# TOOLING THROUGH LASER SINTERING IN MARAGING STEEL FOR HIGH-VOLUME PLASTIC INJECTION MOULDING

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BLOEMFONTEIN

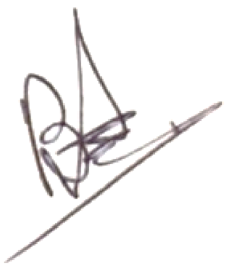
MARCH 2019

# DECLARATION OF INDEPENDENT WORK

**DECLARATION WITH REGARD TO**

**INDEPENDENT WORK**

I, BERTUS VAN AS, identity number and student number , do hereby declare that this research project submitted to Central University of Technology, Free State for the Degree **MASTER OF ENGINEERING IN ENGINEERING MECHANICAL**, is my own independent work; and complies with the Code of Academic Integrity, as well as other relevant policies, procedures, rules and regulations of Central University of Technology, Free State; and has not been submitted before to any institution by me or any other person in fulfilment (or partial fulfilment) of the requirements for the attainment of any qualification.



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# ABSTRACT

Existing techniques to manufacture conventional tool steel inserts for the plastic injection moulding process are expensive and time-consuming. Complex mould inserts, difficult to manufacture with conventional processes, can be produced using Direct Metal Laser Sintering (DMLS). DMLS is an additive manufacturing (AM) process that can produce complex functional metal components directly from computer aided design (CAD) data. Recent advances in materials and laser sintering technologies make it possible to process high-performance metals suitable for production components. Maraging Steel MS1, an AM material made available by EOS GmbH Electro Optical Systems (EOS), is a DMLS metal powder designed for tooling applications. It is an ultra-high-strength alloy that is resistant to corrosion, has good thermal conductivity properties and can be hardened with a thermal age-hardening process. Maraging Steel MS1 can be, and is easily machined and EDM spark-eroded in its 'as-built' state. Unlike conventional methods traditionally used in the manufacturing of metal components, DMLS can produce complex inner structures (such as conformal cooling) that can be beneficial for the tooling sector.

This dissertation describes an investigation into the possible heat transfer benefits of conformal cooling channels using Maraging Steel MS1 inserts which could result in a reduction of cycle times, cost per product as well as improving part quality by eliminating defects such as warpage and heat sinks.

Two AM inserts for an interlocking floor tile with different conformal cooling channel designs were compared using ANSYS® CFD and SIGMASOFT® virtual moulding to determine the most efficient cooling channel design. During the simulations, factors such as heat transfer rates and turbulent flow inside the cooling channels were considered and the most efficient design was selected based upon these factors.

A comparison between the most efficient AM insert design and an insert manufactured through conventional manufacturing techniques was conducted. Simulation results showed that an AM insert with conformal cooling channels can remove heat more effectively than conventionally manufactured cooling channels. By considering the increased solidification rate of the part produced through the AM insert, a reduction in cycle time of 10.7% was possible from the simulation results.

Actual IM trials were conducted and temperatures inside both the AM and conventionally manufactured inserts were recorded. The temperature results recorded from the trials were within 4% of the simulated values. The outcomes from the experimental trials confirmed the simulated results, indicating that simulation software can successfully be used to analyse different cooling channel designs to identify the most efficient cooling channel layout.

After benchmarking the experimental results with the simulation results, the same simulation principles and methodology were applied to an industrial application. Both an AM and conventional insert design were simulated and compared in a virtual injection moulding situation. From the simulated results it was evident that the AM insert with conformal cooling channels was able to remove heat more efficiently than the insert designed for conventional manufacturing, resulting in a reduction of mould temperature and cycle times.

A manufacturing cost and lead-time comparison was conducted. For both cases considered, it indicated that the conventionally manufactured insert reached its break-even point after fewer IM cycles compared to the AM insert due to its lower manufacturing costs. During high-volume production, the AM insert will be more profitable due to its lower running costs and cycle time. From the research results it was concluded that the AM inserts with conformal cooling channels could result in a benefit for high-volume plastic injection moulding, resulting in shorter production times to produce a product.

*This dissertation is dedicated to the memory of my father, Johannes Gysbert van As. I think of him daily and treasure the relationship we had. His continuous support and encouragement throughout my life made me who I am.*

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# PUBLICATIONS

**van As B, Combrinck J, Booysen GJ & de Beer DJ.** DIRECT METAL LASER SINTERING, USING CONFORMAL COOLING, FOR HIGH VOLUME PRODUCTION TOOLING. *South African Journal of Industrial Engineering*. 28(4) 2017. pp.170–182.

