacturing metal parts and tooling. An electrostatic inkjet print head sprays a liquid binder onto a base powder, to harden the powder to form the part geometry, layer-by-layer. The powder is stainless steel based. The “green” part is put in a furnace where the binder is burnt of and the metal particles sintered together. The part is not sintered to full density to reduce the shrinkage of the part. The sintered part is infiltrated with bronze after it is removed from the furnace. The final part is 60% steel and 40% bronze and is not net shape. It must be machined before it can be used as a tool. Tool shrinkage is estimated at 1.5% ±0.2%. Prototype plastic injection moulds has successfully produced 100 000 shots of glass-filled nylon at injection pressures up to 207MPa. [1] The bronze infiltrant increases the thermal conductivity of the tool and conformal cooling can also be accommodated.

2.1.4.5 LENS

Laser Engineered Net Shaping (LENS) uses a high-powered laser to create a molten puddle on the substrate surface. Metal powder is injected into the pool of molten metal. As the laser scans across the surface, the material is deposited in lines to form the geometry of the tool. The platform is moved while the laser remains stationary. The procedure takes place in argon filled chamber to keep oxygen from the process. Parts can be produced in tool steel, stainless steel, aluminium, and alloys of copper, tungsten, nickel and titanium [4].

Software is under development for a controlling a 5-axis laser head, which will enable the forming of difficult geometries.

The process is used to repair existing moulds and for Rapid Tooling applications. Conformal cooling can be embedded in the tools. The process can use different materials to form a part. The different metal powders can be mixed in different percentages to improve thermal mismatches between copper cooling channels in a steel base.

2.1.4.6 POM

Precision Optical Manufacturing (POM) developed a process named DirectTool that produces a fully dense metal tool without sintering. It is a Direct Metal Deposition (DMD) process that uses a laser to melt powdered tool steel. The tool is built on a metal plate. A small amount of powder is fed onto the plate through a nozzle. A CO_2 laser melts and shapes the powder to form the desired part geometry [4]. The process takes place in an inert gas environment to prevent oxidation. The surface finish is very rough requiring finishing. The tools can be extensively polished to produce moulds for optical mirror parts quality. Parts can be produced in various metals (copper and nickel-based alloys, tool steels and stainless steels) as well as functionally graded materials of up to three different metals.

2.1.4.7 Arcam

Uses a process called Electron Beam Melting (EBM) to fuse together layers of powder to form the final product. The use of the electron beam permits the direct fabrication of fully dense parts in final material. The parts can be produced in stainless steel and other materials [1].

An electron beam is accelerated towards the metal powder. The powder melts as the kinetic energy of the electron is converted into heat. The laser beam is directed according to the geometry prescribed by a CAD model and the part is built layer-by-layer. The part is removed and is ready for further processing. The building envelope was 250 x 250 x 200 mm early in 2002. Conformal cooling channels can be incorporated. The durability of the tool material can be compared to that of ordinary tool steel.

2.1.4.8 CNC-Machined Tooling

Machining is a mature technology that is well understood and can be applied successfully to produce tools in final material that are more accurate than RT tools. Also the size of the tool is not such a big concern as with RT techniques. It has also been proved that mould lead times can be reduced substantially with improved planning. Managing the process chain effectively and taking full advantage of information based systems and CAD/CAM software is where CNC-machining can compete successfully with modern RT technologies. [1]

2.1.5 Risk factors for Rapid Tooling

The “soft methods” for Rapid Tool production are not always the best choice for tool production. Human error or the moulding machine easily damages these tools. Repeatability can also be a problem [1].

The mechanical properties of parts produced with “soft tools” can differ considerably from parts produced with production tools. This is especially problematic if the prototypes are produced for mechanical testing purposes. There are a lot of reasons for this: the mould is “saved” to enhance the tool life, the mould material is different, the cooling channels are different or injection pressures are different.

With conventional tooling, the mould is often tested by producing a preliminary part. This part is evaluated and changes are made to the mould to produce the parts within specification. Most RT methods do not allow the same leeway for tool refinement. The RT solution can be a one chance opportunity to get the part right or to produce a new tool [1]. The ability to predict the performance of the tool beforehand becomes invaluable.

2.1.6 The future of Rapid Tooling

How competitive you are in the mould making industry is determined by 3 factors: quality, time and cost. Of these 3, time has the biggest potential for gaining a competitive advantage over the competition.

The best thing about Rapid Tooling is its timing. Never before has there been so much competition to get better quality products to the market quicker and cheaper. Customers are spoilt for choice. Companies are feeling the pressure from competitors and are looking for ways to beat the competition in any means possible. That is why many companies are developing RT processes in-house to get a competitive advantage over competitors.

Rapid Tooling has 3 major advantages over traditional production tooling: manufacturing lead time, tooling cost and conformal cooling. Of these conformal cooling is probably investigated the most at the moment. Results obtained thus far suggest that conformal cooling can reduces cycle times by up to 20%. This will impact part cost and production rates significantly [1].

Another area under intense investigation is improving the quality of parts produced with Rapid Tools. The parts produced with Rapid Tools are becoming more the same quality as parts produced with production tools. A lot of effort is going into new materials and refined process chains to improve the quality of parts produced with Rapid Tools.

Rapid Tooling has limitations but companies are realising that the rewards Rapid Tooling offer substantially outweigh the limitations of current processes. Therefore lots of time, energy and money is invested in Rapid Tooling to address these limitations and to tap into the potential of the concept.

It is realised that the destiny of Rapid Tooling is to become capable production tooling. Production tools that are produced fast, are basically unaffected by complex geometry, has improved cooling through conformal cooling and are accurate will have a huge impact on the manufacturing industry. This is the only way the enormous potential of Rapid Tooling can be fully realised.

So basically, RT must evolve into a mature technology that can be used for prototype creation, bridge tooling, small-, medium- and high volume production. As researchers work hard to meet the requirements of production tooling with RT, process improvements will filter through all the application fields of RT. The aim must be to replace traditional tooling methods by meeting the same part quality with the added benefits of reductions in time and improved efficiency.

2.1.7 Conclusions

The two Rapid Tooling technologies that will be investigated with the LOMOLD process are Aluminium Filled Epoxy Tooling (AFET) and High Speed Cut Aluminium Tooling.

The processes were decided on mainly because of availability. The AFET process is available at the Laboratory for Rapid Product Development (RPD) at the Department of Industrial Engineering. A HSC milling machine should be available at the same department soon. Both processes are therefore available for future use with the LOMOLD process which will reduce the tool lead-time substantially. These 2 technologies also cover Direct and Indirect Rapid Tooling Technologies.

Both processes can produce tooling for large products. The abrasive resistance of both tools can be improved with surface treatments. The AFET tool is probably more suited to prototype or short run production but with the LOMOLD process, the life of the AFET tool may be lengthened substantially. A major advantage of this tool is that conformal cooling can be incorporated in the tool. The aluminium tool can be used for production and offers improved accuracy over the AFET tool. Only conventional straight bored cooling channels can be incorporated in this CNC-tool.

3. *Moulding Fundamentals*

3.1 Introduction

Injection moulding is an established, well documented process that is widely used in plastic forming operations. The terms used in moulding processes are generally applicable to most plastic forming processes. The factors that influence the part quality for injection moulding are more or less the same factors that will influence the part quality of parts produced with the LOMOLD process. The importance of the factors, the interaction of the factors with each other and the effect of these factors will differ. Injection moulding is therefore a good start point for the person that wants to learn about plastic forming processes. Therefore the researcher used literature on injection moulding to get familiar with the art of plastic moulding processes.

3.2 Injection Moulding

3.2.1 The injection moulding machine

Typical IM machines: 20-10000 tons clamping force [5]
1500-2500 bar injection pressure
18-120mm screw diameter

Shot size is the maximum melt volume the IM machine can deliver in one shot. Plasticizing capability is the amount of melt the screw can plasticize in a certain time.

High quality parts are produced in single cavity moulds because all parts are then produced under the same conditions [5].

3.2.2 The phases of injection moulding

Each phase in the injection moulding cycle has an influence on the eventual part quality. For discussion purposes the injection moulding cycle is divided into the following phases [5]:

- Injection phase
- Holding pressure phase
- Cooling phase
- Part Ejection

Every time the injection moulding machine completes all of these phases, a part is produced. The time it takes to complete a cycle is called the cycle time and is of critical importance because it directly affects the cost of the part and the part quality. These phases will now be discussed.

3.2.2.1 Injection phase

The part moulding cycle begins with the closing of the mould. The material is melted in the plasticizing unit. The injection unit moves forward until the injection nozzle rests on the sprue bushing. The material is injected into the mould cavity slowly, then fast and then slowly again for packing of the material. The injection velocity profile depends on the material, the part and other process parameters [5].

The injection time is very important. The average temperature should be constant over the moulding process to ensure quality parts. There is an intermediate injection time for which the injection temperature of the melt and the temperature at the end of the flow path will be the same. The optimum injection time depends on the pressure, temperature and stress (resulting from the flow process), but mainly depends on the type of part being moulded and the material involved.

Flow in the mould

The melt flows through the runner system into the mould cavity and immediately starts cooling. The viscosity profile of the melt behind and in front of the flow front is shown in Figure 4 [5].

The melt in contact with the cold mould wall solidifies and forms the frozen layer. The highest viscosity gradient (shear rate) is in the area of the frozen layer. High shear rates orient the filler material in the direction of flow therefore maximum orientation is expected just below the part surface.

The frozen layer causes the velocity of the melt flow behind the flow front to be faster than the velocity of the melt front. This causes the so-called fountain flow effect. The faster going melt at the back catches up with the flow front. The fountain flow effect causes stretching of the high viscosity front end which in turn causes more orientation [5].

The temperature of the melt rises gradually with time because of dissipation. The highest temperature is in the area of highest shear rate. The melt is getting more and more restricted as the outer material freeze causing the volume flow rate at the centre of the melt to increase. This cause a rise in temperature at the centre of the melt.

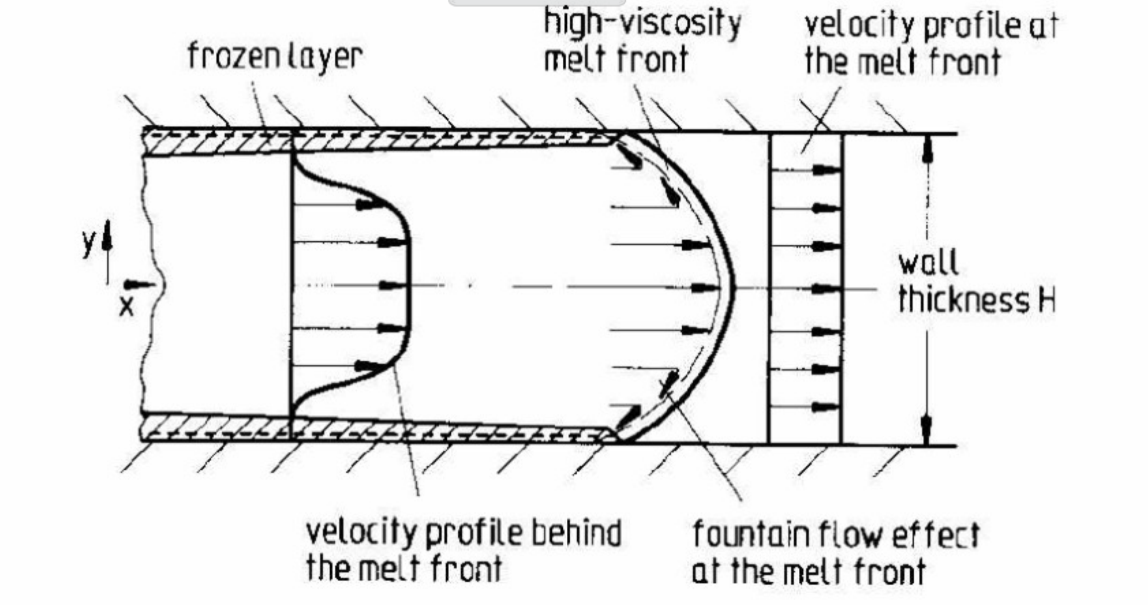


Figure 4: Velocity profile in the cross section

Frozen layer and orientation

The distribution of the frozen layer at the wall end follows a parabolic shape at the end of filling. The hot melt flow at the nozzle and the shorter cooling time at the end of the flow path produces a thin frozen layer at these points. The thickness of the frozen layer does not depend on the holding pressure because the frozen layer is already formed when the holding pressure starts. The thickness of the frozen layer does depend on the temperature because high melt temperatures cause a thinner layer due to slower cooling [5]. At high injection speed, less time is available for cooling in the filling phase so that the frozen layer is thinner at high injection speeds.

The degree of orientation caused by the flow is greater in the frozen layer than anywhere else. The mechanical properties of the moulded part depend strongly on the amount and direction of this orientation. The mechanical properties are higher in the direction of orientation. The highest orientation is at the wall because of the stretched viscous skin of the flow front that forms the surface of the moulded part. Second highest is the layer just below the wall (because of shear) in the transition area between the solidifying frozen layer and the flowing melt. The longer the material flows through this section, the higher the orientation. The degree of orientation decreases with increasing flow path. Orientation is the highest at the gate and decreases to about zero at the end of the flow path. There is no orientation at the centre of the channel because of no shear [5].

The pattern of orientation depends mainly on melt temperature and flow front velocity. Low temperatures are better for orientation because relaxation of orientation happens faster at high temperatures and the frozen layer is thinner at high temperatures. Semi-crystalline materials have a higher thermal contraction therefore more material must be pressed into the mould during the holding phase. This improves the orientation especially in the centre of the mould. The velocity of the flow front also strongly affects orientation. At high injection speeds the orientation is more pronounced and closer to the wall [5].

Pressure in the cavity

The strongest influence on pressure in the cavity is melt temperature and injection speed (Figure 5) [5]. The pressure is higher at the beginning of filling for higher injection speeds. The pressure is independent of the injection speed during the holding phase. Wall temperature has a strong influence on the pressure course (Figure 6) during the holding phase because wall temperature influences the cooling behaviour [5].

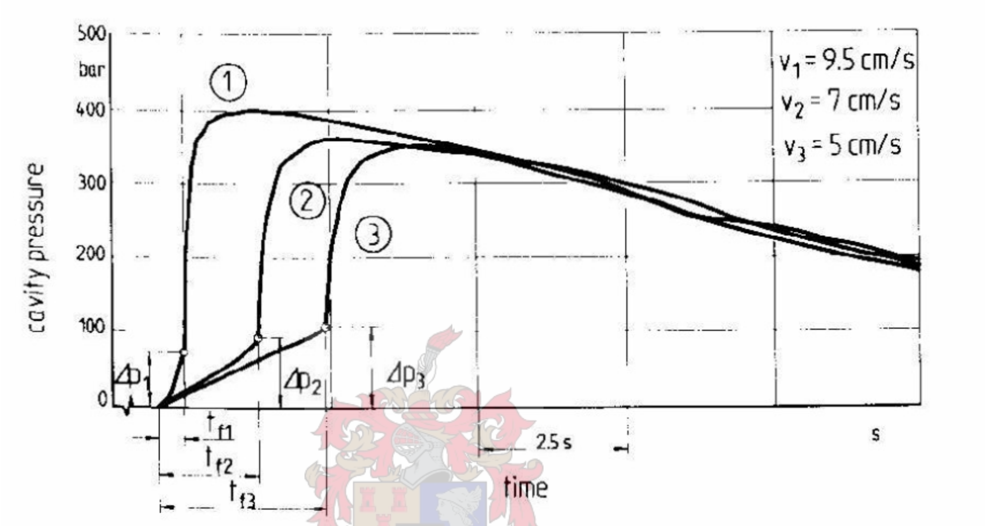


Figure 5: Cavity pressure for different injection velocities

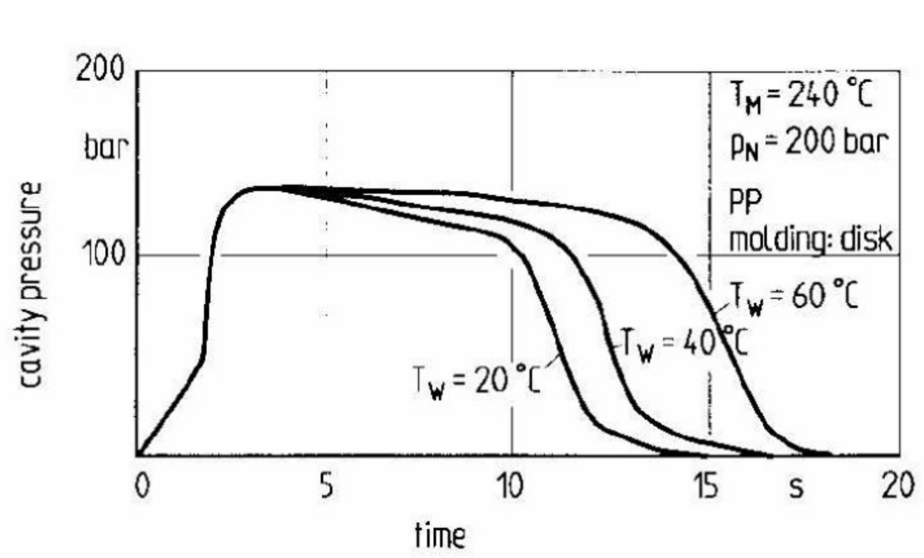


Figure 6: Cavity pressure for different mould wall temperatures

3.2.2.2 Holding pressure phase

Conditions during the filling phase influence the part with regards to quality. During holding pressure phase more material is forced into the mould to compensate for shrinkage. Features such as weight, dimensional accuracy and internal structure are influenced during this stage [5]. During this phase, air bubbles and sink marks in the mould are prevented and shrinkage and warpage are minimized, therefore the pressure profile must minimize shrinkage and warpage of the part.

At the sealing time, the gate is solidified. If the holding pressure lasts longer than the sealing time no further changes occur in the pressure curve. High wall temperature causes slow cooling of the moulding, which produces larger flow cross sections resulting in larger pressure levels in the holding phase [5]. Slower cooling causes the sealing time to lengthen. High melt temperatures increase the pressure inside the cavity.

Quality characteristics related to specific volume like weight, shrinkage and residual stress are largely determined during the holding pressure phase. The point at which pressure in the mould reaches atmospheric pressure is of key importance to shrinkage [5]. At this point the moulding starts to lose contact with the wall of the mould. Shrinkage stops when the moulding reaches room temperature except for semi-crystalline materials where post crystallization can take place. Higher compression and higher melt temperature both lead to lower shrinkage. An increase in wall temperature leads to higher shrinkage.

3.2.2.3 Cooling phase

The cooling of the injection moulded product has a large impact on the profits. An efficient cooling system reduce the cooling time of the part thereby shortening the cycle time and increasing the number of parts that can be produced per hour. Cooling also impacts some of the internal and external properties of the part. Shrinkage and warpage are inhibited mechanically by the cavity during the cooling phase. This leads to the build up of residual stresses in the moulding. After the moulding is ejected from the mould these stresses are relieved through deformations. By extending the cooling time in the mould, shrinkage can be reduced [5] although this will then again negatively impact the productivity of the process. There is an optimal cooling time where the productivity and part quality is both at its best.

Residual stress

Residual stresses are mechanical stresses in the moulded part in the absence of the application of external force. They are caused by the distinctive temperature profile in the moulding during the cooling process. The highest stresses are on the outside. Residual stresses influence a part's mechanical strength, its dimensional accuracy and its resistance to chemicals and other substances. Residual stresses are accompanied by lower shrinkage (inhibited contraction) than in a stress free part. If the distribution of the stress is asymmetrical, the part will warp.

Cause of residual stress

Residual stresses are caused mainly by the different cooling rates in the various layers in the cross section of a moulded part [5]. The cooler outer edge of the moulding impedes the contraction of the warmer core during its slower cooling process. The result is tensile stresses in the core and compressive stresses on the outside of the part. The fact that different layers prevent one another from contracting also leads to reduced shrinkage. Holding pressure and flow effects within the melt also play significant roles. Overpacking/overloading of the moulding i.e. the holding pressure is so high that the pressure in the interior of the mould cannot be reduced thermally, causes the core area to still be under pressure at the moment of removal. The moulding then expands after ejection.

Influence of process parameters on residual stress

The temperature of the melt has a small influence on the level of residual stress. The temperature of the mould wall is the most important factor because it influences the temperature gradient in adjacent layers of the melt. It is the temperature gradient that causes surrounding layers to oppose the contraction of the melt, leading to residual stress. Also, the cooling process is faster when the wall temperature is low. This leads to increased temperature gradients and increased residual stresses.

Shortening the cooling time reduces residual stress. There are two reasons for this: the warmer the part is when it is ejected from the mould the more the part can relax to reduce its residual stress. The second reason is that the sooner the part is removed from the mould, the faster it is exposed to the atmosphere that smoothes the temperature differences over whole part [5].

The thicker the part the less residual stresses will be in the part. Thin parts cool faster resulting in larger temperature gradients and more residual stress.

Crystallization

Crystalline areas in a material is formed when the macromolecules of the material is ordered in some structure. If these structures are randomly distributed throughout the material, the material is called semi crystalline [5]. Semi crystalline structures are formed during the cooling phase. Thermal conditions and flow effects are important to the formation of crystals. The degree of crystallinity is defined as the ratio of crystallized material to material capable of being crystallized. Moulding properties dependent on the degree of crystallinity include the weight of the part, yield strength, Young's modulus and impact strength, all increasing with increasing degree of crystallinity [5].