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# ABBREVIATIONS

| | |
|---|---|
| **3D:** | Three-dimensional |
| **ABS:** | Acrylonitrile butadiene styrene |
| **AM:** | Additive manufacturing |
| **ASTM:** | American Society for Testing and Materials International |
| **CAD:** | Computer aided drawing |
| **CAE:** | Computer aided engineering software |
| **CAM:** | Computer aided manufacturing |
| **CFD:** | Computational flow dynamics |
| **CNC:** | Computer numerical controlled |
| **CRPM:** | Centre for Rapid Prototyping and Manufacturing |
| **CSIR:** | Council for Scientific and Industrial Research |
| **CUT:** | Central University of Technology, Free State |
| **DED:** | Directed energy deposition |
| **DMLS:** | Direct metal laser sintering |
| **EBM:** | Electron beam melting |
| **EDM:** | Electric discharge machining |
| **EOS:** | EOS GmbH Electro Optical Systems |
| **FDM:** | Fused deposition modelling |
| **HDPE:** | High-density polyethylene |
| **HTC:** | Heat transfer coefficients |
| **HIPS:** | High impact polystyrene |
| **IM:** | Injection moulding |
| **LDPE:** | Low-density polyethylene |
| **NC:** | Numerical control |
| **PA:** | Polyamide |
| **PC:** | Polycarbonate |
| **PET:** | Polyethylene terephthalate |
| **POM:** | Polyoxymethylene |
| **PP:** | Polypropylene |
| **PS:** | Polystyrene |
| **PLA:** | Polylactic acid |
| **RT:** | Rapid tooling |
| **RTV:** | Room temperature vulcanizing |
| **SA:** | South Africa |
| **SABS:** | South African Bureau of Standards |
| **SLA:** | Stereolithography |
| **SLM:** | Selective laser melting |
| **SLS:** | Selective laser sintering |
| **SPI:** | Society of plastic industry |
| **STL:** | Stereolithography |
| **VESA:** | Motor Vehicle Security Association of South Africa |
| **VSR:** | Stress relief by vibration |
| **VUT:** | Vaal University of Technology |

# 1 INTRODUCTION

## 1.1 Introduction

Product development is essential for progress when representing education, research, invention, management or manufacturing [1]. The risks involved in product development are substantial and a quick response to market demand is vital to be competitive. During the second half of the 20$^{th}$ century, plastics became the most commonly used material in the global economy and the plastic industry has become an important role player in the product development process [2]. The most used moulding process in the plastic industry for repeatable products is the injection moulding (IM) process [3]. Global energy issues have forced industries to adopt measures that will reduce their energy consumption to ensure a sustainable energy future [4]. For this reason, various approaches, methods and techniques are researched and implemented to improve the IM value chain globally.

## 1.2 Mould development

Mould design and manufacturing represent important links in the plastic IM process and value chain, as shown in Figure 1.1 [5]. The largest expense of a new IM product is usually the manufacturing of an injection mould. However, there is a global drive to reduce the cost and lead-times of injection moulds and inserts as well as the improvement of the quality of products produced [6].

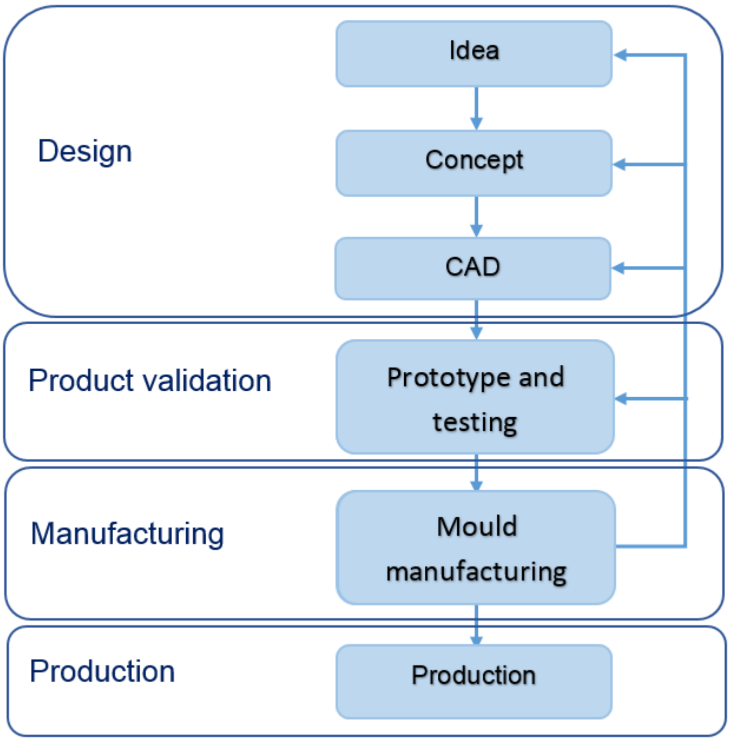



*Figure 1.1: Injection moulding value chain to produce a plastic product [5].*

Plastic injection moulds and mould inserts can either be manufactured using traditional methods (subtractive manufacturing) or through additive manufacturing (AM) methods.