The main factor in determining the degree of crystallinity (DOC) is the cooling rate (see Figure 7). The DOC increases with increasing wall temperature because then the cooling rate is slower and crystallization improves. Thicker parts produce a higher DOC because of longer cooling times.

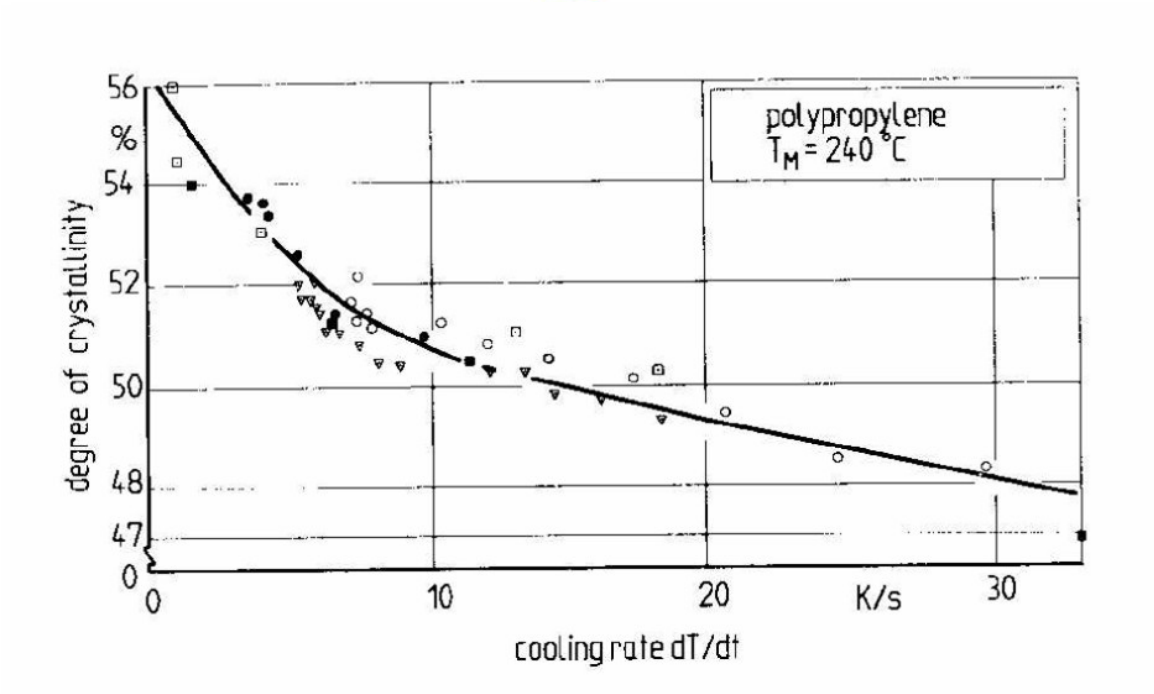


Figure 7: Degree of crystallinity as a function of cooling rate

3.2.3 Influence of internal properties on external properties

The production parameters of a part and its quality are strongly related. The processing conditions determine the internal properties of the part like orientation, frozen layer thickness, residual stress and degree of crystallinity (DOC).

In use it is the external properties of the part that is important. These properties are determined by the part's internal structure. The internal properties again are a function of the process parameters. Different process parameters can produce similar structural properties [5].

Orientation

With increasing molecular orientation, Young's modulus is higher in the direction of orientation and lower perpendicular to it. Tensile strength and yield strength rises linearly with increasing orientation. The mould should therefore be designed so that the gate is located so that flow occurs in the direction the main loading will take place [5].

Frozen layer thickness

As described previously, the level of orientation in the frozen layer is very high. Therefore the thickness of the frozen layer directly influences the mechanical properties of the part. Young's modulus and the tensile strength increases linearly with increasing thickness of the frozen layer [5].

Residual stress

Residual stresses have an influence on the mechanical behaviour as well as dimensional accuracy of the part. The more stress in the part, the less the shrinkage because thermal contraction is opposed [5].

Residual stresses also influence the part distortion. Asymmetrical mould temperatures result in asymmetrical stress patterns which cause the part to distort.

Degree of crystallinity (DOC)

The higher the DOC, the more brittle the part is. Impact strength therefore declines with increasing DOC [5].

3.3 Mould Cooling fundamentals

3.3.1 Introduction

Cooling is a matter of trade off: productivity versus part quality. The colder the mould the faster the cooling cycles and the more parts can be produced per hour increasing the profits. This is not the best situation for most materials, especially crystalline materials. These materials require a warm mould and long cooling times to achieve the highest level of physical strength in the part. Cold moulds will negatively affect the physical properties of the final part and could cause serious quality problems while warm moulds will enhance these same part properties [2].

3.3.2 Cooling methods

The idea is to cool the moulded part as quickly as possible to get it out of the mould without distorting it and sacrificing too much on the part quality. This produces good quality parts at a reasonable cycle time equating into a reasonable cost. The cooling system must ensure a uniform temperature profile over the entire part so that residual stress and part warpage is minimised.

Sufficient cooling must be provided efficiently and the cooling must be uniform. The main parameters influencing the uniformity of the wall temperature is the distance the cooling channels are from the wall and from each other. The further the cooling channels are from the wall and the closer they are to each other the better the uniformity of the temperature profile. Irregularities in the wall temperature cause warpage. Allowable differences in wall temperature are less for semi-crystalline materials than for amorphous materials [5].

Inefficient cooling can cause excessive part warpage. This might necessitate post moulding cooling in a custom made cooling jig. This is time consuming and very costly [8].

3.3.2.1 Conventional Cooling Method

Conventional cooling layouts are straight drilled channels around the tool cavity. Ejector systems, mould parting line and inserts make it impossible to get the drilled cooling channels where it is needed. To improve the cooling, expensive additions like baffles are added.

Machined waterlines should not be closer than 2 times their diameter from the surface of the mould cavity to prevent the pressure in the cavity from breaking through the cavity wall into the waterlines [2].

3.3.2.2 Conformal Cooling Method

The use of conformal cooling systems in moulds became possible with the advent of layer-by-layer manufacturing processes. These Free-Form Fabrication (FFF) processes allow the design and manufacture of cooling channels that follow the geometry of the part closely for improved cooling. This is called conformal cooling and two main benefits are improved productivity and process control [8].

There are numerous advantages associated with conformal cooling. Because of the more efficient cooling, the tool reaches its desired temperature faster from start-up, the temperature distribution in the tool is more uniform resulting in more accurate parts and the cycle time can be significantly reduced [8]. Some studies have shown that cycle time can be reduced with more than 67% in comparison with conventional cooling methods [8].

3.3.3 Cooling time

Cooling time is the major determinant of cycle time. The cycle time determines the productivity of the process. The productivity of the process determines the profitability of the process. Therefore the final part cost and the advantage/disadvantage the product faces in terms of the competition is greatly determined by the process cycle time.

The cooling time is affected by several factors such as the mould material, the part material, the part geometry, the melt injection temperature, the cooling method used, the temperature of the cooling fluid, the ambient temperature etc [8].

The time necessary to cool a part is greatly effected by the wall thickness of the part. The thickest section of the part will determine the cooling time. Other thinner sections of the part will be cooled long before the thickest section is cooled.

3.4 The Economics of Moulding

3.4.1 Introduction

There are two different cost categories [7]:

1. Tooling costs
2. Operational costs

The final part costs are determined from these costs.

3.4.1.1 Tooling costs

The normal practice is to amortize the tool cost over the amount of parts produced. This leads to a problem. The assumption is that production volumes will not vary from the initial estimates of production. However, product volumes often do change. If less parts are produced the price per part will rise and visa versa.

Type of mould material

Moulds can be machined or cast from many different materials. Low-volume moulds are made of epoxy, aluminium, mild steel, urethane or a combination of these materials. Higher-volume moulds are made from pre-hardened steel, tool steel, hot rolled steel, stainless steel or a combination of these. The weight of the material necessary determines the material cost.

Labour rates

The major part of the cost of the mould is made up by labour. Labour rates vary with geographic location and the expertise required to build a given mould. Also, different levels of expertise are required during the making of a mould.

Design costs

This is the cost of designing the mould and is normally ±10% of the final mould cost [7].

Hours to build

The number of hours required to build and assemble a mould depends on the material used, the complexity of the mould and the intended use of the mould (prototype, pre-production or production).

Geographic location

If the mould is build at a distant location, the cost of transporting the mould to its location of intended use must be added to the total cost of the mould.

3.4.1.2 Operational costs

These costs are associated with moulding a product and are heavily dependent on the cycle time achieved during production. The cycle time determines the amount of parts that can be produced per hour (productivity). This amount is used as a basis from which operational costs are calculated.

Material costs

The material needed to manufacture a product is calculated by determining the volume of the product, multiplying the volume by the material's specific gravity and adding a scrap allowance. The cost of this material weight is the material cost.

Labour charges

First the labour rate per hour of the machine operator is determined. This value is divided by the number of parts produced per hour. The result is the labour cost per part produced.

Machine rate costs

This category consists of the set-up charge and the moulding machine operating cost.

Each time a mould is installed on a machine a set-up charge is incurred. This is a once-off fee derived by determining the set-up time and multiplying it by the hourly rate of the machine. This cost must be amortized over the number of pieces moulded in the run.

The moulding machine operating cost includes the cost for utilities and the cost of operating the moulding plant. The cost is expressed as an hourly machine rate.

3.4.2 Final part cost

The cycle time for a product is determined and used to calculate the amount of parts produced in an hour. The hourly rates (labour, machine) are added and divided by the number of parts produced per hour. This value and the material cost per part make up the cost to manufacture the moulded part. Finishing, packaging and other relevant costs are added to the manufacturing cost. A mark-up is added to give the final part cost.

4. The Test Part

4.1 The Volkswagen Citi Golf

The Volkswagen Citi Golf is an icon in South Africa for more than 20 years. No other South African car has been face lifted/improved more than the Citi Golf. In recent years the ageing car has come under lots of pressure from other more modern small cars. The result of this competition is yet another face lift, mostly to the interior of the car.

What makes this face lift different from previous ones is that it was designed and is manufactured in South Africa.

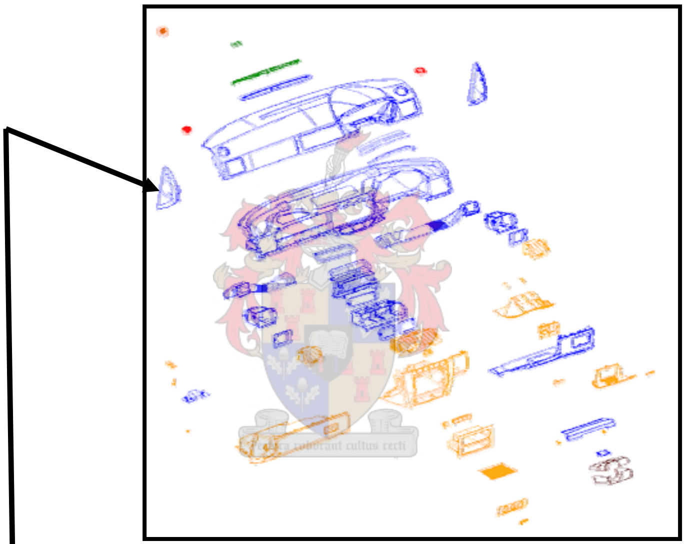


Figure 8: The exploded dashboard assembly

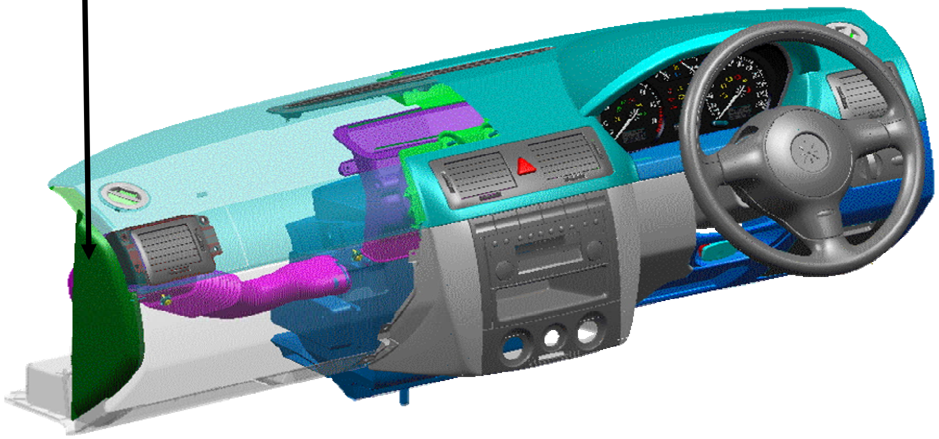


Figure 9: New Golf dashboard designed and manufactured in South Africa

The part identified in Figure 8 and Figure 9 is the part that will be used in this research as the test part. It is a part that is currently in production and is used in the latest VW Citi Golf model. Therefore an example of the production part is available to compare with parts produced on the LOMOLD machine during the research.

4.2 The requirements of the test part

It was mentioned previously that LOMOLD wants to target the automotive industry specifically for the production of large prototype parts in conjunction with Rapid Tools. The test part must therefore prove that:

- Large parts can be manufactured more economically with the LOMOLD process than with other moulding technologies
- The LOMOLD process can produce production quality parts that will satisfy the demands of the automotive industry
- The LOMOLD process can produce aesthetically acceptable parts for the automotive industry

Unfortunately the operational LOMOLD machine available for testing is not big enough to produce the large parts in Figure 8. The small part identified in the above figures was chosen as the test part. Its size will be comfortably within the capacity of the available LOMOLD machine. Also, the part is from the interior of the car. Good fit (accurate part) and aesthetics is required form interior car components.

Unfortunately the part does not have a flat face the plunger can enter on. This will test the ability of the LOMOLD process to use a shaped plunger to form the section of the part wall where the plunger enters the mould cavity. Also, the plunger diameter of the current LOMOLD machine is too large (Ø 80mm) in relation to the surface area of the part. A part this size (about 250mm x 120mm) should have a plunger with a diameter of around 25mm.

4.3 Geometric accuracy of the production part

VW South Africa provided one production part for this research. This gives the opportunity to compare the test parts produced in the research with an actual production part. No significant conclusions can be made from this one part, therefore the results are presented for interest only.

The geometric accuracy of the production part is measured on a Coordinate Measuring Machine (CMM). The results are depicted in the histogram below (Figure 10).

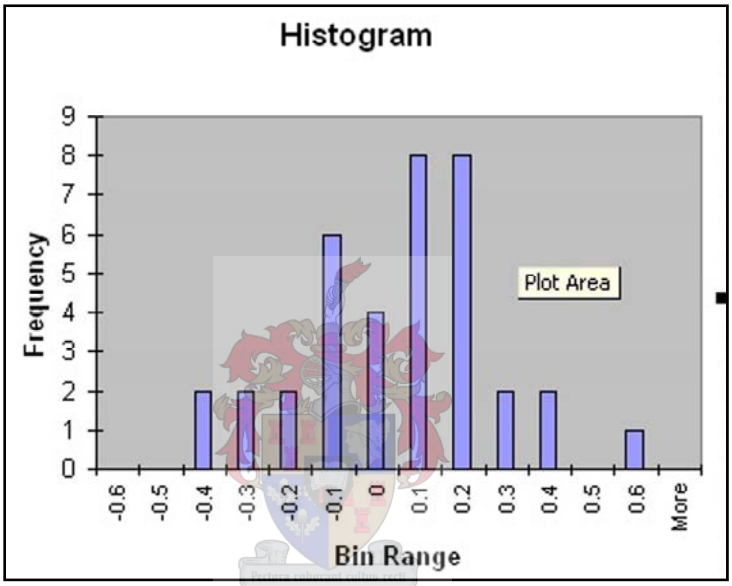


Figure 10: Geometric accuracy of the VW production part

The measurements seem to be Normally Distributed around 0.1. The standard deviation is 0.23 as in Table 3.

Table 3: Summary statistics of measured points on VW production part

Number of points	37
Maximum deviation	0.5460
Mean deviation	0.0046
Minimum deviation	-0.4420
Standard deviation	0.2262

The maximum deviation was measured in Area A (Figure 11). This can be expected since it is an area on the edge of the part and between the 2 “clips”.

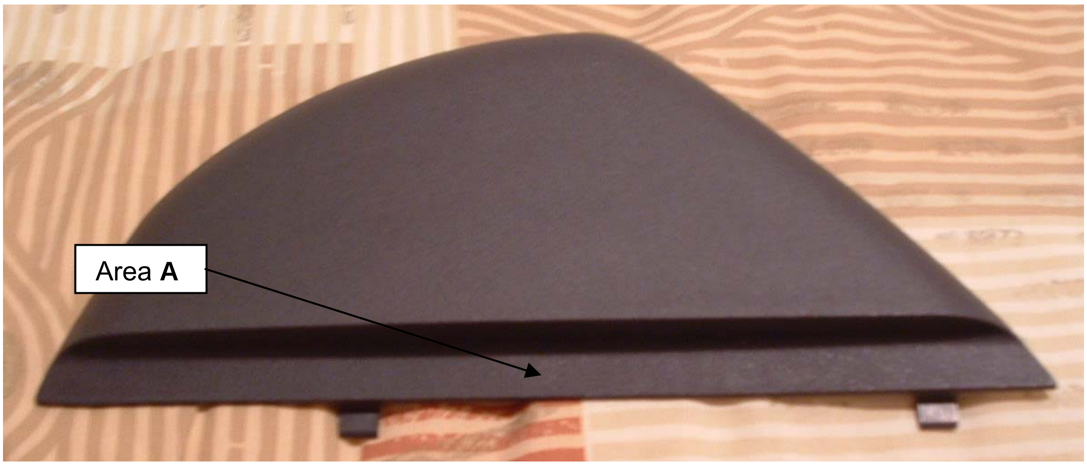


Figure 11: VW production part

The measured results can be used to determine the capability of the process that produced the part. Process capability is a critical performance measure which addresses process results with respect to product specifications [13]. There are two capability indexes that will be used: C_p is the inherent capability of the process and is defined as $\frac{USL-LSL}{6\sigma}$ and C_{PK} is the realised process capability relative to actual production results and is defined as minimum $\{\frac{\mu-LSL}{3\sigma},\frac{USL-\mu}{3\sigma}\}$. A capable process will have both these indexes bigger than 1. An index of 1.67 is considered acceptable and anything bigger than 1.67 is very good. For this research it is assumed that 1.67 is the minimum that VW would expect for a production process.

Referring to Appendix C: Process Capability, and assuming that the specification limits are set at ± 1.2mm, the capability indexes for the VW production part is:

C_p = 1.77

C_{PK} = 176

There are not enough parts to determine these indices with any level of confidence but for comparison, these values will be accepted as process capability indices. These indices would be acceptable and indicate a capable production process. The capability of the LOMOLD process will be compared to these indexes.

5. Aluminium Filled Epoxy Tool (AFET)

5.1 Accuracy of the AFET process chain

The accuracy of the Aluminium Filled Epoxy Tooling process is of great importance. It is a decisive factor when deciding which process to use for the LOMOLD process for a specific application. The Aluminium Filled Epoxy Tooling process is a long process in terms of the number of steps required to produce the tool. The accuracy of the final parts produced by the tool can be influenced at any of these steps. It is therefore important to trace the accuracy of the process through all the process steps. Inaccuracies in the produced parts can then be traced back to where it occurred in the process and corrective procedures can be put in place to prevent the reoccurrence of the problem in future projects. It is also important for the research to know if the inaccuracy results from the tool making process or the moulding process.

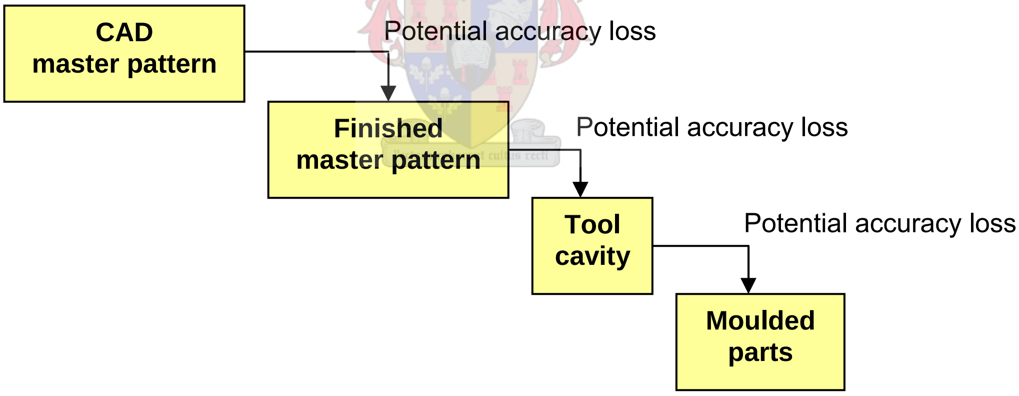


Figure 12: Potential for accuracy loss in the AFET process chain

5.1.1 Geometric accuracy of the finished pattern

The finished master pattern is compared to the original CAD data used to grow the master pattern on the 3D-printer. The CAD model and the physical pattern were aligned using the ‘best fit’ procedure of the software used on the Coordinate Measuring Machine (CMM). Then the Z-values measured on the pattern were compared to the CAD model at the corresponding X- and Y-values. Figure 13 shows the deviation (mm) of the printed pattern in relation to the CAD model used for the printing. The first 90 points were measured close to the edge of the pattern.