### 1.2.1 Subtractive manufacturing

Injection moulds are mostly manufactured through traditional subtractive manufacturing processes such as Electric Discharge Machining (EDM), Computer Numerical Controlled (CNC) machining, wire EDM or through a combination of these processes. These processes can be time-consuming and expensive due to the intensive labour required [5, 7 & 8]. Figure 1.2 illustrates the subtractive manufacturing processes where a material stock is systematically removed by machining to manufacture a product.

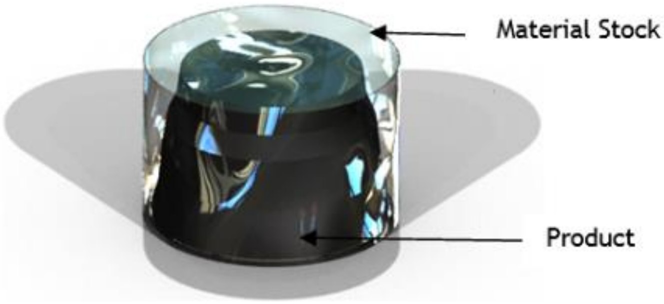
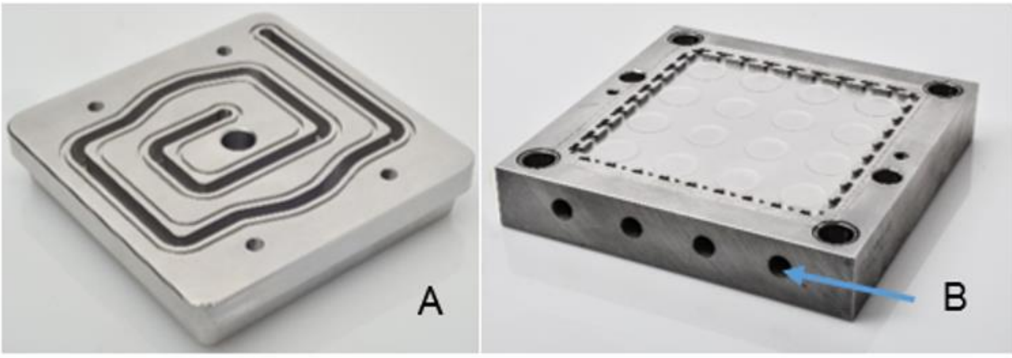



*Figure 1.2: Subtractive manufacturing where the material stock is removed to manufacture a product.*

Other materials, such as aluminium, are often used to manufacture moulds to reduce manufacturing lead-times because aluminium can be machined faster than steel. Aluminium inserts are less durable than steel and are not suited to certain tooling applications such as moulds that require slides. Tool steel cavities are normally the preferred option, due to the longer service life achievable from the moulds [7].

Product geometries and mould cooling systems, functions and performance characteristics are determined by the manufacturing processes used during the manufacturing of a mould. Constraints in conventional manufacturing processes include straight-line drilling and slotting of cooling channels while avoiding mould features such as screw holes and ejector pin holes. Figure 1.3 shows cooling channels machined into one of the surfaces of an insert (Figure 1.3 A) and cooling channels produced through drilling (Figure 1.3 B) while avoiding insert features such as screw and injector pin holes.




A = Slotted cooling channels milled into the insert
B = Straight-line drilled cooling channels into the insert

*Figure 1.3: Cooling channels manufactured using conventional machining methods such as slotting and straight-line drilling.*

### 1.2.2 Additive manufacturing

AM is a process where products are manufactured using a layered technique. Since the commercial introduction of AM in the late 80’s, the technology has become an important part in the product development process chain throughout many industries [9]. AM benefits are well-established [8, 9] and prototype parts can be quickly produced for validation, measurement, and in some cases, actual trials [10]. AM can be a major cost-saver because it allows the designer and manufacturer to see what a part will look like during early development stages allowing design changes or product cancellations when such decisions are least expensive, particularly with highly complex product designs [6, 8 & 10]. Direct Metal Laser Sintering (DMLS) is a process that is suitable to produce high-quality IM tool inserts, prototypes and end products in metal.

The build platform is a tool steel base onto which metal powder is laser melted layer upon layer, as illustrated in Figure 1.4. The tool steel base can also be incorporated into the mould insert design to save additional manufacturing time and costs in removing the AM manufactured insert from the base.

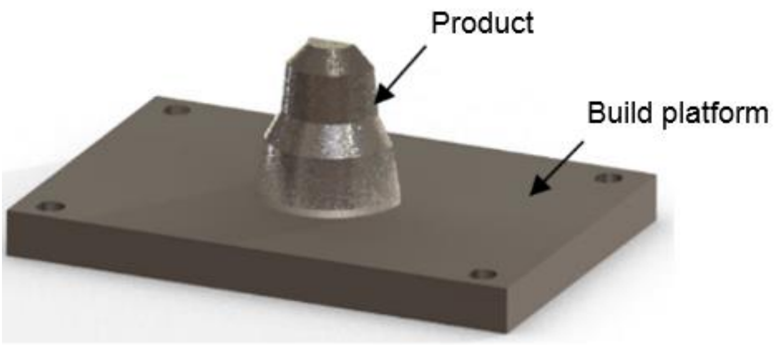



*Figure 1.4: A DMLS product manufactured on a tool steel build platform.*

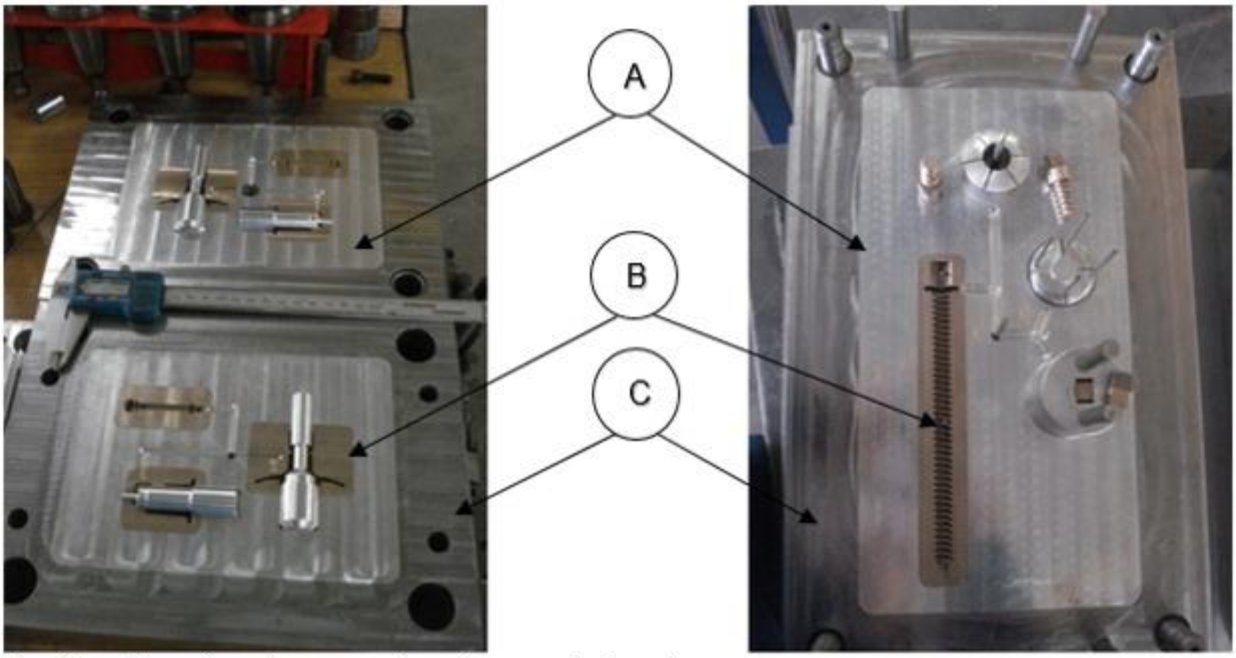
### 1.2.3 Advantages of AM in tooling

Mould inserts consisting of complex geometries that will be time-consuming and difficult to manufacture using conventional processes can be easily produced using AM technologies. Using DMLS Maraging Steel MS1, IM inserts can be manufactured which include complex cooling channels that conforms or fit to the shape of the core or cavity, known as conformal cooling channels [11, 12 & 13].

During the IM cycle, the cooling process can account for up to 70% of the total time taken to produce a product. Traditional methods of creating cooling channels in moulds, such as straight-line drilling and slotting, restrict the manufacturing of cooling channels which can reach critical hot spots. DMLS enables built-in conformal cooling channels that can be optimised to extract heat more rapidly and evenly, allowing mould designers to create more efficient cooling systems for injection moulds [12, 13].

### 1.2.4 Rapid tooling

The demand for faster ways of making prototypes, manufactured from the correct material using the appropriate production method, has led to the development of Rapid Tooling (RT) techniques. RT involves using AM to produce tooling components directly or indirectly. Combining AM and traditional manufacturing techniques to produce tooling, called hybrid tooling, can potentially reduce mould manufacturing lead-times through concurrent manufacturing processes. Examples of hybrid tooling approaches, using materials that are easier to machine (such as aluminum) rather than the tool steels normally used in tooling applications, are shown in Figure 1.5. Complicated mould geometries are produced through AM and inserted into a steel bolster that is manufactured through conventional machining techniques, to create a hybrid IM [2, 10].




A = Aluminium inserts conventionally manufactured
B = AM inserts manufactured by the DMLS process
C = Mild Steel mould frame or "bolster" conventionally manufactured

*Figure 1.5: Rapid tooling moulds used to manufacture different injection-moulded products.*

The potential of RT, as described above, led to tremendous interest in RT solutions for product design and manufacturing. Whether RT is used for prototype tooling, short run tooling, or production tooling, it offers an opportunity to reduce both time and cost of product development [14, 15].