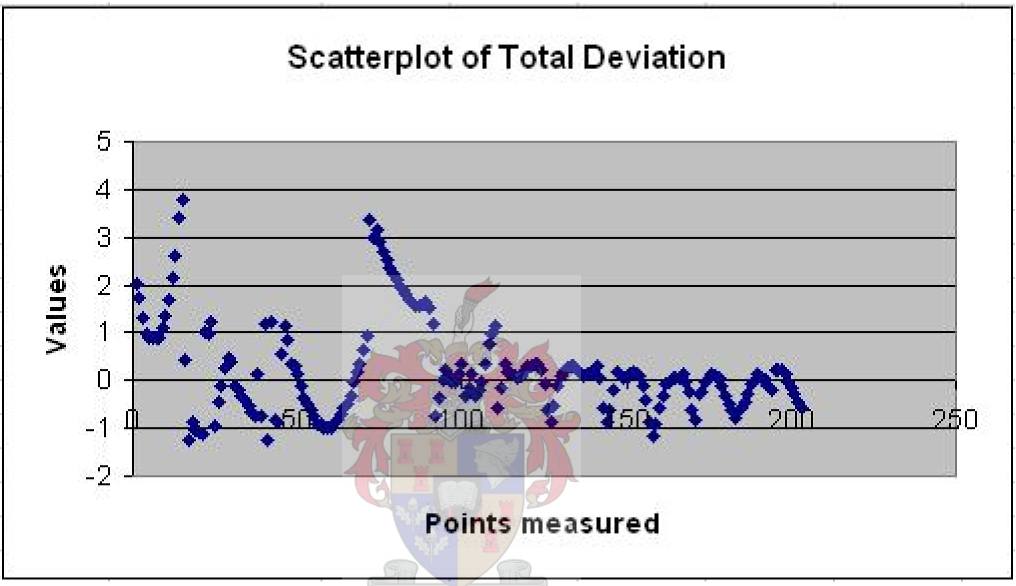


Figure 13: Deviation of measured point relative to CAD model

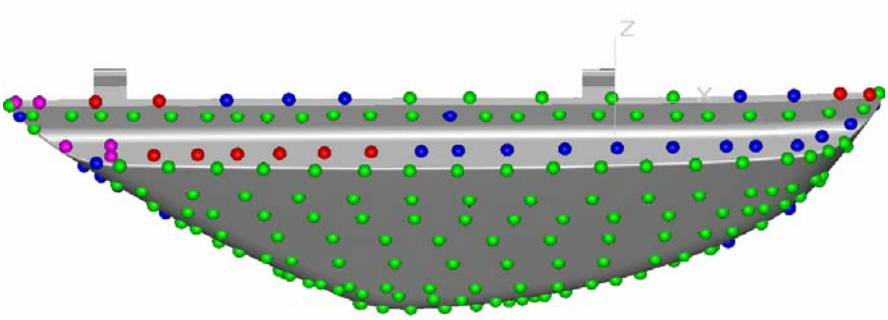


Figure 14: Measured points on the pattern

Figure 14 shows the location of the measured points on the pattern. The deviation increases according to the colour of the point, starting at green and then blue, red and pink representing the largest deviation. It is clear that the largest dimensional deviations of the pattern in relation to the CAD model are located on the edges of the pattern. Figure 15 shows a histogram of the deviation of the pattern from the CAD model. From Table 4 the standard deviation for the pattern is 0.98 mm while from Table 3 the standard deviation of the production part is 0.23. This is a substantial difference already indicating that the parts produced with the AFET mould will not have good geometric accuracy and will not be suitable for producing production quality parts.

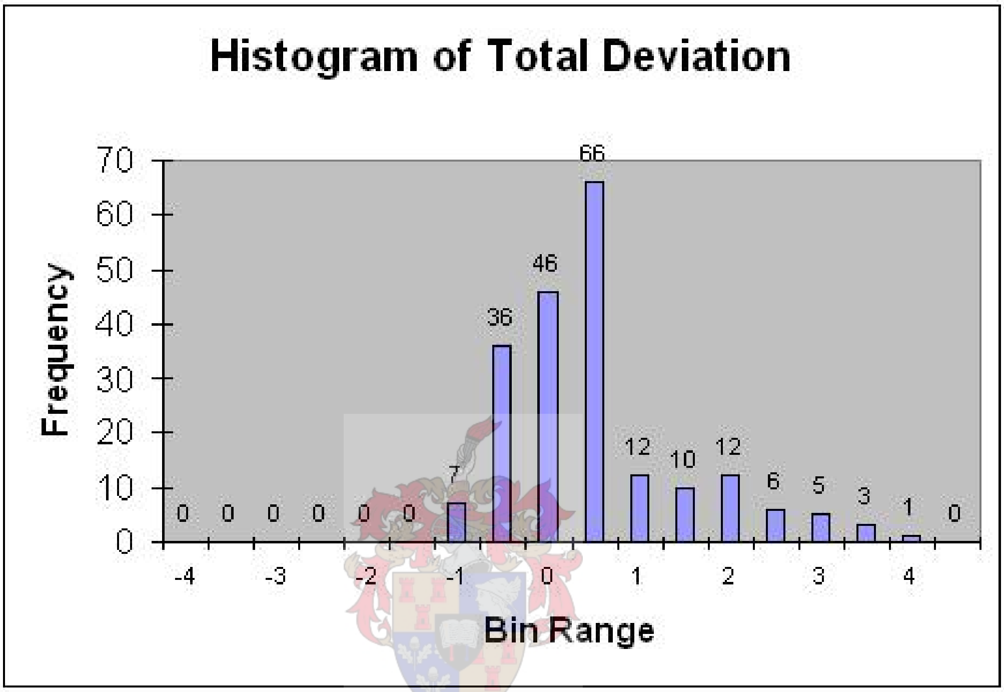


Figure 15: Histogram of total deviation from CAD model

Table 4 shows a summary of the deviations of the points measured on the pattern. The maximum deviation measured is a considerable 3.788 mm! The standard deviation is also quite large and would be unacceptable for production part applications.

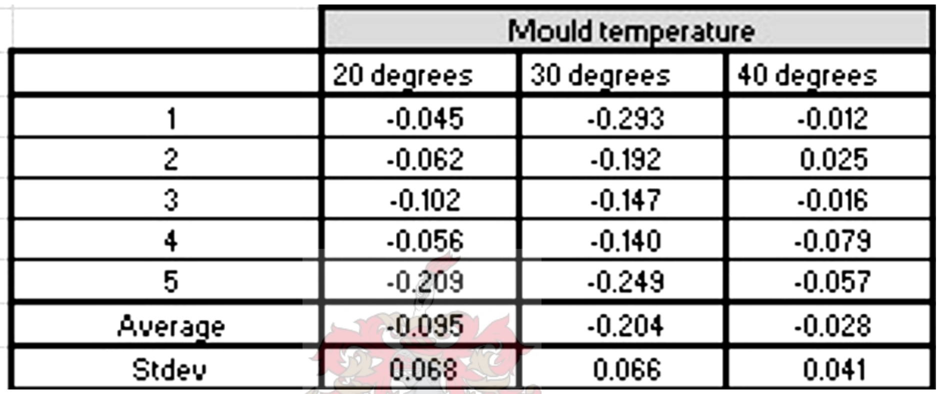
Table 4: Summary statistics of measured points on the master pattern

Number of points	204
Maximum deviation	3.788
Mean deviation	0.236
Minimum deviation	-1.248
Standard deviation	0.972

5.1.2 Accuracy of the moulded parts

The moulded parts are compared to the 3D-CAD data of the original CAD data of test part. Table 5 lists the average deviations of the 5 parts measured at each of the 3 different mould temperatures. The de-moulding temperature was kept constant for all the parts. There seems to be a difference in geometric accuracy for parts produced with the mould temperature at 30 degrees.

Table 5: Average measured deviations of 5 parts produced at different mould temperatures with the AFET



	Mould temperature		
	20 degrees	30 degrees	40 degrees
1	-0.045	-0.293	-0.012
2	-0.062	-0.192	0.025
3	-0.102	-0.147	-0.016
4	-0.056	-0.140	-0.079
5	-0.209	-0.249	-0.057
Average	-0.095	-0.204	-0.028
Stdev	0.068	0.066	0.041

To test whether there is a significant difference between the accuracy of the parts produced at the different mould temperatures, the following hypothesis is stated:

H_0: **All mean measurements are equal**

H_1: **All mean measurements are not equal**

Testing this hypothesis at 95% confidence provides the results in Table 6 below.

Table 6: Single factor ANOVA (all groups) results @ 95% confidence

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
20 degrees				
30 degrees				
40 degrees				

ANOVA

Source of variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	**0.079326315**	**2**	**0.039663157**	**11.2508182**	**0.00177031**	**3.885290312**
Within Groups	**0.042304291**	**12**	**0.003525358**			
Total	**0.121630606**	**14**				

It is clear from Table 6 that the null hypothesis cannot be accepted. There is a significant difference between the accuracy of the parts.

Now to determine which mould temperature produces the most accurate parts. State the following hypothesis at 95% confidence:

H_0: **There is no significant difference between the accuracy of parts produced with the mould temperature set at 20 or 30 degrees**

H_1: **There is a significant difference between the accuracy of parts produced with the mould temperature set at 20 or 30 degrees**

According to the results of Table 7 the null hypothesis cannot be accepted. Although the p-value is not as small as in Table 6, the difference between parts produced with the mould temperature set at 20 degrees is significantly different from when the mould temperature is at 30 degrees.

Table 7: Single factor ANOVA results between 20 and 30 degrees

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
20 degrees	**5**	**-0.474406977**	**-0.094881395**	**0.004564025**
30 degrees	**5**	**-1.021604651**	**-0.20432093**	**0.00436976**

ANOVA

Source of variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	**0.029942529**	**1**	**0.029942529**	**6.703212604**	**0.03216026**	**5.317644991**
Within Groups	**0.035735139**	**8**	**0.004466892**			
Total	**0.065677669**	**9**				

Now state the following hypothesis at 95% confidence:

H_0 **There is no significant difference between the accuracy of parts produced with the mould temperature set at 30 or 40 degrees**

H_1: **There is a significant difference between the accuracy of parts produced with the mould temperature set at 30 or 40 degrees**

The results in Table 8 show again that the null hypothesis cannot be accepted. There is a significant difference between the accuracy of parts produced with the mould temperature set at 30 or 40 degrees.

Table 8: Single factor ANOVA results between 30 and 40 degrees

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
30 degrees	5	-1.021604651	-0.20432093	0.00436976
40 degrees	5	-0.139418605	-0.027883721	0.001642288

ANOVA

Source of variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.077825222	1	0.077825222	25.88975593	0.00094351	5.317644991
Within Groups	0.02404819	8	0.003006024			
Total	0.101873412	9				

State the following hypothesis at 95% confidence:

H_0 **There is no significant difference between the accuracy of parts produced with the mould temperature set at 20 or 40 degrees**

H_1: **There is a significant difference between the accuracy of parts produced with the mould temperature set at 20 or 40 degrees**

Table 9 shows that the null hypothesis cannot be rejected.

Table 9: Single factor ANOVA results between 20 and 40 degrees

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
20 degrees	5	-0.55855814	-0.111711628	0.017657431
40 degrees	5	-0.151918605	-0.030383721	0.001271583

ANOVA

Source of variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.016535571	1	0.016535571	1.747113766	0.22278463	5.317644991
Within Groups	0.075716059	8	0.009464507			
Total	0.09225163	9				

The result of these hypotheses is that it can be confidently stated that there exists a significant difference between parts produced with the mould temperature at 30 degrees and both the other temperature settings. Between 20 and 40 degrees, there is no significant difference in part geometric accuracy.

The best geometric accuracy is achieved with the mould temperature at 40 degrees. The difference between this best accuracy and the geometric accuracy of parts produced with the mould temperature set at 20 degrees is not significant.

Therefore the best mould temperature setting must be 20 degrees. According to Figure 16 the cooling time for the product is 65 seconds (according to the trend line of actual measurements taken) if the mould temperature is 20 degrees and 180 seconds if the mould temperature is set at 40 degrees. The shortest cooling time is achieved with the mould temperature set at 20 degrees. This will provide the shortest cycle time and the accuracy is not significantly worse than with the mould temperature set at 40 degrees.

Using the measured data for the parts produced with the mould temperature at 20 degrees (the best temperature setting), process capability indices like the ones calculated in paragraph 4.3 are determined. The specification limits are ±1.2 mm, the same as with the production part. The results are (see Appendix C)

$$C_P = 0.59$$

$$C_{PK} = 0.55$$

This result shows a process that is not capable of consistently producing parts within the customer requirements. Also referring to Appendix C, the standard deviation of the parts measured is smaller than that of the master pattern. This is interesting. In other words, during the replication step of using the master pattern to create the mould cavity, the mould cavity had to become more accurate than the master pattern itself!

5.2 Tool lead time

In Chapter 3 (Appendix A) the tool lead time of the AFET is discussed. It is shown that the tool can be completed in about 80 hours or 10 days. This is achieved with working 8 hours per day and with completing some of the process steps in parallel. The total hours of work required to produce the tool is about 105 hours. The days to complete the mould can be reduced if work is done during night time.

Referring to Table 10 this technology can require between 2 and 4 weeks for producing a tool. This time obviously depends on many factors like the part geometry, part dimensions, skill and experience of the pattern/tool maker and the strength of the tool required. If the tool is used on the LOMOLD process it is not required to be as robust as if it was used for example with Injection Moulding.

Table 10: Rapid Tooling Technologies

	Aluminium-filled epoxy	**Spray metal**	**Cast kirksite**	**3D Keltool**	**Machined Aluminium**
Lead time (weeks)	2 to 4	2 to 4	3 to 7	3 to 6	2 to 6
Cost ($)	2500 to 10000	2000 to 15000	4000 to 15000	3500 to 10000	4000 to 25000
Typical part quantities	50 to 1000	50 to 1000	50 to 1000	50 to 1 million	50 to 100 000
Materials	Thermo plastics	Thermo plastics	Thermo plastics	Thermo plastics	Thermo Plastics

Wohlers Associates [1]

5.3 Cost of manufacturing the tool

According to Table 10 this tooling technology could cost anything between R 15 000 and R 60 000 (with $1 = R6). This obviously depends on the factors discussed in paragraph 5.2.

Chapter 4 (Appendix A) discusses the tool cost. The total tool cost is R 39 134. This is in-line with the costs in Table 10.

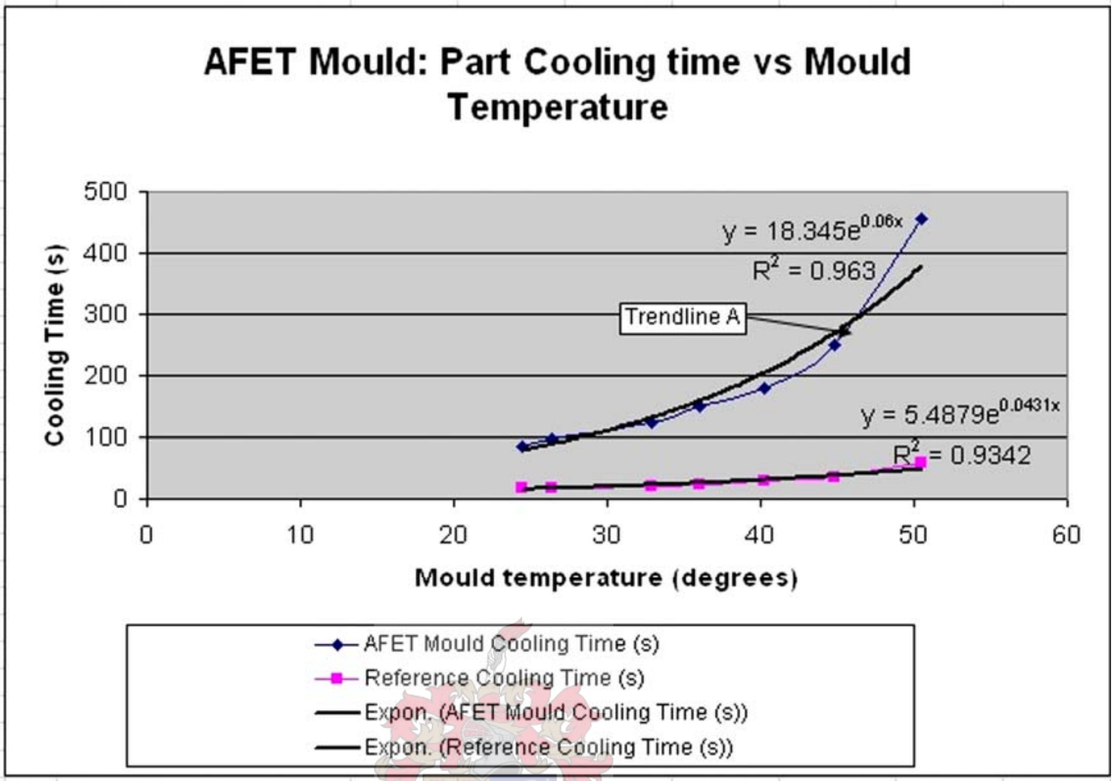
5.4 Tool life estimation

The AFET tool produced about 500 parts on the LOMOLD machine without any problems or any visible signs of wear. Based on past experiences with the tool (refer to Appendix A), a confident tool life estimate is at least 1000 parts. This is the maximum value presented in Table 10. The researcher is confident that at least 1500 parts can be produced but no evidence exists to prove this statement.

5.5 Process productivity

Process productivity depends on the best cycle time achievable while still producing a product that meets specifications. In paragraph 5.1.2 the best mould temperature was identified to be 20 degrees. Referring to Figure 16 the cooling time is estimated to be about 65 seconds.

Add another 65 seconds for (this includes de-moulding time) to get a cycle time of 130 seconds. Therefore about 27 parts can be produced per hour.



Mould temperature (degrees)	24.5	26.33	32.86	36.03	40.23	44.87	50.5
Estimated Cooling Time (s)	85	97	124	150	180	250	455

The reference cooling time is theoretical values for Injection Moulding (Appendix D)

Figure 16: AFET Cooling Time vs Mould Temperature

5.6 Cost per part

The part cost is calculated only to be compared with the part cost obtained for the HSC Aluminium Tool therefore the material cost (polypropylene for parts) which is the same for both moulds will be ignored. From paragraph 5.5 only 27 parts can be produced per hour.

Assume the following costs:

Machine operator hourly rate: R 75

Machine fixed overhead hourly rate: R 220

Machine variable overhead hourly rate: R 90

TOTAL hourly rate: R 385

The tool cost is R 39 134.36 and with an estimated tool life of 1000 parts, the tool cost per part is:

R 39.13

The comparative cost per part is then:

R 14.26 for overheads and labour

R 39.13 for tool cost

R 53.39

6. HSC Aluminium Tool

6.1 Accuracy of the HSC Aluminium tool process chain

Figure 17 shows the 3 stages in the process chain that will affect the accuracy of the moulded parts. The chain starts with the CAD master pattern. From this a mould structure must be added around the pattern. This structure must fit onto the platens of the injection moulding machine and must have corresponding locations for fitment on the platens.

The NC code must be created next. The accuracy loss in this step is minimal and can be ignored. The tool cavity is machined using a high speed milling machine with the correct parameters and cutting tools. These milling parameters will influence the accuracy of the cavity.

The cavity is used to produce parts on the LOMOLD machine. Here the moulding parameters selected, the moulding process and the mould characteristics will influence the accuracy of the moulded parts.

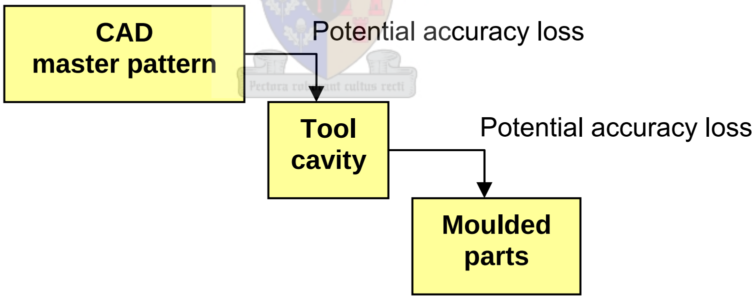


Figure 17: Accuracy loss in the HSC process chain

6.1.1 Accuracy of the HSC process

The 2 cavity plates are compared to the 3D-CAD data the CNC-programming was created from.

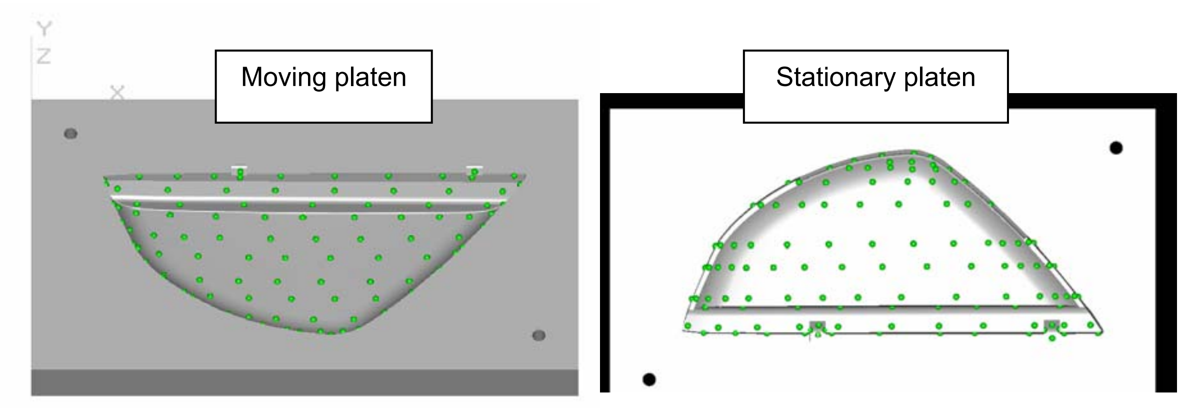


Figure 18: Measured points on the cavity plates

The summary of the measurements in Table 11 shows that the cavity plates are very accurate. This is expected due to the accuracy of the milling process. It is interesting to notice that the standard deviation of the measurements for the two platens is very different. The stationary platen standard deviation is substantially larger than that of the moving platen. The only explanation could be that the stationary platen forms the inside of the part and therefore is the male and the moving platen the female. This difference in geometry might explain why the one platen is more accurate than the other.

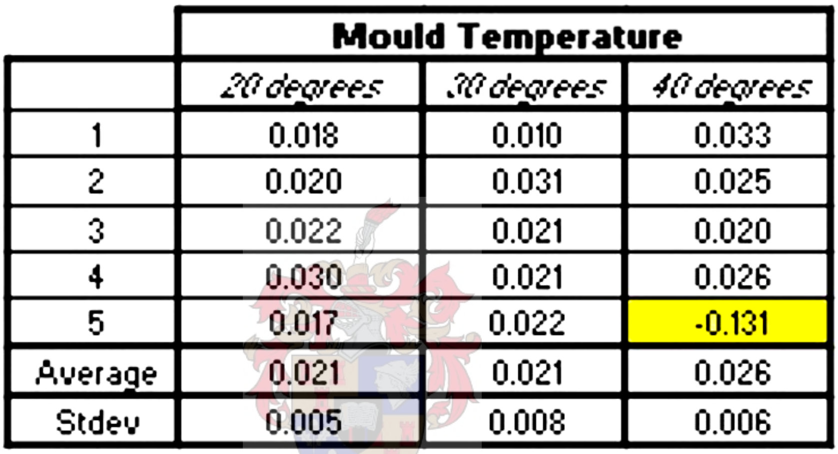
Table 11: Summary statistics of measured points on the 2 cavity plates

	Moving platen	**Stationary platen**
Number of points	104	104
Maximum deviation	0.320	0.897
Mean deviation	-0.006	-0.0023
Minimum deviation	-0.174	-0.347
Standard deviation	0.065	0.172

6.1.2 Accuracy from the cavity to the moulded parts

The moulded parts are compared to the original CAD data of the test part. The following table lists the average deviation of the 5 parts measured at each mould temperature setting. There is one part produced with the mould temperature at 40 degrees that differ substantially from the rest of the parts produced at the same temperature. This is indicated in yellow in Table 12. This measurement is excluded from this following investigation.

Table 12: Average measured deviations of 5 parts produced at different mould temperatures with the HSC Aluminium Tool



	Mould Temperature		
	20 degrees	*30 degrees*	*40 degrees*
1	0.018	0.010	0.033
2	0.020	0.031	0.025
3	0.022	0.021	0.020
4	0.030	0.021	0.026
5	0.017	0.022	-0.131
Average	0.021	0.021	0.026
Stdev	0.005	0.008	0.006

In order to determine the mould temperature setting that determines the most accurate parts, state the following hypothesis and then test it at 95% confidence:

H_0 **: All mean measurements are equal**
H_1 **: All mean measurements are not equal**

Based on the ANOVA results from Table 13 there are no evidence to reject the null hypothesis. Thus, at the 95% confidence level, there is no significant difference between the accuracy of the parts at the different mould temperatures tested.

There should be differences in the internal properties of these parts like part strength. This research does not investigate these internal properties. Based on the information obtained, the best mould temperature setting must be 20 degrees.

This setting will give the shortest cooling time and therefore the shortest cycle time and good part accuracy.

Table 13: Single factor ANOVA results @ 95% confidence

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
20 degrees	**4**	**0.089108**	**0.022277**	**2.56E-05**
30 degrees	**4**	**0.083255**	**0.020814**	**7.09E-05**
40 degrees	**4**	**0.104118**	**0.026029**	**3.08E-05**

ANOVA

Source of variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	**5.79E-05**	**2**	**2.9E-05**	**0.682418**	**0.529737**	**4.256492**
Within Groups	**0.000382**	**9**	**4.24E-05**			
Total	**0.00044**	**11**				

Using the measured data for the parts produced with the mould temperature at 20 degrees (the best temperature setting), process capability indices like the ones calculated in paragraph 4.3 are determined. The specification limits are ±1.2 mm, the same as with the production part. The results are (see Appendix C)

$$C_P = 1.28$$

$$C_{PK} = 1.26$$

This result shows a process that is not capable enough to be considered for a production process. About 1.67 would be acceptable for a production process. Also referring to Appendix C, the standard deviation of the produced parts is worse than that of the mould cavity plates.

6.2 Tool lead time

Referring to Chapter 3 in Appendix B, the time to produce this tool is 132 hours or about 17 days. This is with working 8 hours per day and completing some of the process steps in parallel. The tool can therefore be completed faster if work can be done during the night. The total amount of hours required on the tool is 146 hours (refer Table 2 in Appendix A).

Table 10 shows that between 2 and 6 weeks can be expected for this technology. The time does depend heavily on the complexity of the part geometry, the part dimensions, the cooling system incorporated, the machine tool used, the experience of the tool path creator and the moulding process this tool will be used on. The LOMOLD process does not require such a robust tool as for example Injection Moulding and therefore less material is required resulting in less machining time.

6.3 Cost for manufacturing the tool

Referring to Chapter 4 in Appendix B, the total tool cost is R 37 987.36. This includes material cost, high speed milling on a CNC machine, labour and machining cost and CAD modelling costs.

Referring again to Table 10 the tool could cost between R 24 000 and R 150 000. The tool cost is therefore in-line with information found in literature. This cost obviously depends on factors mentioned in Paragraph 6.2 like part geometry, part dimensions and the moulding process the tool will be used on.

6.4 Tool life estimation

Table 10 shows expected part quantities between 50 and 100 000. The LOMOLD process is not as abrasive on the tool as for example Injection Moulding. If the mould is designed taking this into account, a less robust mould will be produced and the difference would be eliminated and the LOMOLD process and Injection Moulding could be considered equal for tool life estimation. It also depends on factors like what material is moulded, the use of fibre in the material etc.

No experimental work has been done on this topic for the LOMOLD process for this tooling technology to be able to estimate the tool life with any confidence. However, based on experiments done with the AFET tool and observations made with that tool (see Paragraph 5.4), it can be expected that the LOMOLD process would produce more parts with a tool than the quantities stated in the literature.

Being conservative, the researcher would confidently estimate 100 000 parts to be produced with this tool and the LOMOLD process based on the information in Table 10.

6.5 Process productivity

Process productivity is all about cycle time. Based on the discussion in Paragraph 6.1.2 the best mould temperature setting for the HSC Aluminium tool is 20 degrees.

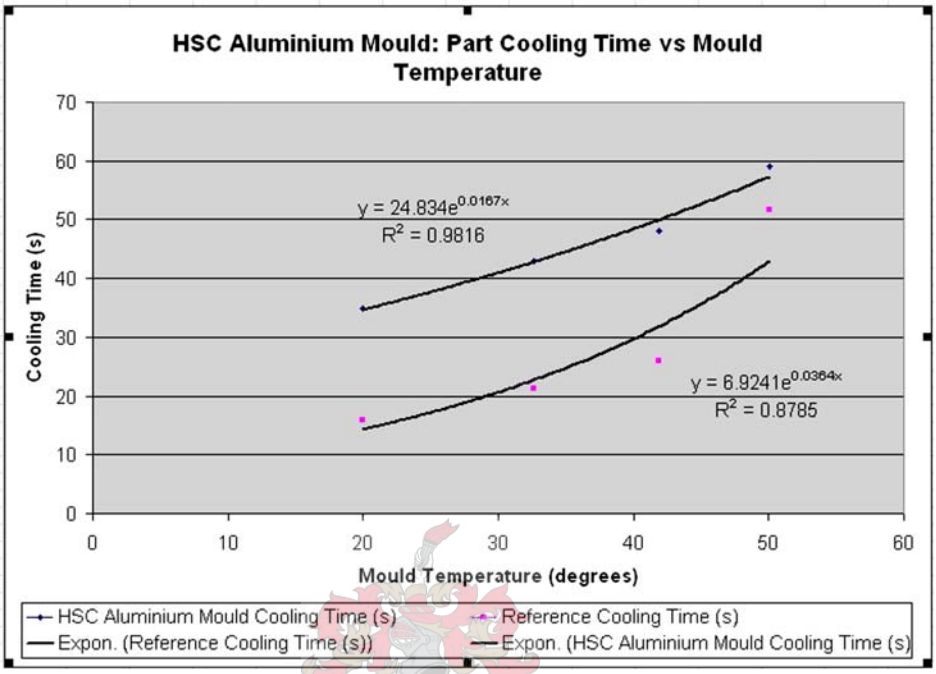


Figure 19: HSC Aluminium Cooling Time vs Mould Temperature

At this mould temperature the cooling time is 35 seconds. To get the cycle time, 65 seconds is added to the cooling time. This includes the time for de-moulding. The cycle time is therefore 100 seconds. Therefore 36 parts can be produced per hour with this mould. The melt temperature is then about 240 degrees.

The reference cooling time (Appendix D) assumes Tool Steel for the mould material and a flat part. This may account for the differences obvious in Figure 19

6.6 Cost per part

The cost of the part will be compared with the part cost obtained with the AFET tool. The part material cost (polypropylene) will be ignored because it will be the same for both tools. The researcher is only interested in differences between the 2 tools therefore assume the following:

Machine operator hourly rate: R 75

Machine fixed overhead hourly rate: R 220

Machine variable overhead hourly rate: R 90

TOTAL hourly rate: R 385

The tool cost is R 37 987.36 and with an estimated tool life of 100 000 parts, the tool cost per part is:

R 0.38

The comparative cost per part is then:

R 10.70 for overheads and labour

R 0.38 for tool cost

R 11.08

Obviously, the required quantity of parts will have a significant influence on deciding which tooling technology to use. To compare the part cost directly with that of the AFET, assume that only 1000 parts will be produced with the HSC Aluminium mould. Then:

R10.70 for overheads and labour

R37.99 for tool cost

R48.69

7. Discussion on mould cooling

The question is: must a cooling system be incorporated into the mould if small production runs are being manufactured with the mould? Especially if the part being manufactured are prototype parts that do not have strict accuracy or surface finish requirements.

Figure 20 shows what happens with the mould temperature when no cooling is used. The HSC-Aluminium tool temperature rises more than the AFET tool. This is due to the better heat conductivity of aluminium. The epoxy of the AFET tool does not allow the heat inside the mould cavity to spread throughout the mould. Therefore the mould itself stays cool and all the heat is trapped inside the mould cavity. If the temperature inside the mould cavity is measured, Figure 20 would be very different. The HSC-aluminium tool cavity will be cooler than the AFET tool cavity.

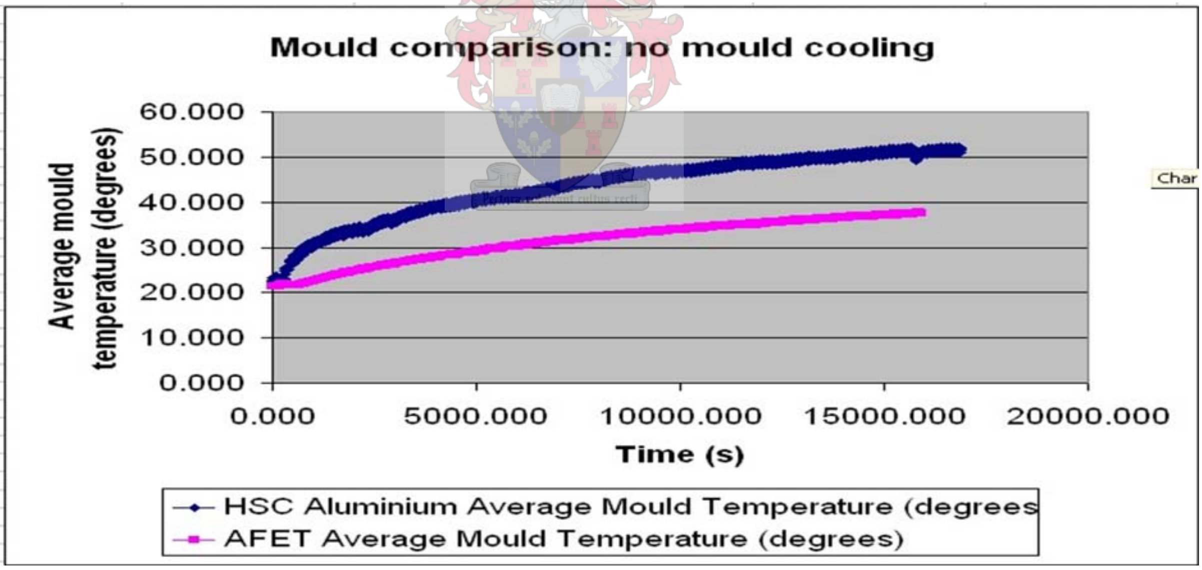


Figure 20: Mould temperature with no mould cooling

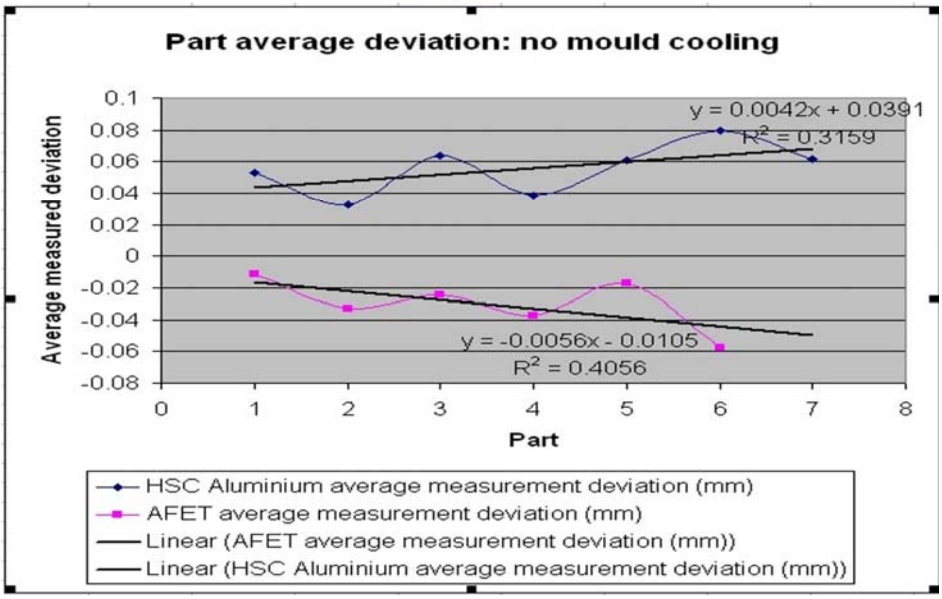


Figure 21: Part accuracy: no mould cooling

Only 7 parts from the HSC-Aluminium mould and 6 parts from the AFET mould were measured on the CMM to obtain the data displayed in Figure 21. These parts were produced by keeping the cycle time constant and while not applying cooling to the moulds. Every fifthteenth part produced were measured. Unfortunately not enough information exist to state confident facts regarding the part geometrical accuracy if no mould cooling is applied.

Figure 21 shows that the part geometric accuracy does decrease as the mould temperature increases. The average accuracy is not that different to the results displayed in Table 5 There seems to be no real difference in the accuracy of parts produced with the AFET and using cooling or not. This questions the effectiveness of the AFET cooling system of removing heat from the cavity.

Again, Figure 21 shows that the part geometric accuracy decrease as the temperature of the HSC-Aluminium tool increases. Referring to Table 12 it does seem that the average part accuracy for the HSC Aluminium mould is worse when no cooling is applied to the mould. Again, there is not enough data on these statements to confirm them. This could be interesting research for future researchers. From Figure 22 it is clear that the cooling system is affective in keeping the mould temperature relatively constant. It seems the cooling system on the AFET is better but because of the low heat conductivity of the epoxy, the heat stays trapped in the mould cavity and does not spread to the surrounding metal therefore the cooling system does not have to remove so much heat as with the

HSC-Aluminium tool. The temperature of the HSC-Aluminium tool varies with each part produced. This illustrates the effectiveness of the aluminium in conducting the heat in the mould cavity. The temperature response of the AFET is much slower, showing the inability of the epoxy to conduct the mould cavity heat to the surrounding aluminium structure.

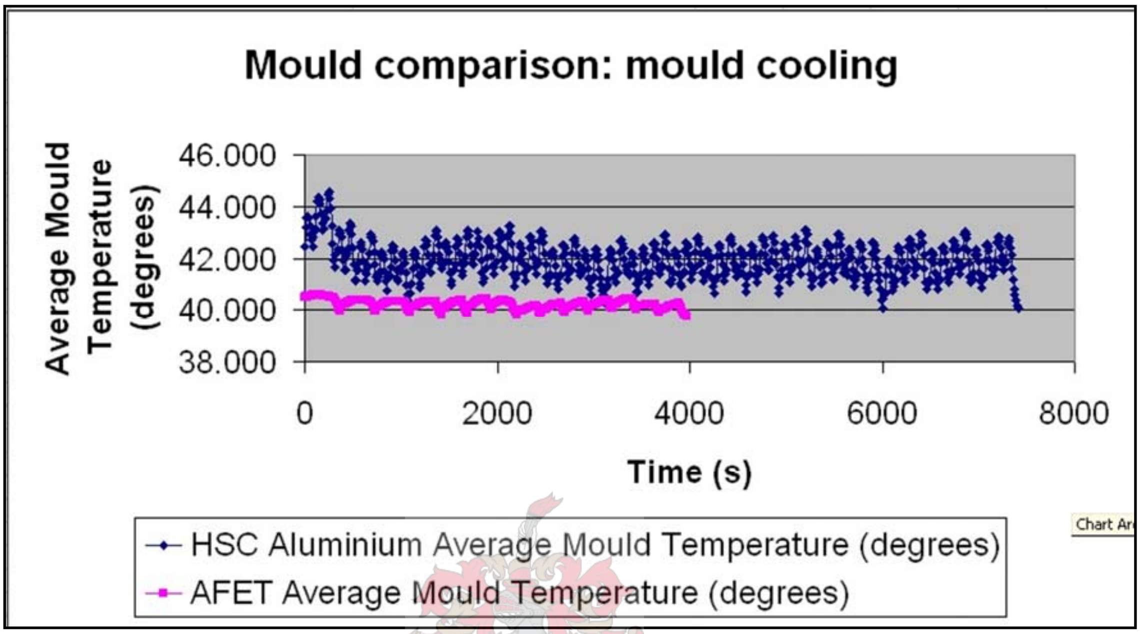


Figure 22: Average mould temperature with mould cooling

There is a point where the mould temperature is too high to produce parts within the specified accuracy limits. From Figure 21 the AFET tool part accuracy decreases faster than the HSC-Aluminium tool part accuracy. Assume both tools start with producing exactly the same accurate part within the specification limits required, then with no cooling applied to the moulds, the AFET tool will produce less parts within the specification limits than the HSC-Aluminium tool. This implies that if for example only 200 parts must be produced with the tool, then the HSC-Aluminium tool can produce the parts within the specified accuracy without applying cooling but if 300 parts are required, then cooling needs to be added. This has significant tool cost implications.

This is a topic that can be investigated in future research.

8. Summary

A part of the dashboard assembly of the new Volkswagen Chico Golf is used as a test part for this research. A production version of the part is supplied by Volkswagen (VW) to compare the results of the research with an actual production part.

The part supplied by VW is measured on a Coordinate Measuring Machine (CMM) and compared to the original CAD data of the part, also supplied by VW. The results are shown in Table 14 below. The part is very accurate with a tight standard deviation of measured values.

Table 14: Geometric accuracy statistics of VW production part

Number of points	37
Maximum deviation	0.5460
Mean deviation	0.0046
Minimum deviation	-0.4420
Standard deviation	0.2262

From these values two process capability indices, widely used in industry can be calculated. These indices measure the performance of the process relative to actual production specifications. C_p is the inherent capability of the process and C_{PK} is an actual capability relative to actual production results. A capable process will have both these indexes bigger than 1. An index of 1.67 is considered acceptable and anything bigger than 1.67 is very good. A capable production process should have a C_P and C_{PK} value of at least 1.67 to indicated process capability. Using specification limits of ±1.2 mm, the following values for the process that produced the production part can be obtained:

$$C_P = 1.77$$

$$C_{PK} = 1.76$$

There are not enough parts to determine these indices with any level of confidence but for comparison purposes, these values will be accepted and compared to results obtained with the LOMOLD process and the two rapid tools.

Two Rapid Tooling (RT) technologies, at opposite ends of the technology spectrum is used together with the new plastic forming process under development, the LOMOLD process. The RT technologies are Aluminium Filled Epoxy Tooling (AFET) and High Speed Cut (HSC) Aluminium. AFET is an indirect technology because a master pattern must be created from which the mould cavity is formed. HSC-Aluminium is a direct technology because the mould cavity is machined directly from a CAD model.