Some of the advantages of existing RT techniques include [5, 6, 7, 14, 15, 16 &17]:

- Shortening of the tooling lead-time.
- Lower cost of tooling (cost is reduced due to the shortened lead-time).
- Functional test of parts in the early design stage is possible. Due to shortened lead-time, many engineers prefer to produce parts for functional tests. Most of the errors are corrected before production commences.
- Automation. Many of the RT processes can build tooling sets 24 hours a day, seven days per week.
- Building multiple cavity/core sets. Additional cavity core sets can be built with a first set at reduced cost.
- Creative design possibilities. The possibilities are not limited to creating a design that is possible with traditional manufacturing techniques.
- Recent advances in materials and AM systems allow DMLS processes to produce tooling inserts suitable for high-volume injection moulding (such as Maraging Steel MS1).

Shortcomings of existing RT techniques include [6, 7, 14, 15, 16 & 17]:

- High material and equipment costs associated with most AM processes.
- Dimensional limitations of the machine build envelope limit the size of inserts that can be manufactured through AM processes.
- Post-processing operations.

Figure 1.6 illustrates how AM technologies have altered the product development cycle to improve the manufacturing lead-time of a new plastic product. Also, mould manufacturing processes are shown to run concurrently or sequentially depending on the need.

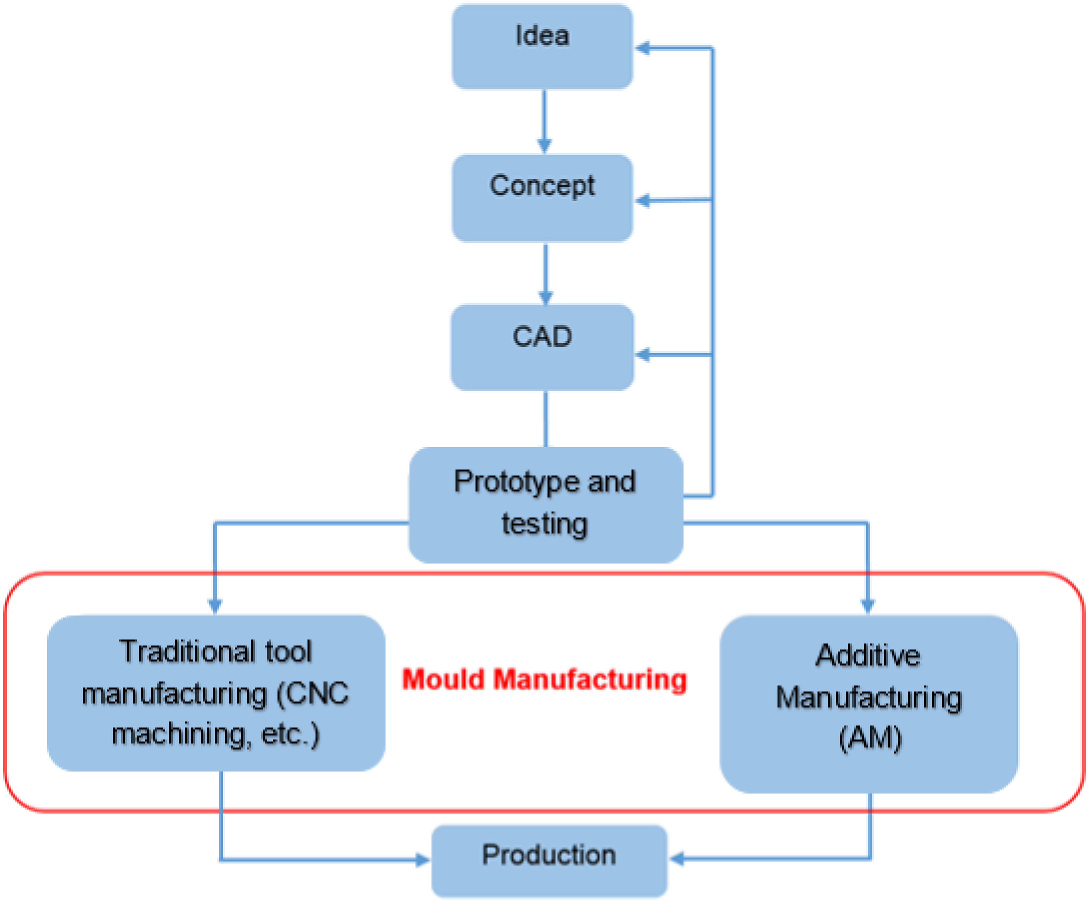



*Figure 1.6: Product development cycle for new products using AM technologies and conventional machining processes.*

## 1.3 Problem statement

Existing techniques used to produce conventional steel tooling for plastic IM are expensive and time-consuming. Limitations of traditional manufacturing processes can constrain design possibilities and the full potential of the IM process will not be achieved.