Table 15: AFET and VW production part accuracy

	Number of points measured	**Maximum deviation (mm)**	**Minimum deviation (mm)**	**Mean deviation (mm)**	**Standard deviation (mm)**
VW production part	37	0.5460	-0.442	0.005	0.226
Finished master pattern	204	3.788	-1.248	0.236	0.972
Best produced part*	86	1.731	-1.209	-0.045	0.595

*Part produced with mould temperature set at 20 degrees (see Appendix C)

Table 16: HSC-Aluminium tool and VW production part accuracy

	Number of points measured	**Maximum deviation (mm)**	**Minimum deviation (mm)**	**Mean deviation (mm)**	**Standard deviation (mm)**
VW production part	37	0.5460	-0.442	0.005	0.226
Moving platen	104	0.32	-0.174	-0.006	0.065
Stationary platen	104	0.897	-0.347	-0.0023	0.172
Best produced part*	102	0.778	-1.476	0.0174	0.292

*Part produced with mould temperature set at 20 degrees (see Appendix C)

Refer to Table 15. It is interesting that the accuracy of the best produced part is better that that of the finished master pattern used to create the mould cavity. The produced part had to warp after it was removed from the mould to get his improved accuracy. This again points to the inefficiency of the AFET cooling to reduce the part temperature inside the cavity to a point where the part can be removed from the cavity in a rigid state.

Table 16 shows that minimal warpage occurred after the part was removed from the mould cavity because the accuracy of the best produced part is not significantly worse than that of the stationary platen. The standard deviation of points measured on the best produced part compares favourably with that of the VW production part.

Parts were produced with the two tools at three different mould temperature settings: 20, 30 and 40 degrees. These produced parts were measured on a Coordinate Measuring Machine (CMM). The best geometric accurate parts are produced with the mould temperature set at 40 degrees for the AFET and at 20 degrees for the HSC-Aluminium tool (see paragraphs 5.1.2 and 6.1.2). There is however no significant difference between the accuracy with the mould at 20 degrees or at 40 degrees for the AFET therefore the recommended mould temperature is 20 degrees because it provides the shortest cycle time.

Table 17: Process Capability indices for both rapid tools

AFET	C_P = 0.59	C_{PK} =0.55
HSC-Aluminium tool	C_P =1.28	C_{PK} =1.26

The results in Table 17 show the difference between the two tools. The capability of the AFET tool to consistently produce parts on the LOMOLD machine that meet the customer specifications (±1.2mm in this case) is poor. It cannot be considered a capable production process. The capability of the HSC-Aluminium tool is significantly better than that of the AFET tool but it is still not good enough to be considered for a production process. Since HSC-Aluminium tools are used in production processes, this identifies the LOMOLD machine/process, as used in this research, as not consistent enough to be used in a production process.

Table 18: Tool summary

	Lead time (days)	**Tool cost (R)**	**Cycle time (seconds)**	**Estimated tool life**	**Final part cost @ estimated tool life**	**Final part cost @1000 part tool life**
AFET	10	R 39 134	130	1 000	R 53.39	R 53.39
HSC-Aluminium tool	17	R 37 987	100	100 000	R 11.08	R 48.69

The AFET tool has the shortest lead time because most of the process steps can be completed in parallel. The AFET cycle time is considerably longer than that of the HSC-Aluminium tool. The expected life of the HSC-Aluminium tool is 100 000 parts compared to a conservative estimate of 1000 parts for the AFET. The part cost of the HSC-Aluminium tool will always be less than that of the AFET cost because of lower initial cost and a faster cycle time.

If no mould cooling is applied to the moulds, the temperature of the HSC-Aluminium mould increases faster than that of the AFET mould. The heat of the plastic part is trapped in the cavity of the AFET mould due to epoxy not conducting the heat to the surrounding aluminium frame. The HSC-Aluminium tool conducts the heat quickly to the surrounding aluminium. It is also shown that the part accuracy decreases for both the moulds as the temperature of the moulds increase. The accuracy of the AFET produced parts decrease faster than that of the HSC-Aluminium produced parts due to better conductivity of the latter. Referring to Figure 21 and the accuracy data in Appendix C of parts produced with cooling, the accuracy of the parts produced without cooling is worse than that of parts produced with cooling on the HSC-Aluminium tool. For the AFET mould there seems to be no real difference in accuracy between parts produced with cooling and parts produced without cooling. This shows that the cooling system on the HSC-Aluminium tool is more effective than that on the AFET mould.

9. Conclusions and Recommendations

The only advantage that the AFET has over the HSC-Aluminium tool is a shorter lead-time. In terms of tool cost, tool life, part geometric accuracy, part cost and cycle time, the HSC-Aluminium tool is superior. Considering this information, the application of AFET is limited to small volume, prototype and pre-production runs. It is ideal for tool design confirmation, part functional testing and part appearance testing.

The accuracy of the parts produced with the AFET is poor in relation to the VW production part and the parts produced with the HSC-Aluminium tool. The reason for this is that the master pattern used to create the AFET cavity was so inaccurate compared to the CAD model used to build the pattern on a 3D Printer. The actual parts produced on the AFET are more accurate than the master pattern. This shows a process that is difficult to control and is evident in the significant accuracy variations of the parts produced on the AFET. The main reason for this inconsistency is the ineffective cooling system on the AFET. The part is not cooled uniformly before it is removed from the cavity and then it warpes. The cooling on the HSC-Aluminium tool is much more effective and therefore the accuracy is more consistent. Also influencing the part accuracy variations is the lack of an ejector system on both tools.

In general, the piston diameter on the current LOMOLD machine is too big in relation to the part. This influence the cooling time, the part accuracy, part appearance and accuracy consistency negatively.

The LOMOLD process is not consistent enough to be considered for a production process. This statement may be limited to the current LOMOLD machine that was used in this research. The piston diameter is too big in relation to the product. Also, the temperature control of the melt as it moves through the machine is not consistent enough. Other factors that will improve the part quality are a part ejector system and improved mould cooling.

It was also demonstrated that there may exist significant savings in tool manufacturing costs if tools are produced without cooling systems. The effectiveness of the AFET cooling system is shown to be poor, therefore for short pre-production or prototype runs the cooling system can be omitted from the tool. Exactly how many parts can be produced within required tolerances without applying a cooling system may be a point for future research. Also for future research must be fibre loading of components. Using fibres in the product will decrease the warpage and therefore increase the consistency of the part accuracy. It also has obvious benefits in terms of part strength. The expected tool life will decrease, especially for the AFET and this must be determined. Also, the influence of surface coatings on the mould life must be determined.

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APPENDIX A:

ALUMINIUM FILLED EPOXY TOOL (AFET) PROCESS CHAIN

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1. Introduction

The Aluminium Filled Epoxy Tooling (AFET) process is a Rapid Tooling technology. The process is usually used in conjunction with a Rapid Prototyping process to make it even more rapid. The basic procedure is the following:

1. Produce the master pattern, usually using a Rapid Prototyping process.
2. Decide on a suitable framework into which the epoxy will be cast.
3. Secure the master pattern on a joining board to form the mould split line.
4. Cast the one half of the mould and let it cure.
5. Cast the second half of the mould and let it cure.
6. Do final finishing on the mould.

The manufacturing of the LOMOLD Aluminium Filled Epoxy Rapid Tool (AFET) will be discussed in the following sections. The basic process chain will be expanded on by adding detail gained from the practical experience. The accuracy, time and cost of the AFET process for producing the tool are very important factors in Rapid Tooling and will be discussed in detail.

The tool will produce the part in Figure 1. It is an automotive part and is a visible component in the dashboard of a motorcar. For more on the prototype part, refer to section 2.1.1.

Figure 1: The prototype part

2. The Process Chain

The steps for producing the RT were carried out in series because of capacity constraints at Sentrale Meganiese Dienste (SMD).

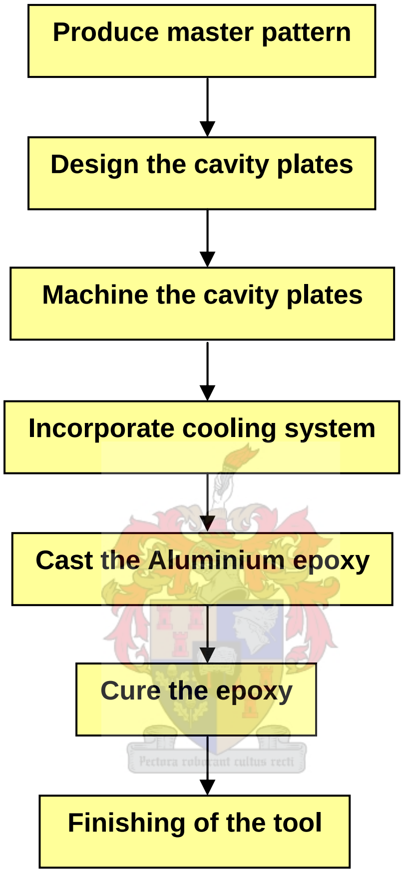

Figure 2: The LOMOLD AFET Process Chain

2.1 Produce the master pattern

2.1.1 CAD design of the master pattern

The part that will be used for the research is part of a dashboard assembly of a Volkswagen motorcar. The design of the part was done by Volkswagen engineers using the 3D modelling software, CATIA. Only Pro/ENGINEER is available at RPD (Rapid Product Development) for 3D modelling. Therefore the part was prepared in Pro/ENGINEER for growing on the 3D printer. The file formats of

CATIA and Pro/ENGINEER differ resulting in a considerable amount of CAD work to prepare the part for 3D printing. The CAD file of the part is send to the 3D printer in STL file format.

2.1.2 Grow the master pattern

2.1.2.1 *The Rapid Prototyping equipment*

The Rapid prototyping equipment available at the RPD laboratory is a 3D printer from Z-Corporation in America, a waxer for infiltrating parts with wax and vacuum casting equipment from MCP in Germany.

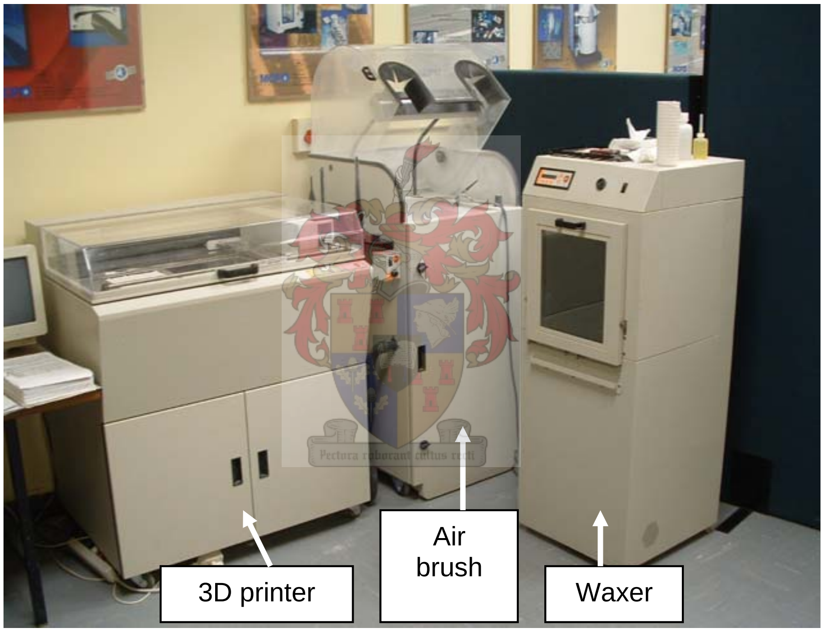

Figure 3: The 3D printer from Z-Corporation, USA

Figure 4: The vacuum casting equipment from MCP-Hek, Germany

2.1.2.2 Growing the part

The part was grown in one piece. To achieve this it was placed diagonally across the build volume of the printer. It is known from previous research that the dimensions grown in the z direction of the printer are too big.

Table 1: Master pattern printing information

Job number	03-07-18 stud
Job name	Holder 2
Anisotropic scaling	X: 1 Y: 1 Z: 1
Layer thickness	0.0035 inch
Powder type	Zp100
Part volume	7.04 in^3
Build time	3 hrs 10 min
Binder used	70g
Part mass before infiltration	141g
Impregnation material	Zi 580
Mass of impregnation material	129g

2.1.3 Remove the master pattern from the 3D-printer

Removing the printed part from the printer is a meticulous process. The model is left undisturbed in the printer for about 2 hours to set after printing stopped. The part is very weak at this stage and can be damaged easily therefore a brush is the most appropriate removal tool to use. A strategy is needed to remove the part quickly and successfully. The exact position of the part in the build volume is required. The powder acts as a support structure for the weak part therefore the mass of powder that does not support the part is removed first. Care must be taken to remove the supporting powder on both sides of the part simultaneously so that the support is removed in equal steps.

2.1.4 Clean the master pattern

The next step is to remove the excess powder still clinging to the printed part. An air brush is used for this purpose. Once the part is clean it is ready to be infiltrated.

2.1.5 Infiltrate the master pattern

The part is placed in the $40°C$ oven for ±10 minutes to dry out and increase the infiltration capabilities of the part.

The infiltrant that will be used is Zi 580 resin which works well with Zp 100 and allows the part to be finished to a very good surface finish. The infiltrant consists of 2 separate components (A and B) that must be mixed together in a 100:12 relation. For this part 200 g of infiltrant is prepared. The part is then soaked in the infiltrant to give a strong pattern. Where the infiltrant is not thoroughly absorbed, some infiltrant is applied with a brush. The part is then placed in the vacuum chamber for ±15 minutes to remove air from the infiltrated pattern. The pattern is inspected and if necessary infiltrant is applied to dry patches.

2.1.6 Cure the master pattern after infiltration

If the pattern is infiltrated to the satisfaction of the operator it is placed in the $40^{\circ}C$ oven to dry. The part must be turned at short regular intervals to prevent it from sticking to the wire surface of the oven. It takes ±1 hour for the part to dry sufficiently before the finishing process can begin.

Figure 5: An example of the infiltrated master pattern after some sanding

2.1.7 Finishing the pattern

Finishing the pattern is quite a lengthy process in relation to the other steps. It is also a very important step because the surface finish of the moulded parts is to a large extent determined here. The time finishing takes is determined to a large extent by the surface finish requirements of the final parts. The better the surface finish requirements, the longer finishing of the master pattern will take.

Figure 6: The exterior surface of the finished master pattern

The first step is to remove the worst roughness from the part surfaces using sandpaper. Next a layer of PVA paint is applied to the pattern using a brush. The PVA fill cracks in the surface thereby smoothing the surface of the pattern. The pattern is sanded again to obtain a very good surface finish. To identify bad patches on the pattern, the pattern is spray painted with a black paint. Identified rough patches are sanded and painted again and again until the surface is smooth.

Figure 7: The inside of the finished master pattern

2.2 Design the cavity plates

2.2.1 Design

The Aluminium Filled Epoxy Tooling (AFET) process requires a cavity in the 2 tool plates and the cooling plate that are bigger than the master pattern used to create the moulding cavity. The design of the required cavity is straight forward. Normally the outline of the master pattern is offset a distance to create the larger cavity required by the casting process. The resulting cavity must not be too big so that the amount of epoxy needed to create the moulding cavity is minimised. The cavity must not be too small either because this will unnecessarily complicate working with the cavity plates. The cavity plate that will be put on the stationary platen must also have a round feature for the platen locating ring on the LOMOLD machine to fit in.

Once the pouring cavity is designed, the size of the cavity plates can be determined. The plates must be big enough to incorporate the leader pins and attaching slots, but at the same time the plates must be as small as possible to minimise the cost of the plates.

It is important to design 2 holes into the 2 cavity plates for locating dowels to fit in. These 2 dowels will ensure that the 2 cavity plates remain aligned relative to each other. This is necessary to ensure a correct moulding cavity. Leader pins will replace the dowels in the final tool. The correct leader pins must be decided on based on the design of the cavity plates.

2.2.2 Order the material

The size of the aluminium needed to produce the cavity plates and the cooling plate is determined during the design of the cavity plates. The required material can now be ordered. The leader pins must also be ordered.

2.3 Machine the cavity plates

2.3.1 Generate the CNC tool path

The tool path for machining the pouring cavity from the 2 aluminium frames and the cooling plate is created by SMD for use on their CNC milling machine. The tool path for the round feature that will house the stationary platen locator ring is also created by SMD.

2.3.2 Machine the aluminium frames on CNC milling machine

As soon as the ordered material arrives, it must be prepared for CNC machining. This preparation includes squaring of the plates to the same size and skimming of the surfaces to ensure flat surfaces. The pouring cavity is now cut out of the 2 aluminium frames and the cooling plate. The round feature for the locator ring on the stationary platen is cut from the plate that will be attached to the stationary platen. The holes for the dowels are also machined. The CNC milling machine at SMD is used for this machining.

2.3.3 Insert the leader pins

Holes are drilled to accommodate the leader pins. To keep the 2 cavity plates in exactly the same position relative to each other, 2 leader pins in opposite corners of the dowels are inserted first. With 2 leader pins in place to secure the 2 cavity plates in the correct position, the dowels are removed and replaced with leader pins. The diameter of the holes must allow the leader pins to fit with a press fit. The stationary platen and the cooling plate will stop the leader pins from falling out when the tool is closed.

2.3.4 Machine attaching slots

The tool is secured to the LOMOLD machine with grab handles. Slots must be machined into the 4 corners of each cavity plate for the grab handles to grab on to. A milling machine is used for machining the slots.

2.3.5 Machine a backing plate

The moving platen on the LOMOLD machine has a big hole directly opposite to where the piston enters the moulding cavity. The hole allows an ejector system to be used. The epoxy in the moving platen in front of this hole is too thin to resist the pressure in the moulding cavity without the support of the stationary platen in this area. A backing plate is needed for support.

The backing plate is machined from a steel plate to the same size as the cavity plates. It is skimmed to ensure that the flat surfaces are flat.

2.3.6 Drill and tap holes

The backing plate is attached to the cooling plate using 4 (M8) bolts/cap screws. Four holes must be drilled and tapped into the cooling plate for this purpose. The cooling plate is attached to the moving platen cavity plate using 4 (M8) bolts/cap screws. Holes must be drilled and tapped into the moving platen cavity plate for this purpose.

2.4 Incorporate the cooling system

2.4.1 Decide on a cooling system

The characteristics of the Cast Aluminium Epoxy Rapid Tooling process allow any one of 3 possible cooling systems to be incorporated:

i. Conventional machined cooling channels
ii. Conformal cooling that closely follows the contour of the pattern surface
iii. Cooling using copper pipes

The last option was chosen. The fact that a casting process is used to make the tool allows more creativity than to use the conventional system. The conventional system cannot follow the shape of a curved part closely resulting in uneven cooling of the moulded part. This will cause moulded-in stresses in the final part. Conformal cooling is an option but at a considerable cost. A conformal cooling system would require CAD modelling time, the cooling system must be created physically to use as a pattern during the casting process and it would complicate the tool making process considerably. Using copper pipe to create cooling channels is effective, easy to implement and also the cheapest and fastest option. The copper pipes can be shaped in any form desired. It can closely follow the contour of the master pattern just like conformal cooling. Possible hot spots in the cavity can receive more cooling by increasing the amount of pipe in the proximity of the hot area. This is a very effective means of cooling.

2.4.2 Design the cooling system

The purpose of a cooling system is to remove heat from the tool and to maintain the mould temperature at an optimal level. To achieve this cold water must be supplied to the hot areas in the mould as quickly as possible and the supply of cold water must be maintained **[2, p.121]**.

The hottest area in the tool cavity is directly in front of the piston head on the moving platen side of the tool. The cooling system must ensure that the bulk of the cooling water is transported to this hot spot first. Therefore 2 pipes (marked enter in Figure 8) enter the tool just below this hot spot and after passing the spot turns 180 degrees to cover the edges of the hot spot again. After supplying the hot spot with cold water the water is not so cold anymore. It is guided to the outer edges of the cavity to cool the rest of the part before exiting the tool (marked exit in Figure 8). Figure 8 also shows the approximate location of the hot spot created by the molten plastic that enters the moulding cavity.

The idea with the cooling lines used in the stationary platen cavity plate is to target the sleeve that guides the piston that transports molten plastic into the moulding cavity. The copper pipes form a circular cooling system all around the sleeve (Figure 9).

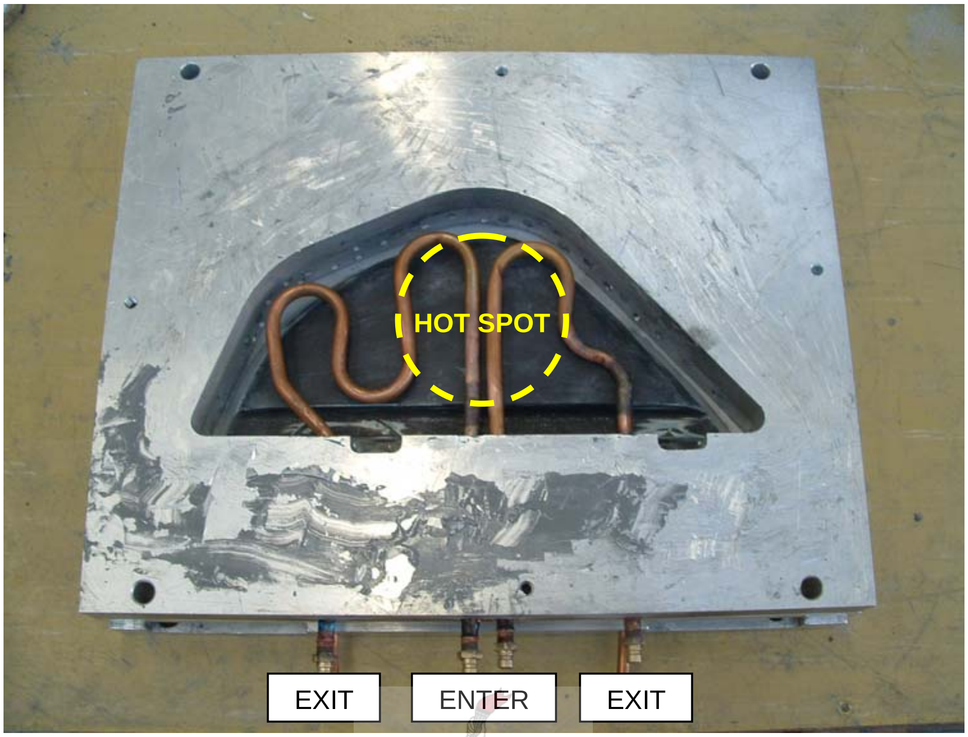

Figure 8: The cooling pipes in the moving platen cavity plate

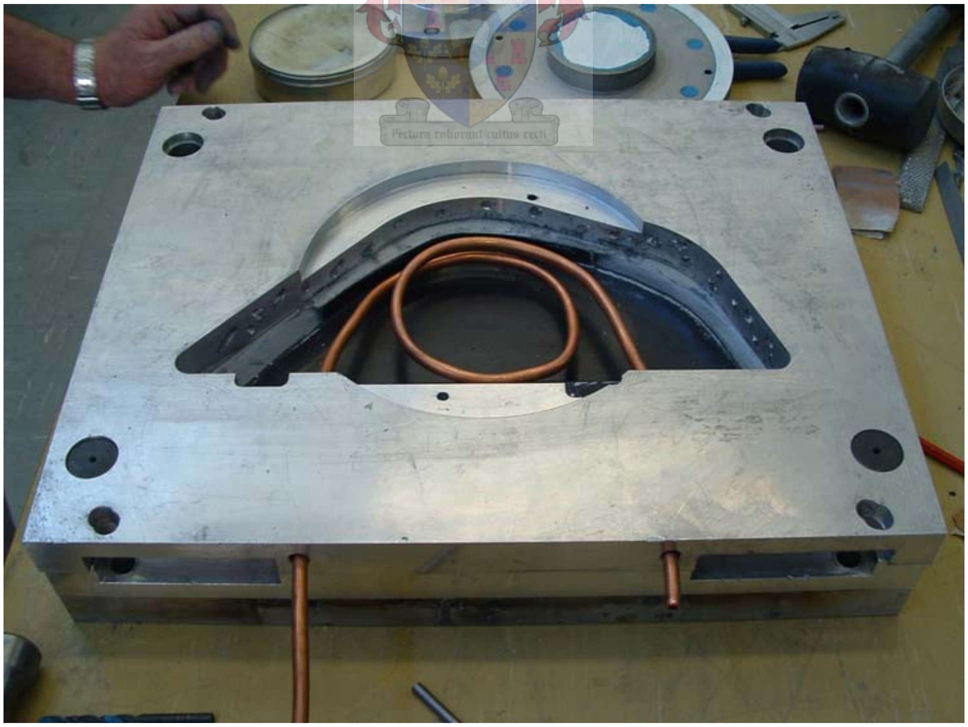

Figure 9: The cooling pipes in the stationary platen cavity plate

2.4.3 Produce the cooling system

2.4.3.1 Bend the copper pipes

The copper pipes are formed according to the design as can be seen in Figure 8 and Figure 9. The pipes are formed using a pipe bender.

2.4.3.2 Silver solder the quick-disconnect fittings

The water-cooling system used with the LOMOLD machine is fitted with the female part of quick-disconnect fittings on cooling pipes that transport the water to and from the mould. It is therefore necessary to fix the male part of these quick-disconnect fittings to the ends of the copper pipes that exit and enter the tool. The fittings are silver soldered to the copper pipes (Figure 10).

Figure 10: The male quick-disconnect fittings

2.5 Cast the aluminium epoxy

2.5.1 Make joining board

Before the tool can be produced it is necessary to decide on a tool parting line. This is the line where the mould separates to form two mould halves **[2, p.58]**. There can be more than one parting line depending on the complexity of the tool. The number of parting lines needed is determined by the geometry of the part to be moulded, the number of cavities produced, the type and style of the runner system, the type of gating used and the method of ejecting the moulded product.

The primary tool split line is where the 2 tool halves (cavity plates) separate from each other. This is the plane exposed when the tool is opened. The parting line follows the contour of the part that will be moulded. The more complex the part contour, the more complex it is to create the parting line in the tool.

A joining board is used to create the parting line on the part. The master pattern is recessed into a press wood board until only the part of the pattern that will form the cavity in the one cavity plate is exposed. Plasticine is used to fill any gap between the joining board and the master pattern. The cavity plate is placed over the joining board so that the joining board basically resemble the other cavity plate.

A cavity plate from a previous tool was used as a joining board. The master pattern is secured in its position in this previous cavity plate and the cavity plate that must be cast is placed in position over the master pattern (Figure 11).

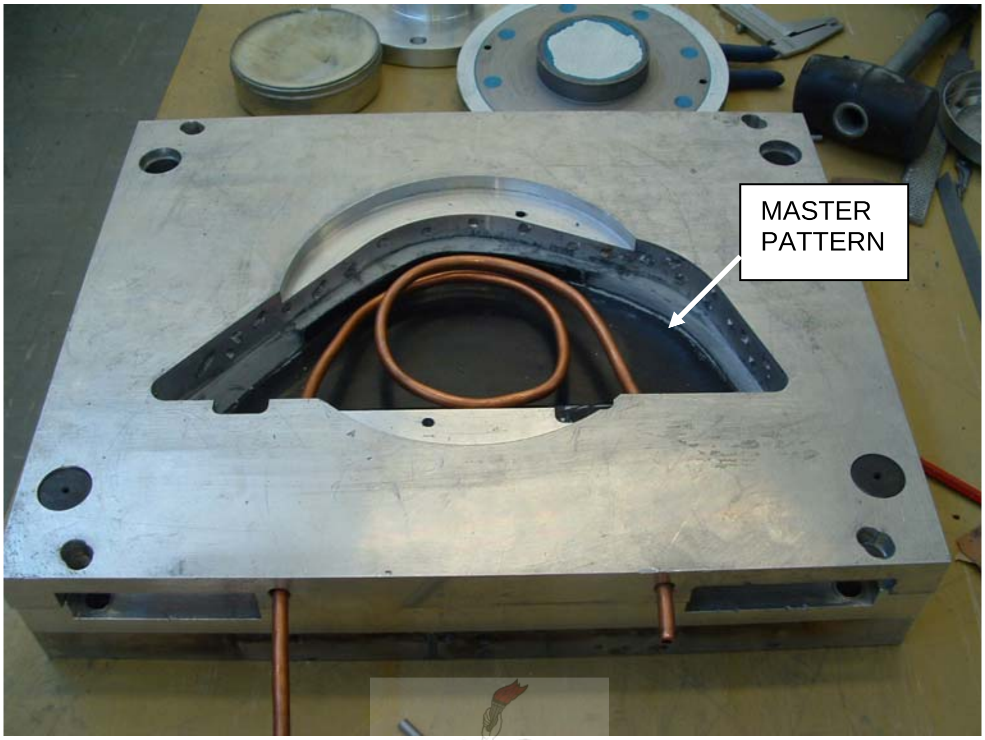

Figure 11: The "joining board" using the previous tool half

2.5.2 Prepare the tool for casting

The inside edge of the cavity plate must be "indented" to ensure that the epoxy is secured in the plate cavity. The epoxy fill these indents during the casting process thereby minimising the chance of the epoxy being pressed out of the cavity plate during the moulding process.

Wax is applied to the areas that will come in contact with the cast epoxy to ensure that the cast cavity plate can be separated from the joining board and pattern after the casting process.

A sleeve that will locate the hole where the piston will enter the cavity must be prepared next. The sleeve will also minimise the amount of epoxy used keeping costs down. Countersunk holes in the sleeve must be filled with plasticine to keep the epoxy out. The hole where the piston passes through the sleeve must also be closed. The sleeve is sprayed with mould release to make the removal of the sleeve after casting easier (Figure 16).

The cavity plate that must be cast first is placed over the joining board (Figure 11). The 2 cavity plates are secured together using clamps. The tool is now prepared for casting.

Figure 12: "Indents" inside the cavity in the cavity plate

2.5.3 Prepare the aluminium epoxy

The aluminium epoxy resin is placed in the $70°C$ oven to decrease the viscosity of the material. The material is removed from the oven and a mixer is used to mix the material. With time the aluminium sags down to the bottom of the container and the resin remain on the top. The material must be thoroughly mixed to homogenise the aluminium and the resin (Figure 13).

Figure 13: Mixing of the resin

When the material is mixed properly, the correct mass of resin must be weighed into a container. The container must be 4 to 5 times the volume of the material in it to allow for material expansion during the degassing process. The correct amount of hardener is added to the resin in the container. This must be mixed thoroughly to ensure that the hardener is equally dispersed through the resin to guarantee that the cast epoxy will harden during the curing phase.

After mixing the material is placed in the vacuum chamber for ±20 minutes for degassing. During degassing, the material expands as the air is sucked from it. The air bubbles and the volume to which the material expanded are clearly visible in Figure 14. This is why the mixing container must be 4 to 5 times the volume of the material.

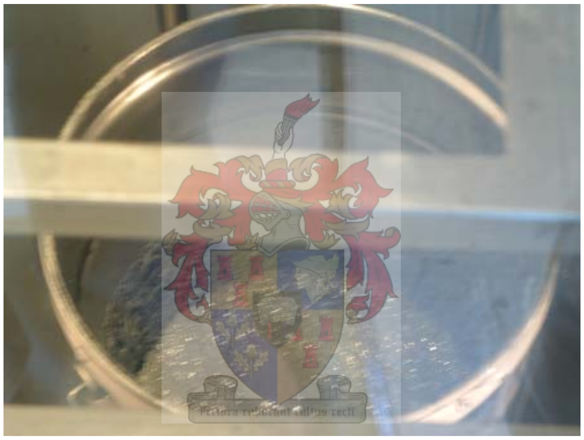

Figure 14: Degassing of the material in the vacuum chamber

2.5.4 Cast the stationary platen cavity plate

The aluminium epoxy is poured into the cavity at a steady rate. Air is absorbed as the material folds over itself during casting (Figure 15). The cavity is filled until the copper pipes are covered.

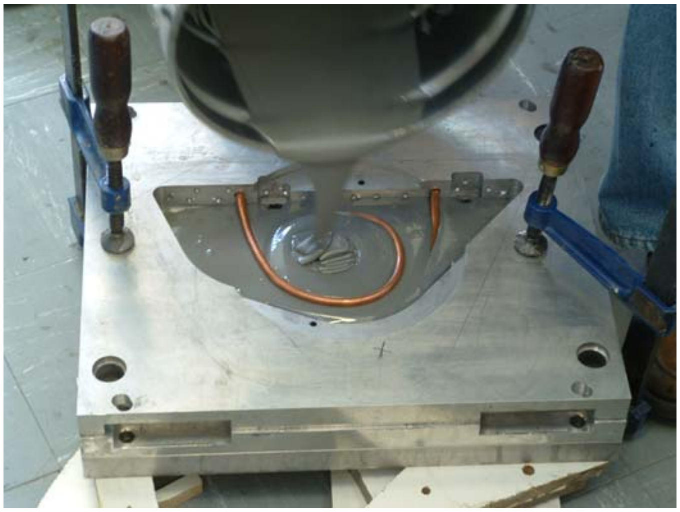

Figure 15: Pouring of the epoxy

The locating sleeve is pressed into position (Figure 16). There are 2 spots where the epoxy can be cast into the cavity. Two plasticine dams (Figure 17) are built around these spots to prevent the material from spilling over during the second degassing phase.

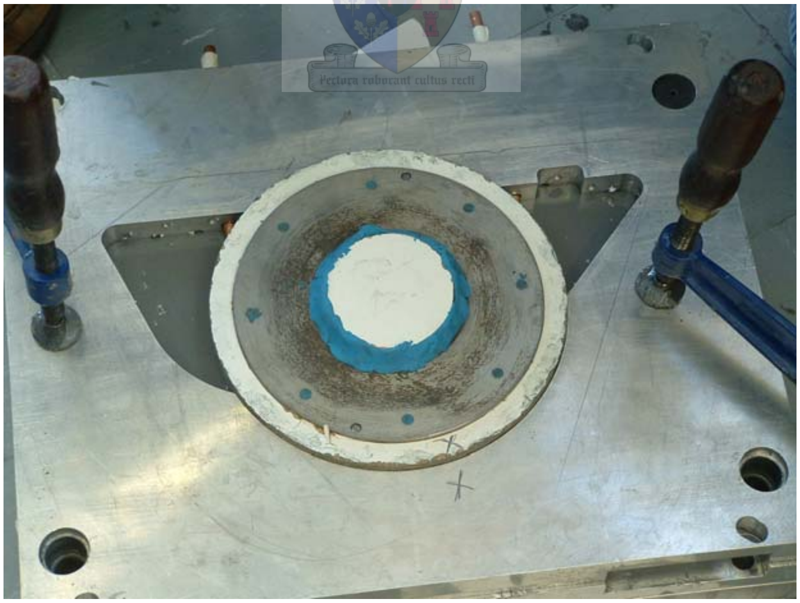

Figure 16: The locating sleeve

It is important to mention that pouring of the epoxy continues through one of these plasticine dams only. This is to minimise the amount of air trapped in the material during casting. It is also to prevent air from being trapped under the locating sleeve. The epoxy level in the plasticine dam marked A in Figure 17 is clearly higher than in the other dam because pouring continued into this dam.

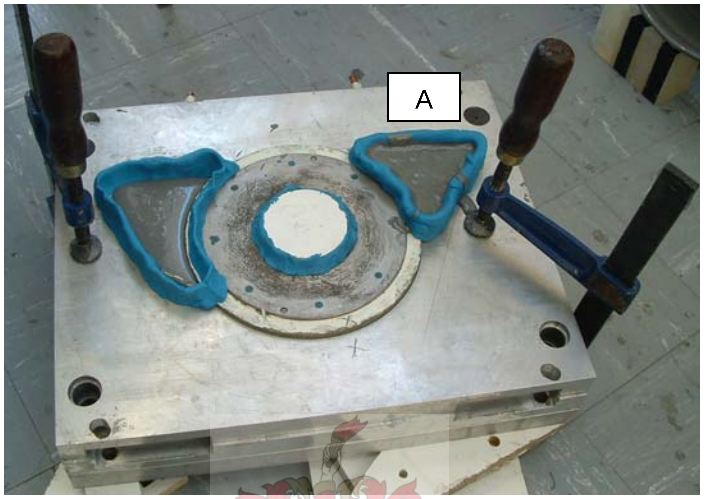

Figure 17: The cavity plate after casting of the epoxy

The tool is now placed for ±20 minutes in the vacuum chamber for degassing of the material after casting. During degassing, material spills over the plasticine dams (Figure 18). The chamber is de-gassed, more material is placed inside the plasticine dams. The material is degassed for another ±15 minutes before the initial curing process can begin. The tool is placed in the $40\,^{\circ}C$ oven for 6 to 7 hours for the material to cure.

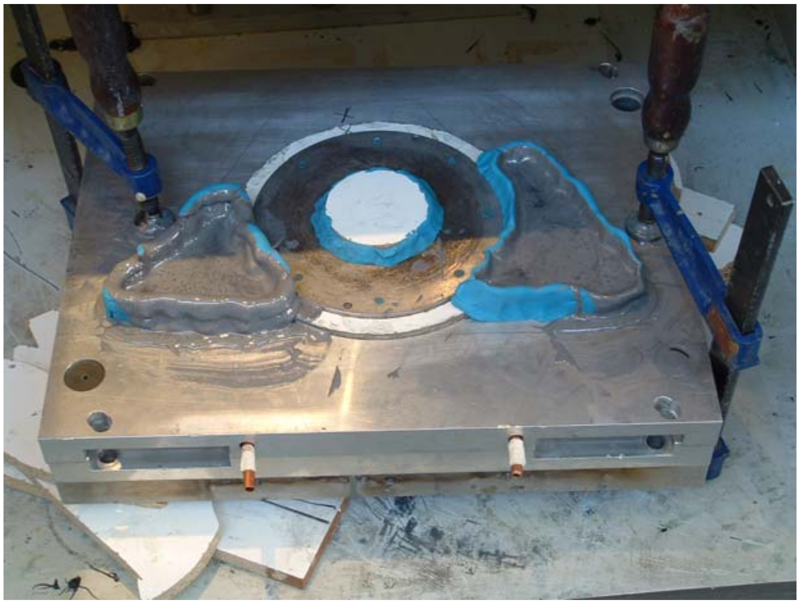

Figure 18: The tool after the final degassing phase

After this initial curing phase, the tool can be prepared for casting of the other cavity plate. The locating sleeve and the plasticine dams (Figure 18) are removed. The excess epoxy is removed using a milling machine. The back of the cast cavity plate is shown in Figure 19.

Figure 19: The back of the stationary platen cavity plate

2.5.5 Cast the moving platen cavity plate

The master pattern is still intact on the casted stationary platen. This is used to cast the moving platen. The pattern is checked for surface impurities and fixed if necessary. Wax is applied to the pattern and aluminium surface. This will form the parting surface.

Figure 20: The stationary platen

Exactly the same process as used for the stationary platen is repeated for the moving platen.

Figure 21: The cooling pipes in the moving platen

Figure 22: Casting of the moving platen

2.6 Final curing of the aluminium epoxy

The mould was placed in the $40°C$ oven overnight to cure properly.

2.7 Finishing of the tool

The excess epoxy was skimmed off at SMD on a lathe. The hole for the piston sleeve was machined into the stationary platen. The last step is to polish the cavity surface with sandpaper until the desired surface finish is achieved.

The sleeve and piston head is machined on the CNC milling machine (the same as for the HSC Aluminium tool) using reverse engineered CAD data to conform to the surface of the part. The backing plate is attached to the moving platen cavity plate. The tool is now ready to produce parts on the LOMOLD machine.

Figure 23: The machined sleeve and piston head for the HSC Aluminium tool.

3. Tool Lead-Time

Time is a very important factor in Rapid Tooling. The time required to produce the tool is called the tool lead-time. This is the main attraction of Rapid Tooling: the ability to produce production and/or prototype tooling in days.

An important factor that has a major influence on the time factor is whether or not a cooling system is incorporated in the tool. Depending on the intended use of the tool the decision could be made to leave out a cooling system.

3.1 Tool lead time

It is clear form Figure 24 (next page) that some tasks can be done in parallel. This shortens the lead time of the tool considerably. It is then possible to finish the tool in 10 days.

Table 2: Rapid tooling technologies information

	Aluminium-filled epoxy	**Spray metal**	**Cast kirksite**	**3D Keltool**	**Machined Aluminium**
Lead time (weeks)	2 to 4	2 to 4	3 to 7	3 to 6	2 to 6
Cost ($)	2500 to 10000	2000 to 15000	4000 to 15000	3500 to 10000	4000 to 25000
Typical part quantities	50 to 1000	50 to 1000	50 to 1000	50 to 1 million	50 to 100 000
Materials	Thermo plastics	Thermo plastics	Thermo plastics	Thermo plastics	Thermo Plastics

Referring to Table 2 [1] it is clear that this 10 day lead time is in-line with what can be expected from this technology.

Table 3 summarises the times allocated to the activities in the AFET process chain.