RT techniques using AM processes, such as DMLS Maraging Steel MS1, can be used to manufacture inserts for the IM process. Although higher manufacturing costs and size limitations are associated with DMLS, this process allows for more design freedom and the creation of complex geometries, such as conformal cooling channels, that can improve the injection moulding value chain.

## 1.4 Aim of study

The aim of this research was to:

- Analyse different cooling channel designs by applying heat transfer principles as well as Computational Flow Dynamic (CFD) simulations to identify the most efficient cooling design for an injection mould.
- Evaluate the differences between tooling inserts produced through AM and conventional manufacturing processes by:
  - Comparing heat transfer capabilities of AM and conventionally manufactured inserts as well as the flow characteristics of the cooling channels using Computer Aided Engineering software (CAE) and CFD software simulations.
  - Comparing manufacturing costs and lead-times of AM and conventionally manufactured inserts.
- Apply results obtained from experimental inserts to an industrial application.

## 1.5 Hypothesis

It is possible to use DMLS Maraging Steel MS1 inserts to improve the injection moulding value chain by creating cost effective and value adding inserts with conformal cooling channels. This technique is likely to reduce mould manufacturing lead-times and costs of plastic injection-moulded products by reducing IM cycle times.

## 1.6 Objectives

The objectives of this research study were as follows:

- Conduct a literature review on product development using thermoplastic materials, the IM process and RT techniques using AM.
- Investigate the influence of different layouts of conformal cooling channels inside a DMLS insert.
- Determine the most efficient conformal cooling channel layout using simulation software such ANSYS® CFD and SIGMASOFT® virtual injection moulding software.
- Use simulation software to compare a DMLS insert with a conventionally manufactured insert.

- Compare the simulated results with experimental values during actual IM trials.
- Conduct manufacturing time and cost comparisons between Maraging Steel MS1 inserts and conformal cooling channels and conventionally manufactured inserts.

## 1.7 Research Methodology

The research methodology can be summarised as follow:

- Conduct a literature review on polymer consumption, the IM process, manufacturing through IM as well as existing AM processes and RT techniques.
- Design inserts for an IM product application consisting of different conformal cooling channel designs. Through CAE and CFD simulations, the insert with the most efficient conformal cooling channel design will be identified and used during further comparisons.
- The most efficient conformal cooling design will be compared to a conventionally manufactured insert for the same IM product. Through CAE and CFD simulations, warpage, quality of products produced, cooling times and cycle times of the inserts will be determined.
- The insert with the conformal cooling channel design will be manufactured through an AM process and placed inside an IM tool for actual trials. The same procedure will be followed for an insert manufactured through conventional manufacturing techniques. The data acquired from the actual IM trials will be compared to the simulated results. Temperature probes will be inserted into the inserts to compare the actual temperatures inside the insert with the simulated values.
- Results/data obtained from the simulations and comparisons will be applied to an industrial IM product application. CAE and CFD simulations will be used to optimise the conformal cooling channel design of the insert. Manufacturing lead-times and cost comparisons between the AM insert and a similar insert manufactured conventionally will be conducted. Cycle times, warpage and quality of products produced through an AM insert will be simulated and compared to a conventionally manufactured insert. Manufacturing lead-times and cost comparison between the AM insert and the conventionally manufactured insert will be conducted.

Figure 1.7 illustrates the research methodology graphically. Three aspects of the IM value chain, (design, mould manufacturing and production) were evaluated during the four phases.