Table 3: Summary of AFET tool lead time

Activity	**Hours**	**Rate per hour (R)**	**Total cost (R)**
CAD modelling	16	200	3200
Programming NC code	4	200	800
NC-Machining	18	170	3060
3D printing	6	300	1800
Operator	61	145	8845
TOTAL	**105**		**17705**

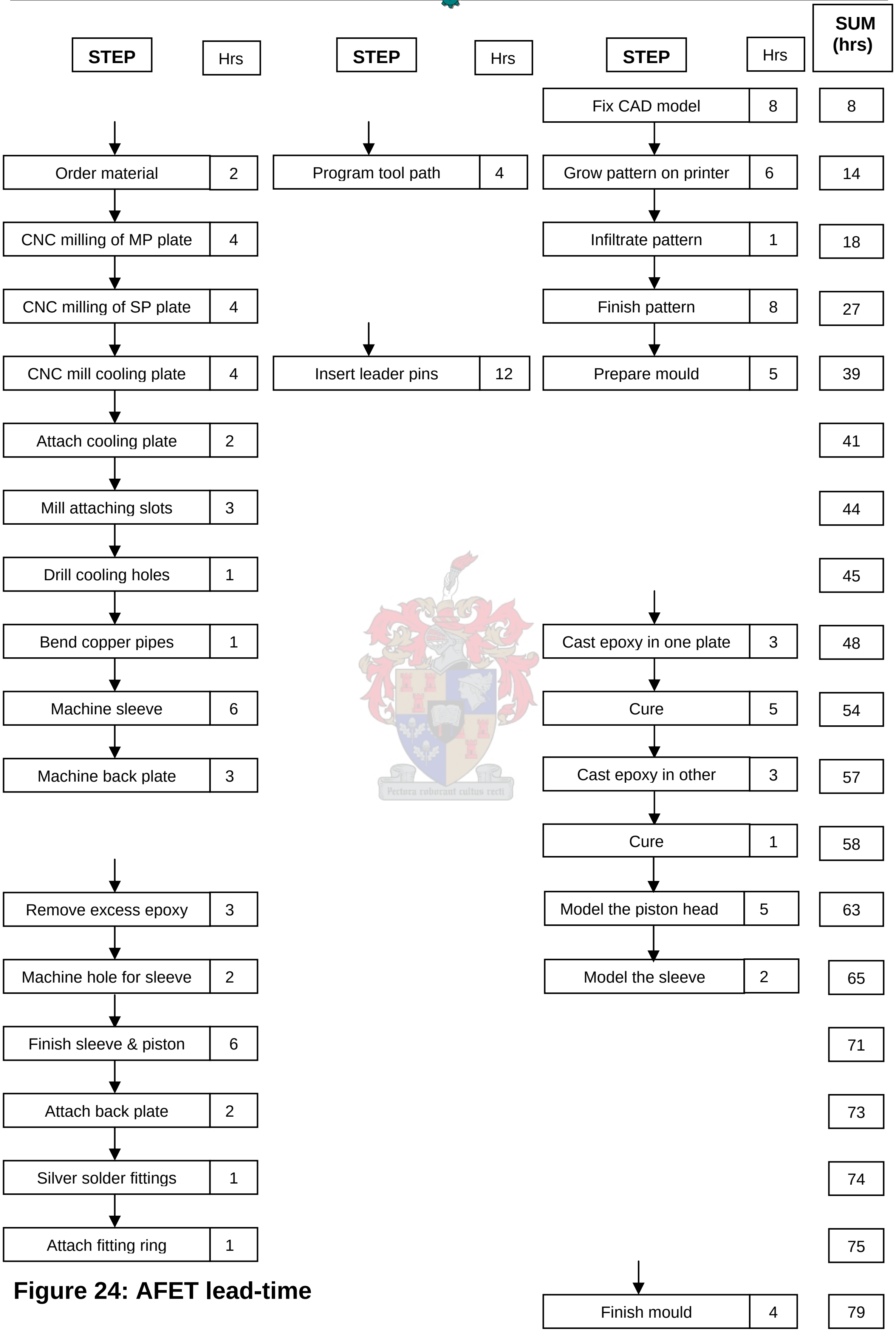

Figure 24: AFET lead-time

4. Tool Cost

The cost of the tool is very important in Rapid Tooling. Whether or not to use a Rapid Tooling solution can be decided by the costs involved. However it must be expected to pay more for a Rapid Tool because of the cutting edge technology that enables the rapid production of the tool.

Another important factor that has a major influence on the cost factor is whether or not a cooling system is incorporated in the tool. Depending on the intended use of the tool the decision could be made to leave out a cooling system.

The normal practice is to amortize the tool cost over the amount of parts produced. The amount of parts that can be produced with the AFET is not known. The literature estimates the maximum tool life to be 1000 parts (Table 2). The calculations made in this Appendix will use 1000 parts as the tool life. If less parts are produced the price per part will rise and visa versa.

4.1 Tooling costs

4.1.1 Rapid Product Development (RPD) laboratory costs

The RPD requested R 11 462 for producing the completed master pattern. Their labour amounts to R 2900 (20 hours at R145 per hour). CAD modelling is R 3200 according to Table 3. Seven kilograms of tooling resin must also be added, R 6300 (R900 per kg). The total cost at RPD is R 23 862.

4.1.2 Sentrale Meganiese Dienste (SMD) costs

The material used by SMD to create the frame for the epoxy tool and other components necessary for tools (leader pins) are listed in Table 4.

Table 4: SMD material cost

Material	Material Price (R)	Unit Description	Size (mm)	Unit Price (R)	Units	Total cost (R)
7075 Aluminium		Plate	475 x 385 x 30	1063	3	3189
6082 Aluminium		Bar	Ø200 x 70	333	1	333
Mild steel		Plate	475 x 385 x 10		1	200
Copper pipe		Pipe	Ø8		1	0
Leader pins	N/A	Male	FSN 16-26-26	60.45	4	241.80
Leader pins	N/A	Female	FSN 16-26	70.85	4	283.40
					TOTAL	**4247.20**

Referring to Table 5 the other work SMD did amounts to R 11 025 (everything except the CAD modelling).

Table 5: Other SMD work

Activity	Hours	Rate per hour (R)	Total cost (R)
Programming NC code	4	200	800
NC-Machining	18	170	3060
3D printing	6	300	1800
Operator	37	145	5365
TOTAL	**146**		**11025**

4.1.3 Total Tooling cost

The total tooling cost for producing the AFET is calculated in

Table 6: Aluminium Filled Epoxy Tool cost

Provider	Cost (R)
RPD	23 862.00
SMD	15 272.20
TOTAL	**39 134.00**

5. Conclusions and Recommendations

It is now understood that all manufacturing on the aluminium plates (two mould halves) must be done before casting of the epoxy. This will ensure perfect alignment between the two mould halves to minimise flashing.

The backing plate must be fitted more precisely. The crack in Figure 10 resulted because of a slight gap between the moving platen mould half and the backing plate.

The sleeve must extend into the mould cavity. This will prevent the moving piston from coming into contact with the brittle aluminium epoxy thus extending the tool life substantially. The epoxy is very brittle.

The piston diameter must be carefully selected. The piston diameter is far too big for this particular part. It is recommended that for this part a piston diameter should not exceed 20 mm.

APPENDIX B:

HIGH SPEED CUTTING (HSC) ALUMINIUM TOOL PROCESS CHAIN

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1. Introduction

The other rapid tooling technology that will be used in this research is High Speed Cutting Aluminium Tooling. This tooling technology will be compared with the Aluminium Filled Epoxy Tooling (AFET).

High Speed Cutting (HSC) is an older and therefore more mature technology than the new layer manufacturing processes. It is also a subtractive (material removal) process whereas layer manufacturing is additive. This is one significant distinction that immediately points to different capabilities and specific applications.

The last few years HSC came to the fore as serious competition to other Rapid Technologies. Improved machine tools and more availability, high speed spindles, improved tool bits, better control systems together with the use of much improved CAD/CAM capabilities increased the effectiveness and speed of HSC. This together with the fact that almost any material can be processed with HSC really renewed interest in the capabilities of this technology as a Rapid Technology.

The process chain followed to produce the HSC tool used in this research will be discussed next together with lead-time, tool cost and recommendations.

2. The Process Chain

Figure 1 shows the process chain followed to produce the HSC Aluminium tool used in this LOMOLD research. The second step (manufacturability investigation) is very important. Not all designed features can be machined on a milling machine. If this is the case an alternative plan must be made with either the design changed (if possible) or an alternative processing technology must be identified that can produce the specific part feature. The decision on what to do must be made early in the process chain so that the impact on tool cost and tool lead-time can be determined and considered.

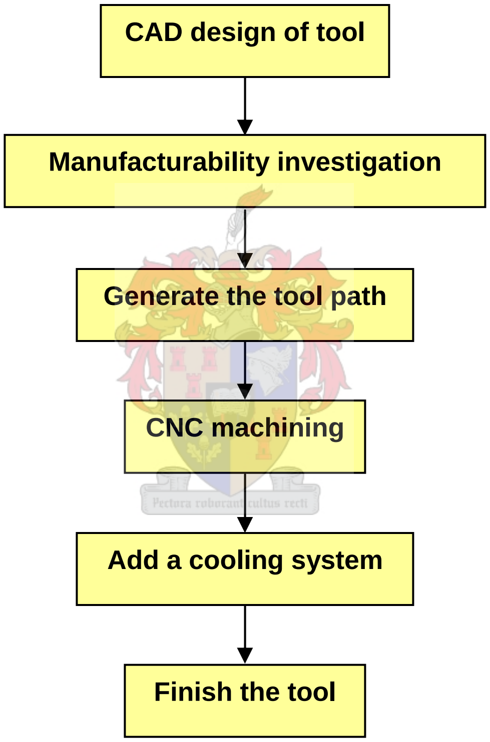

Figure 1: HSC Aluminium Tool process chain

2.1 CAD design of the tool

2.1.1 The part

The part is the same part the AFET tool will produce. The CAD file of the part needed considerable fixing before it could be used to design the cavity plates. This is probably because the file was created in CATIA and needed to be opened in PRO ENGINEER for designing the cavity plates. The fixing of the CAD file took about 8 hours of work.

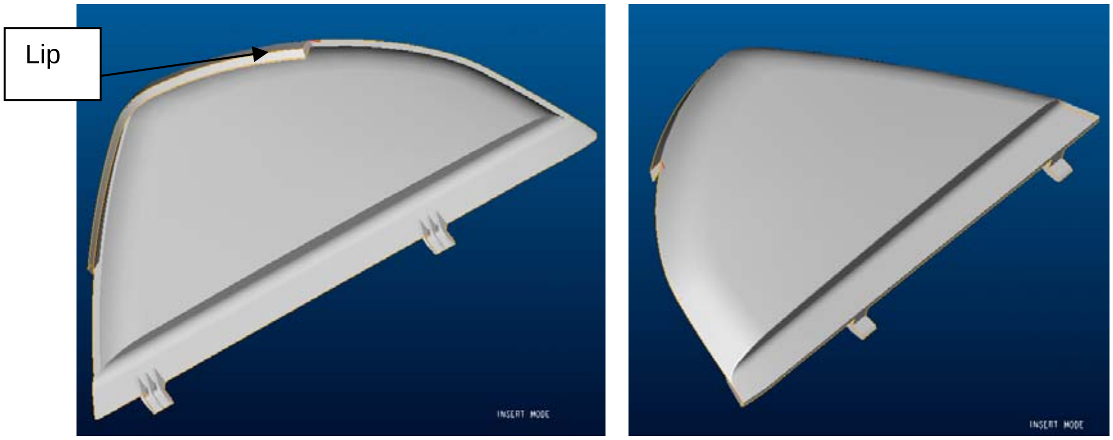

Figure 2: The part the HSC Aluminium mould will produce

2.1.2 The cavity plates

From the part CAD data the two cavity plates were designed. Two holes were added to ensure that the 2 mould halves will align perfectly on top of each other.

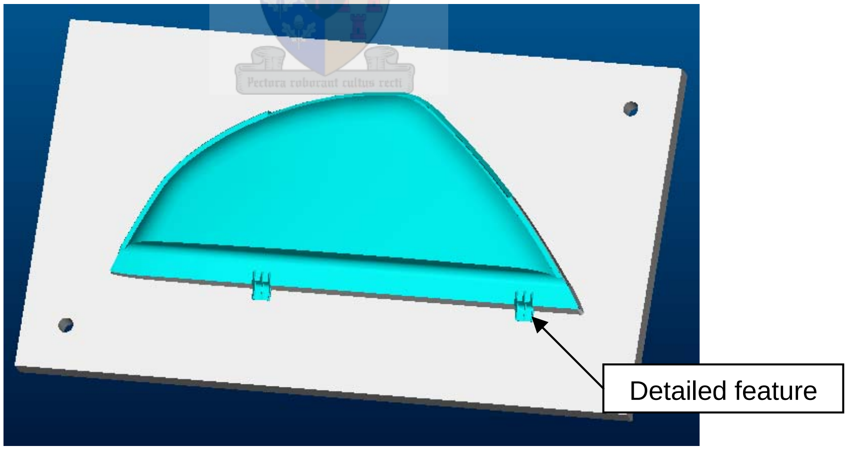

Figure 3: The stationary platen cavity plate

The CAD data for both cavity plates took about 8 days of modelling to complete. An experience CAD modeller would probably be able to complete the same work in 4 days or less.

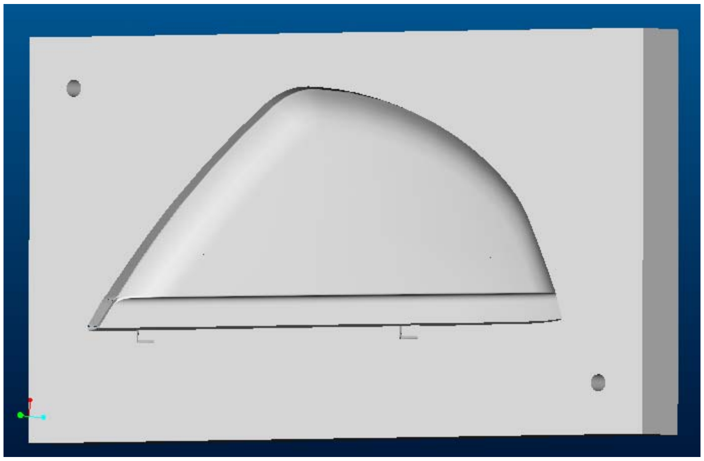

Figure 4: The moving platen cavity plate

2.2 Manufacturability investigation

Before starting with the tool path programming, the CAD models were discussed with an experienced CAD modeller/NC machinist. The small feature in Figure 3 was a concern from a manufacturing point of view. The machining would require a small diameter (1 mm) cutter that had to be long enough to reach down into the cavity. It was recommended that Electronic Discharge Machining (EDM) be used for machining this feature. Due to time and cost constraints and the unimportance of this feature for this research, it was decided to remove this feature from the CAD model (see Figure 5). Removing the feature from the CAD model took about 3 hours.

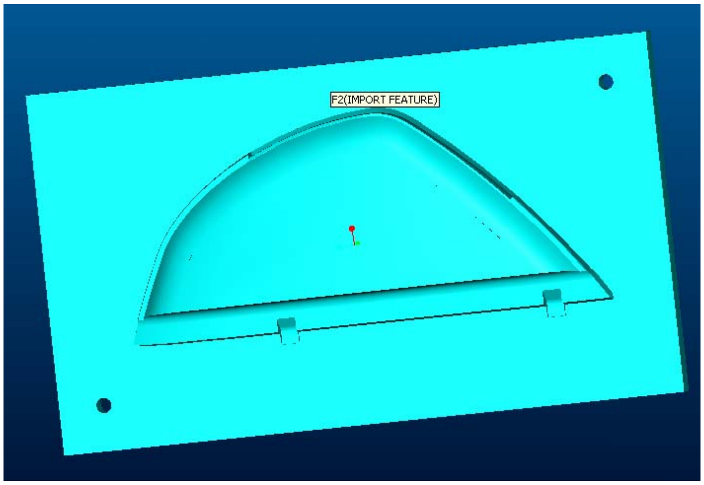

Figure 5: The stationary platen without the small feature

The lip shown in Figure 2 also had to be modified in the CAD model to make manufacturing easier. A cross section of the original lip is shown together with what it was modified too.

Figure 6: The original and modified lip

2.3 Generate the tool path

The NC program was created with the software Gib-CAM. Two programs were created for each cavity plate: a rough cut program (using a 7mm tool bit) and a finishing cut program (using a 4mm tool bit).

The programming time per cavity plate was about 2 hours for a total time of 4 hours. This programming was done by an expert.

2.4 CNC machining

The machining was done on a NC milling machine with a 16 000 rpm spindle speed capability. Based on the cutting simulations run on the milling machine, the total machining time should be around 35 hours.

Figure 7: The HSC Aluminium cavity plates

2.5 Add a cooling system

Cooling channels were machined into the back of the moving platen. The channels have a diameter of 10 mm and finishes in the standard fittings that attach the cooling fluid pipes to the mould. An extra aluminium plate had to be added to accommodate the cooling channels.

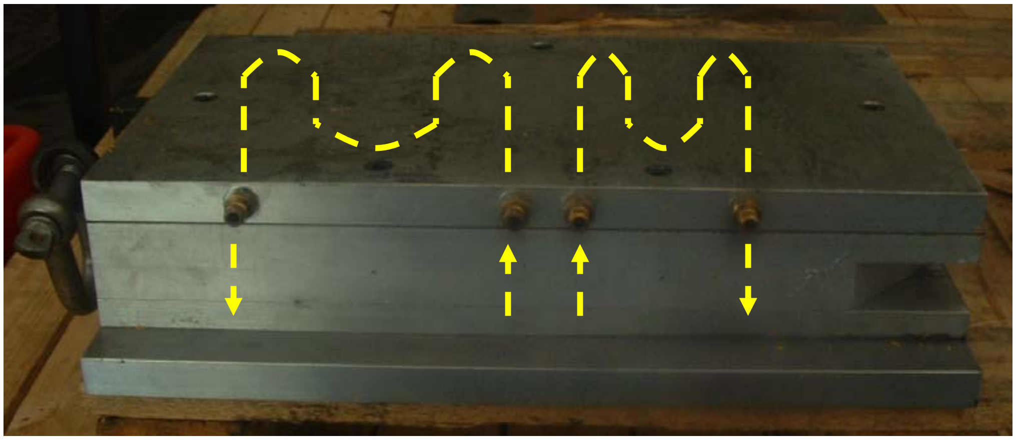

Figure 8: Cooling channels in moving platen cavity plate

The machining of the extra aluminium plate and fitting this plate to the cavity plate, milling the cooling channels and adding the fittings took about 7 hours to complete.

2.6 Finishing of the tool

The tool was sanded down with fine sandpaper. Leader pins were added to keep the 2 cavity plates aligned to each other. An extra plate of aluminium was added to the stationary platen cavity plate to allow fitting of the tool on the LOMOLD machine. A U-bolt is fitted to the mould to allow the use of an overhead crane to move the mould into and out of the machine.

Figure 9: Shaped piston head with matching sleeve

The piston head were CAD modelled and cut on an NC milling machine so that the head conforms to the surface of the part. The sleeve that guides the piston into the mould cavity also needed to be NC machined so as to have the same contour as the part surface and piston head.

3. *Tool Lead-Time*

The steps to produce the HSC Aluminium tool are presented in Figure 10 together with the time (hours) each step takes to complete.

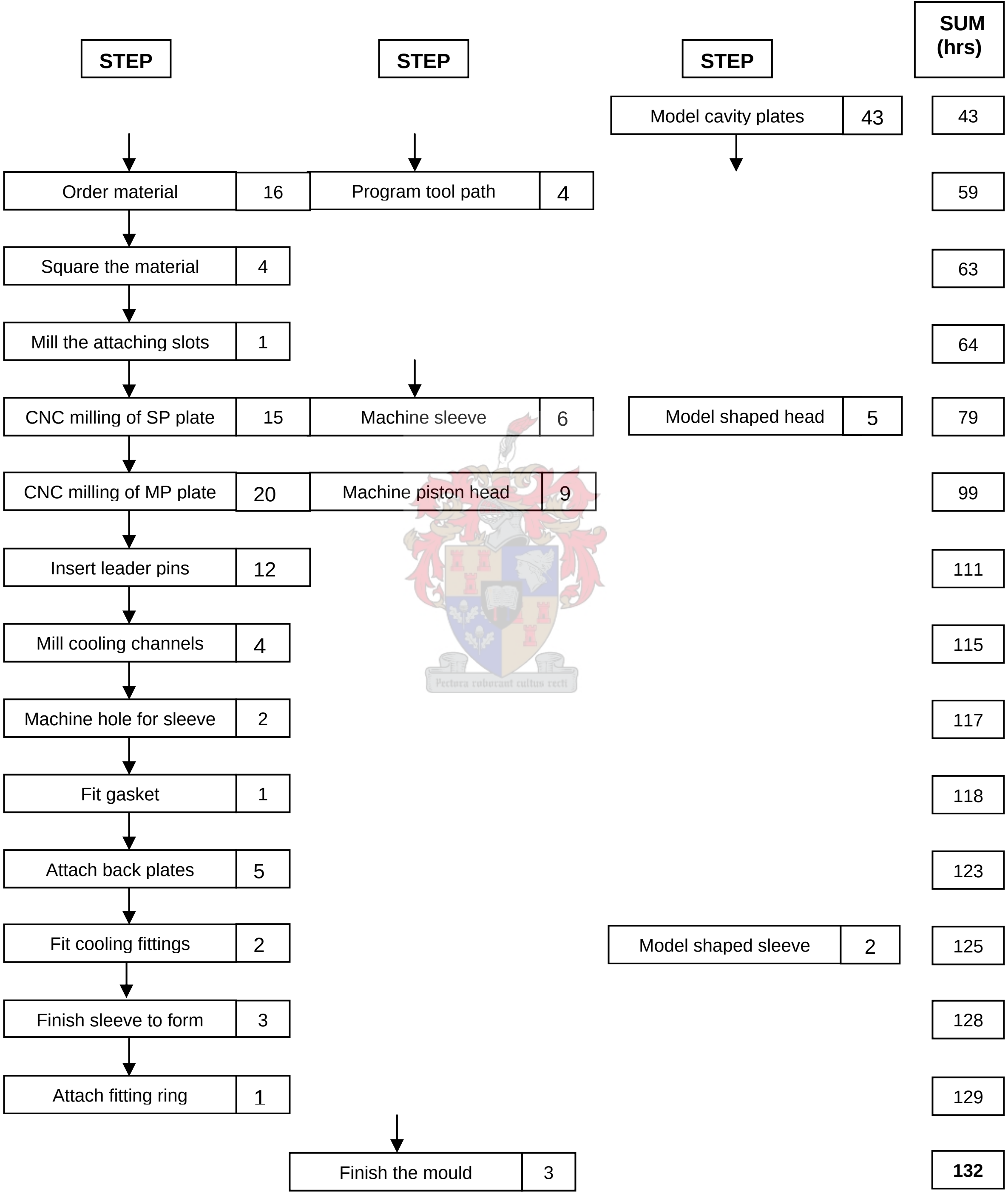

Figure 10: HSC Aluminium Tool lead-time

Figure 10 shows that the HSC Aluminium tool can be made in about 17 days if some of the tasks are performed in parallel. The times are based on milling the cavity plates on a High Speed Milling machine and doing the rest of the work at the University of Stellenbosch.

The lead-time is about 4 weeks which corresponds with the data provided in Table 1.

Table 1: Rapid Tooling technologies [1]

	Aluminium-filled epoxy	**Spray metal**	**Cast kirksite**	**3D Keltool**	**Machined Aluminium**
Lead time (weeks)	2 to 4	2 to 4	3 to 7	3 to 6	2 to 6
Cost ($)	2500 to 10000	2000 to 15000	4000 to 15000	3500 to 10000	4000 to 25000
Typical part quantities	50 to 1000	50 to 1000	50 to 1000	50 to 1 million	50 to 100 000
Materials	Thermo plastics	Thermo plastics	Thermo plastics	Thermo plastics	Thermo Plastics

The steps in Figure 10 are summarised in Table 2 below.

Table 2: Summary of HSC Aluminium tool lead-time

Activity	**Hours**	**Rate per hour (R)**	**Total cost (R)**
CAD modelling	50	200	10000
Programming NC code	8	200	1600
Machining	41	350	14350
Operator	47	145	6815
TOTAL	**146**		**32765**

4. Tool Cost

4.1 Tooling costs

4.1.1 Material cost

Table 3: HSC Aluminium tool material costs

Material	Material Price (R)	Unit Description	Size (mm)	Unit Price (R)	Units	Total cost (R)
7075 Aluminium		Plate	420 x 240 x 45	952.76	2	1905.53
7075 Aluminium		Plate	420 x 300 x 20	529.31	2	1058.63
6082 Aluminium		Bar	Ø200 x 70	333	1	333.00
Leader pins	N/A	Male	FSN 16-26-26	60.45	4	241.80
Leader pins	N/A	Female	FSN 16-26	70.85	4	283.40
					TOTAL	**3822.36**

4.1.2 Advanced machining cost

Table 4: HSC Aluminium tool advanced machining costs

Task description	Machine	Cost per hour (R)	Hours	Total cost (R)
CNC milling of 2 cavity plates	Hermle	450*	35	15750
			TOTAL	**15750**

*Based on quotes received in South Africa

4.1.3 Labour cost

4.1.3.1 RPD labour cost

Table 5: HSC Aluminium tool labour costs

Task	Task description	Cost per hour (R)	Hours	Total cost (R)
Programming	Create code to CNC mill 2 cavity plates	200	8	1600
			TOTAL	**1600**

4.1.3.2 Sentrale Meganiese Dienste (SMD) labour cost

Referring to Table 2 the SMD operators cost is **R6815**.

4.1.4 Modelling cost

Table 6: HSC Aluminium tool CAD modelling costs

Task	Task description	Cost per hour (R)	Hours	Total cost (R)
CAD modelling	Model the 2 cavity plates	200	43	8600
CAD modelling	Model the shaped piston head and sleeve	200	7	1400
			TOTAL	**10000**

4.1.5 Total HSC Aluminium Tool cost

Table 1 shows that this technology can produce a tool at a cost of between R 24 000 and R 150 000. The cost of this particular tool is about R 38 000 as indicated in the table below. As mentioned in the main document, this tool cost is dependent on many factors including the part geometry, part dimensions, the cooling system incorporated, the knowledge and experience of the tool designer, the machinist and the moulding process this tool will be used with.

A quote obtained for designing, modelling and manufacturing of the 2 cavity plates only is R 26 000.

Table 7: HSC Aluminium tool cost

Category	Cost (R)
Material	3822.36
Advanced Machining	15750.00
Labour	8415.00
Modelling	10000.00
	37987.36

5. Conclusions and Recommendations

The process chain for the HSC Aluminium Tool is relatively short in comparison with other Rapid Tooling technologies in terms of the number of steps required to produce the tool. Its main steps are CAD modelling, NC machining and finishing of the tool. Completing some of these steps in parallel, the lead-time of the tool can be limited to 17 days for this specific geometry. It is important to mention that if the original part (with lip and small features) had to be produced by this tool, EDM would be included in the process chain considerably increasing the tool lead-time and tool cost.

The tool cost is not very expensive due to the limited use of labour. It is not cheap either due to the use of high tech equipment, modelling software and the cost of skilled labour. The cost is also heavily dependent on the part geometry, part dimensions, incorporated cooling system and the moulding process the tool will be used with. The LOMOLD process with its lower cavity pressures (under investigation) does not require such a robust tool as for example Injection Moulding and therefore material and machining cost savings can be significant.

Comparing this process with the AFET process for the same part, there is no significant difference in the cost of the tools. The HSC Aluminium Tool process is faster to complete and requires considerably less effort.

APPENDIX C:
PROCESS CAPABILITY

ALUMINIUM FILLED EPOXY (AFET) TOOL

USL	1.2	mm
LSL	-1.2	mm

						Ave
Mean:	-0.04534	-0.06192	-0.10191	-0.05576	-0.20949	***-0.09488***
Max:	1.731	1.897	1.541	1.865	1.867	***1.7802***
Min:	-1.209	-1.322	-1.542	-1.552	-1.465	***-1.418***
Sigma:	0.595256	0.75781	0.640787	0.66798	0.732807	***0.678928***
C_p	0.67198	0.527837	0.624233	0.59882	0.545847	***0.593743***
C_{pk}	0.646592	0.500601	0.571221	0.570997	0.450556	***0.547994***

	PARTS				
Measurement	G1-20-02	G1-20-17	G1-20-22	G1-20-31	G1-20-47
1	1.731	1.897	1.541	1.865	1.867
2	0.769	0.807	0.471	0.818	0.767
3	-0.061	-0.118	-0.446	-0.177	-0.214
4	-0.625	-0.755	-1.074	-0.916	-0.907
5	-1.102	-1.244	-1.539	-1.476	-1.427
6	-1.209	-1.315	-1.542	-1.552	-1.465
7	-1.052	-1.236	-1.333	-1.467	-1.373
8	-0.869	-1.142	-1.07	-1.232	-1.244
9	-0.912	-1.213	-1.01	-1.045	-1.256
10	-1.018	-1.315	-1.03	-0.982	-1.321
11	-1.074	-1.322	-0.994	-0.868	-1.326
12	-0.949	-1.135	-0.767	-0.607	-1.127
13	-0.633	-0.696	-0.387	-0.129	-0.686
14	-0.391	-0.347	-0.009	-0.006	-0.512
15	-0.571	-0.596	-0.261	-0.213	-0.762
16	-0.673	-0.721	-0.428	-0.333	-0.917
17	0.272	-0.702	0.328	-0.31	-0.905
18	-0.053	-0.123	-0.083	0.019	-0.925
19	-0.332	-0.39	-0.597	-0.375	-0.994
20	-0.735	-0.806	-0.707	-0.456	-1.106
21	-0.777	-0.853	-0.811	-0.504	-1.213
22	-0.254	-0.892	-0.907	-0.551	-1.313
23	0.013	-0.787	-0.541	-0.426	-1.254
24	0.455	0.615	0.441	0.501	0.681
25	0.5	0.604	0.456	0.484	0.631
26	0.511	0.582	0.451	0.451	0.568
27	0.522	0.594	0.467	0.43	0.507
28	0.431	0.513	0.393	0.312	0.353
29	0.288	0.37	0.284	0.154	0.167
30	0.22	0.312	0.252	0.078	0.04

31	0.261	0.273	0.201	0.119	0.074
32	0.289	0.287	0.22	0.195	0.107
33	0.375	0.407	0.329	0.344	0.214
34	0.455	0.542	0.44	0.505	0.334
35	0.579	0.785	0.608	0.705	0.502
36	0.474	0.846	0.528	0.702	0.446
37	0.371	0.533	0.546	0.552	0.425
38	0.099	0.266	0.349	0.352	0.26
39	0.048	0.086	0.179	0.144	0.121
40	-0.345	-0.028	0.042	-0.031	0.011
41	-0.037	0.243	0.271	0.228	0.283
42	0.434	0.669	0.655	0.644	0.691
43	0.666	0.869	0.836	0.83	0.846
44	0.61	0.795	0.766	0.759	0.69
45	0.691	1.261	0.634	0.876	0.648
46	0.435	0.977	0.305	0.627	0.385
47	0.725	1.002	0.556	0.857	0.628
48	0.897	1.017	0.697	0.931	0.774
49	0.682	0.804	0.509	0.685	0.557
50	0.85	1.012	0.754	0.901	0.758
51	0.998	1.223	0.954	1.126	0.947
52	1.111	1.483	1.076	1.273	1.078
53	-0.04	-1.141	0.039	-0.161	0.122
54	0.114	-0.479	-0.115	0.064	-0.014
55	-0.093	-0.531	-0.282	-0.189	-0.364
56	-0.005	-0.466	0.06	-0.07	-0.234
57	-0.405	-0.762	-0.563	-0.544	-0.703
58	-0.582	-0.849	-0.732	-0.716	-0.838
59	-0.583	-0.848	-0.732	-0.717	-0.837
60	-0.703	0.593	-0.858	-0.847	0.574
61	-0.498	-0.529	-0.624	-0.668	-0.688
62	-0.557	-0.614	-0.689	-0.726	-0.752
63	-0.175	-0.12	-0.246	-0.365	-0.362
64	0.187	0.265	0.208	0.024	-0.031
65	0.4	0.553	0.558	0.559	0.429
66	0.186	0.325	0.286	0.286	0.055
67	-0.268	-0.142	-0.169	-0.198	-0.514
68	-0.564	-0.509	-0.53	-0.662	-0.896
69	-0.598	-0.635	-0.625	-0.811	-0.897
70	-0.553	-0.612	-0.655	-0.741	-0.772
71	-0.578	-0.624	-0.76	-0.709	-0.743
72	-0.622	-0.63	-0.845	-0.712	-0.749
73	-0.518	-0.477	-0.746	-0.606	-0.653
74	-0.145	-0.097	-0.335	-0.241	-0.324
75	0.497	0.579	0.287	0.464	0.355
76	0.954	1.118	0.795	1.023	0.856
77	-0.324	-0.349	-0.593	-0.448	-0.511
78	-0.2	-0.416	-0.53	-0.33	-0.499

79	-0.071	-0.498	-0.359	-0.193	-0.432
80	-0.109	-0.531	-0.289	-0.206	-0.376
81	-0.338	-0.584	-0.401	-0.399	-0.593
82	-0.468	-0.574	-0.485	-0.48	-0.764
83	-0.339	-0.3	-0.28	-0.283	-0.603
84	-0.141	0.132	0.063	-0.012	-0.237
85	-0.043	0.205	0.148	-0.031	-0.115
86	0.193	0.284	0.232	0.039	-0.019
Average	-0.04534	-0.06192	-0.10191	-0.05576	-0.20949
Stdev	0.595256	0.75781	0.640787	0.66798	0.732807

HSC ALUMINIUM TOOL

USL	1.2	mm
LSL	-1.2	mm

						Ave
Mean:	0.018255	0.019676	0.021598	0.029578	0.017363	***0.021294***
Max:	1.037	0.936	0.944	1.24	0.778	***0.987***
Min:	-1.085	-1.291	-1.268	-1.41	-1.476	***-1.306***
Sigma:	0.30521	0.319849	0.318735	0.333682	0.292329	***0.313961***
$\boxed{C_p}$	1.310572	1.250591	1.25496	1.198745	1.368323	***1.276638***
$\boxed{C_{pk}}$	1.290635	1.230085	1.232373	1.169198	1.348525	***1.254163***

	PARTS				
Measurement	G1-20-9	G1-20-17	G1-20-23	G1-20-38	G1-20-43
1	0.532	0.664	0.714	0.964	0.679
2	0.185	0.272	0.303	0.475	0.244
3	0.169	0.217	0.217	0.328	0.142
4	0.3	0.253	0.18	0.144	0.121
5	0.828	0.739	0.614	0.474	0.591
6	1.037	0.936	0.778	0.584	0.778
7	0.102	0.042	0.041	0.084	0.197
8	-0.125	-0.162	-0.155	-0.068	-0.175
9	-0.172	-0.191	-0.165	-0.132	-0.335
10	0.204	0.235	0.192	0.197	0.118
11	0.019	-0.003	0.033	0.04	0.198
12	0.014	-0.106	-0.002	0.048	0.037
13	0.406	0.369	0.314	0.395	0.244
14	-1.044	-1.291	-1.268	-1.41	-1.476
15	-0.577	-0.63	-0.584	-0.246	-0.621
16	-0.772	-0.761	-0.705	-0.465	-0.51
17	-0.753	-0.388	-0.668	-0.555	-0.294
18	0.28	0.352	0.291	0.272	0.308
19	0.215	0.247	0.194	0.18	0.167
20	0.237	0.27	0.223	0.226	0.164
21	0.181	0.212	0.158	0.179	0.081
22	0.11	0.128	0.096	0.12	-0.007
23	0.044	0.043	0.027	0.063	-0.094
24	-0.013	-0.03	-0.03	0.004	-0.168
25	-0.049	-0.08	-0.073	-0.042	-0.217
26	-0.096	-0.131	-0.11	-0.092	-0.26
27	-0.129	-0.15	-0.121	-0.095	-0.276
28	0.086	-0.052	-0.005	-0.075	-0.016
29	0.13	0.04	0.072	0.032	0.056
30	0.162	0.137	0.142	0.141	0.125

31	0.177	0.169	0.154	0.167	0.174
32	0.102	0.083	0.09	0.105	0.165
33	-0.002	-0.067	-0.005	0.013	0.1
34	-0.158	-0.226	-0.13	-0.071	0.011
35	-0.179	-0.279	-0.153	-0.054	-0.052
36	-0.01	-0.139	-0.019	0.04	-0.004
37	0.081	-0.054	0.026	-0.002	0.009
38	-0.105	-0.1	-0.123	-0.028	-0.138
39	-0.076	-0.089	-0.094	-0.017	-0.098
40	-0.042	-0.065	-0.072	0.003	-0.054
41	-0.004	-0.025	-0.047	0.038	0.01
42	0.033	0.02	-0.008	0.051	0.08
43	0.066	0.043	0.025	0.066	0.139
44	0.11	0.078	0.062	0.091	0.209
45	-0.089	-0.164	-0.175	-0.053	0.043
46	-1.085	-1.267	-1.194	-1.03	-0.964
47	-0.198	-0.044	0.944	1.24	0.247
48	0.096	0.064	-0.009	0.042	0.116
49	0.201	0.216	0.148	0.185	0.269
50	0.142	0.145	0.099	0.152	0.19
51	0.121	0.133	0.101	0.147	0.16
52	0.146	0.199	0.144	0.186	0.203
53	0.188	0.253	0.19	0.242	0.256
54	0.312	0.367	0.317	0.327	0.331
55	0.409	0.422	0.353	0.359	0.358
56	-0.083	-0.179	-0.225	-0.205	-0.207
57	0.031	-0.114	0.106	-0.261	-0.348
58	-0.411	-0.431	-0.294	0.022	-0.307
59	0.112	0.1	0.171	0.318	0.09
60	0.362	0.425	0.401	0.382	0.27
61	0.555	0.573	0.575	0.622	0.436
62	0.366	0.32	0.273	0.339	0.134
63	-0.027	0.142	0.096	0.1	0.135
64	-0.148	-0.034	-0.132	0.004	-0.009
65	-0.223	-0.123	-0.202	-0.022	-0.099
66	-0.237	-0.192	-0.198	-0.168	-0.186
67	-0.16	-0.206	-0.181	-0.357	-0.155
68	-0.099	-0.138	-0.126	-0.358	-0.108
69	0.108	0.111	0.138	-0.059	0.1
70	0.294	0.364	0.351	0.223	0.242
71	0.401	0.439	0.487	0.42	0.389
72	0.243	0.316	0.332	0.26	0.276
73	0.051	-0.02	0.037	0.057	0.102
74	0.094	0.014	0.067	0.067	0.096
75	0.099	-0.005	0.053	0.017	0.052
76	0.081	-0.076	-0.026	-0.11	-0.042
77	0.032	-0.16	-0.099	-0.285	-0.132
78	-0.081	-0.175	-0.146	-0.367	-0.136

79	-0.175	-0.165	-0.189	-0.416	-0.115
80	-0.222	-0.149	-0.216	-0.413	-0.092
81	-0.219	-0.128	-0.218	-0.365	-0.086
82	-0.182	-0.107	-0.193	-0.284	-0.075
83	-0.13	-0.07	-0.137	-0.183	-0.046
84	-0.094	0.002	-0.061	-0.047	0.023
85	-0.042	0.099	0.041	0.107	0.117
86	0.144	0.243	0.182	0.228	0.251
87	0.26	0.32	0.264	0.278	0.314
88	-0.179	-0.191	-0.149	0.145	-0.258
89	0.304	0.337	0.346	0.433	0.221
90	0.444	0.531	0.497	0.342	0.351
91	0.262	0.321	0.305	0.173	0.226
92	0.151	0.199	0.184	0.004	0.167
93	0.031	0.097	0.048	-0.152	0.093
94	-0.082	-0.002	-0.084	-0.278	0.013
95	-0.16	-0.054	-0.172	0.268	-0.057
96	-0.26	-0.172	-0.249	-0.389	-0.111
97	-0.296	-0.211	-0.27	-0.35	-0.15
98	-0.28	-0.209	-0.243	-0.242	-0.173
99	-0.201	-0.158	-0.147	-0.098	-0.174
100	-0.126	-0.105	-0.067	-0.026	-0.172
101	-0.159	-0.156	-0.123	-0.093	-0.267
102	-0.034	-0.07	0.069	-0.233	-0.383
Average	0.0183	0.0197	0.0216	0.0296	0.0174
Stdev	0.3052	0.3198	0.3187	0.3337	0.2923

VW Production part - Process Capability

USL	1.2	mm
LSL	-1.2	mm

Mean:	0.004622
Max:	0.546
Min:	-0.442
Sigma:	0.226245
$\boxed{C_p}$	1.767992
$\boxed{C_{pk}}$	1.761183

Measurement	**Value**
1	0.147
2	-0.262
3	-0.442
4	-0.332
5	-0.18
6	0.141
7	0.546
8	0.045
9	-0.149
10	-0.001
11	0.053
12	0.022
13	0.168
14	0.18
15	0.244
16	-0.036
17	-0.195
18	-0.142
19	-0.057
20	0.053
21	0.175
22	0.246
23	-0.155
24	-0.122
25	0.024
26	0.102
27	0.077
28	0.073
29	0.389
30	0.136
31	0.025
32	-0.279

33	-0.422
34	-0.352
35	-0.075
36	0.126
37	0.4
Average	0.004622
Stdev	0.226245

APPENDIX D:

REFERENCE INJECTION MOULDING PROCESS

Theoretical cooling time: Injection Moulding reference

Injection Moulding - An Introduction
Gerd Potsch & Walter Michaeli
HANSER Publishers, Munich, 1995

Calculations:

Thermal diffusivity: *page 34*

$$a = \frac{\lambda}{\rho \times C_p}$$

where

$a = thermal\_diffusivity$
$\lambda = thermal\_conductivity$
$\rho = density$
$C_p = heat\_capacity$

Using the effective thermal diffusivity in the figure below,
sufficiently accurate results for Injection Moulded parts can be obtained:(p. 36)

Estimating the cooling time to cool a plate from melt to demoulding temperature
the following equation can be used: *page 10*

$$t_c = \frac{s^2}{\pi^2 a} \ln\left(\frac{8}{\pi^2}\frac{T_M - T_W}{\overline{T_D} - T_W}\right)$$

where

$t_c = estimated\_cooling\_time$
$s = wall\_thickness$
$a = thermal\_diffusivity$
$T_M = melt\_temperature$
$T_W = wall\_temperature$
$\overline{T_D} = part\_mean\_demoulding\_temperature$

0.8105695

8.9162642

WITH MOULD COOLING

	HSC Aluminium mould: Set mould wall temperature						
	20 degrees	25 degrees	30 degrees	35 degrees	40 degrees	45 degrees	50 degrees
a_{eff}	0.07	0.06875	0.0675	0.06625	0.065	0.06375	0.0625
T_W	20	25	32.65	35	41.93	45	50.1
T_M	240	240	240	240	240	240	240
$\overline{T_D}$	51	50	50.24	50	53.21	50	51.05
S	2.5	2.5	2.5	2.5	2.5	2.5	2.5
t_c	15.83	17.89	21.17	22.99	25.87	34.31	51.55

	Aluminium Epoxy mould: Set mould wall temperature						
	20 degrees	25 degrees	30 degrees	35 degrees	40 degrees	45 degrees	50 degrees
a_{eff}	0.07	0.06875	0.0675	0.06625	0.065	0.06375	0.0625
T_W	24.5	26.33	32.86	36.03	40.23	44.87	50.5
T_M	240	240	240	240	240	240	240
$\overline{T_D}$	49.43	52.95	49.3	48.7	49.2	50	51
S	2.5	2.5	2.5	2.5	2.5	2.5	2.5
t_c	17.61	17.25	21.80	24.55	28.19	34.06	58.03


Pectora roborant cultus recti