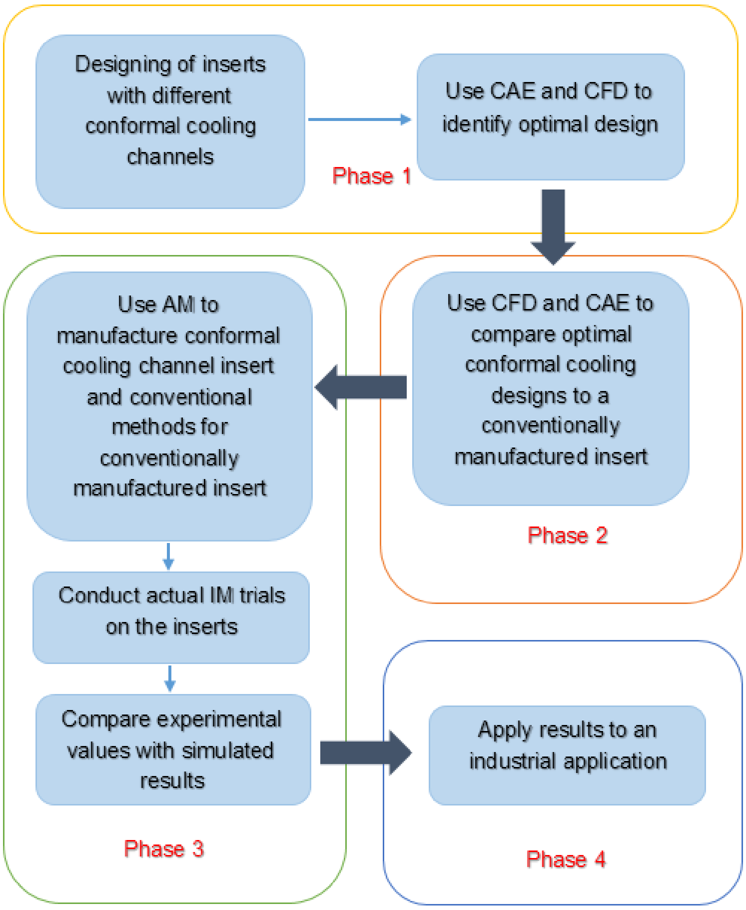



*Figure 1.7: Graphical representation of research methodology.*

## 1.8 Limitations of study

The high cost of DMLS Maraging Steel MS1 inserts limited the insert sizes and design interactions during conformal cooling channel design development for the AM inserts during actual IM trials.

## 1.9 Original contribution to the field of study

This research study investigated whether a DMLS insert with conformal cooling channels justifies the higher cost as compared to a conventionally manufactured insert, using CAE and CFD simulation software. By using simulation software, the cooling performance of different conformal cooling channel designs can be quantified and compared to a conventionally manufactured insert. This information can be used to obtain the most effective conformal cooling channel design before major capital is invested to produce an AM insert with conformal cooling for the IM process.

## 1.10 Structure and layout of dissertation

**Chapter 1** briefly discusses product development as well as why IM is an important part thereof. Also, the problem statement, hypothesis, aim of the study, methodology and limitations of the study are outlined.

**Chapter 2** links global and local plastic consumption with the different processes used to produce plastic products. This chapter consists of a literature study on injection moulds and the IM process. Also, the manufacturing process steps are explained during the development of an IM.

**Chapter 3** introduces AM and briefly explains the different AM processes, attributes and workflow. RT techniques are explained, and the theory of IM production volumes and their classification are discussed. Maraging Steel MS1 is introduced as a DMLS material suitable for high-volume IM applications. Thereafter, conduction heat transfer and its role in the design of an IM cooling system is briefly explained.

**Chapter 4** gives an account of the experimental work done on the design, manufacturing and physical IM trials during the development of an experimental IM, in a comparative manner.

**Chapter 5** describes an RT for an industrial application and analyses and compares the RT with a similar conventional design.

**Chapter 6** concludes the work done with an overall discussion and recommendations.

# 2 PRODUCT DEVELOPMENT

## 2.1 Introduction

Product development is a process of design, creation and marketing of new products for potential customers. The complete process of developing new products is filled with uncertainties and the risks involved are significant [1, 18]. The drive behind a new product's development can be due to a decrease in sales of an existing product line, the end of a product's life cycle or that a competitor in the marketplace offers a better alternative. Constant product development is essential for companies striving to keep up with changes and trends in the marketplace to ensure their future profitability and success [19, 20].

To ensure the survival of a company, the investment in new product development needs to be well-managed and planned, as shown in Figure 2.1 [6]. A company-wide commitment to create products which will fulfil customer needs or characteristics results in a competitive product development strategy [20]. As modern products' lifecycles are decreasing, it is important to introduce new products quicker and more efficiently to the market. For these reasons, design and development teams are interested in technologies that shorten lead-times as well as the time to market [1, 18 & 21].

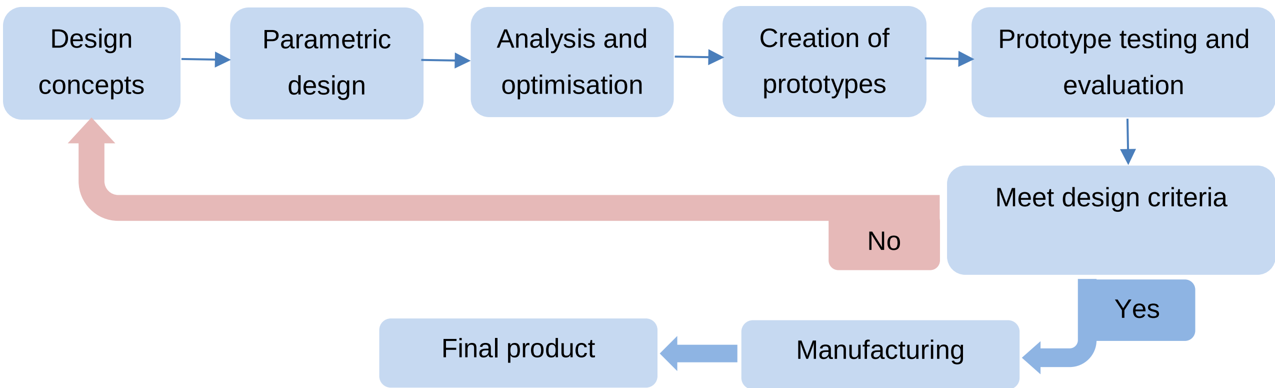



*Figure 2.1: Steps involved in the product development cycle.*

Manufacturing techniques (such as AM and RT) can improve the traditional product development cycle by reducing the time required to create prototypes and manufacture tooling. This can be done without the constraints associated with traditional manufacturing techniques [6].

Due to thermoplastics' relative low cost, versatility, and ease of manufacture, their usage in new product developments is increasing [1, 11 & 22].

## 2.2 Global plastics consumption

According to the association of plastics manufacturers in Europe, (the European Plastics Converters (EuPC)), during 2017 the plastic industry accounted for an estimated 1.5 million jobs with a combined turnover of more than 355 billion Euro in the European Union [22]. EuPC also stated that plastics had become one of the most versatile and most commonly used materials in the global economy during the second half of the 20$^{th}$ century [22, 23]. The plastics industry has benefited from 50 years of progression with a year-on-year growth of 8.6% from 1950 to 2015 [24]. Production increased from 1.5 million tonnes during the 1950's to about 348 million tonnes in 2017. Figure 2.2 shows the continuous growth in the global and European plastics industry during the past 50 years [22, 24].

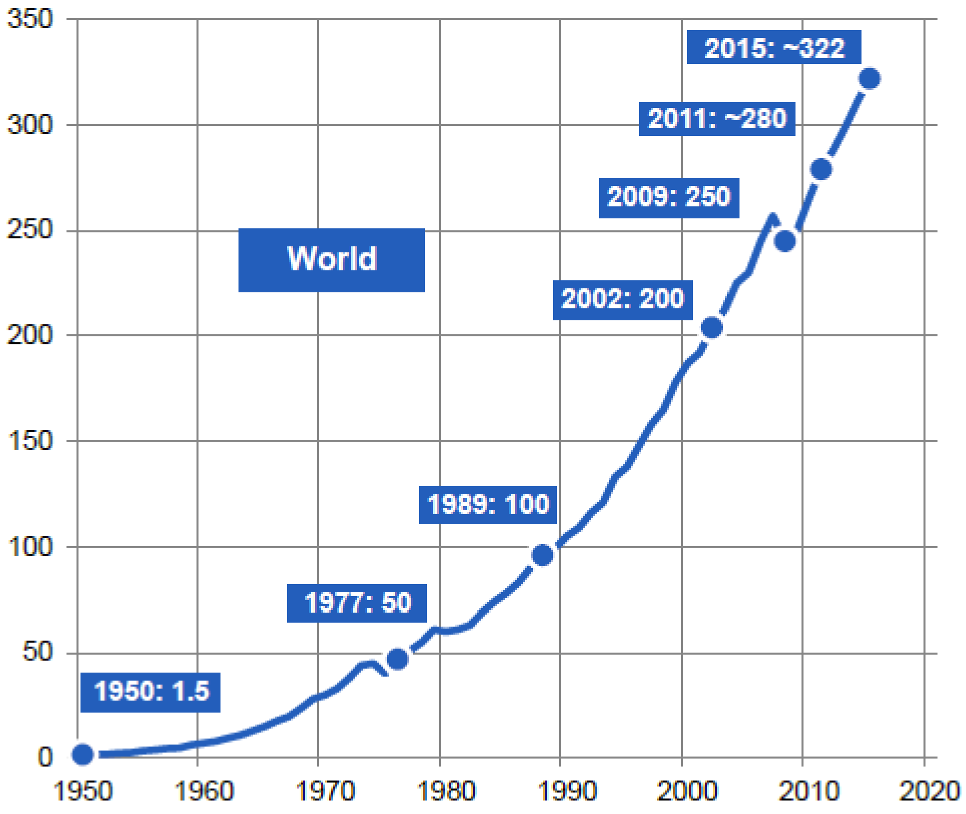



*Figure 2.2: World and European growth in plastics production from 1950 till 2015 [24].*

## 2.3 Plastic consumption in South Africa

Plastic manufacturing in South Africa (SA) contributes 1.9% to the gross domestic product, while the plastic industry contributes 16.5% to the overall manufacturing industry in SA. The plastic manufacturing industry in SA comprises ± 1 800 companies and employs over 60 000 people. This industry was defined as a priority sector by the South African government to grow and expand, according to Plastics SA's annual review of 2015/2016 [25]. Plastic material converted during 2015 was approximately 1.5 million tons and about 55% of all plastic production was used by the packaging industry. The combined turnover of the SA plastics industry is estimated to be between R45 & R53 billion annually. Annual consumption of plastic materials in South Africa from 2005 to 2016 is illustrated in Figure *2.3* [25].

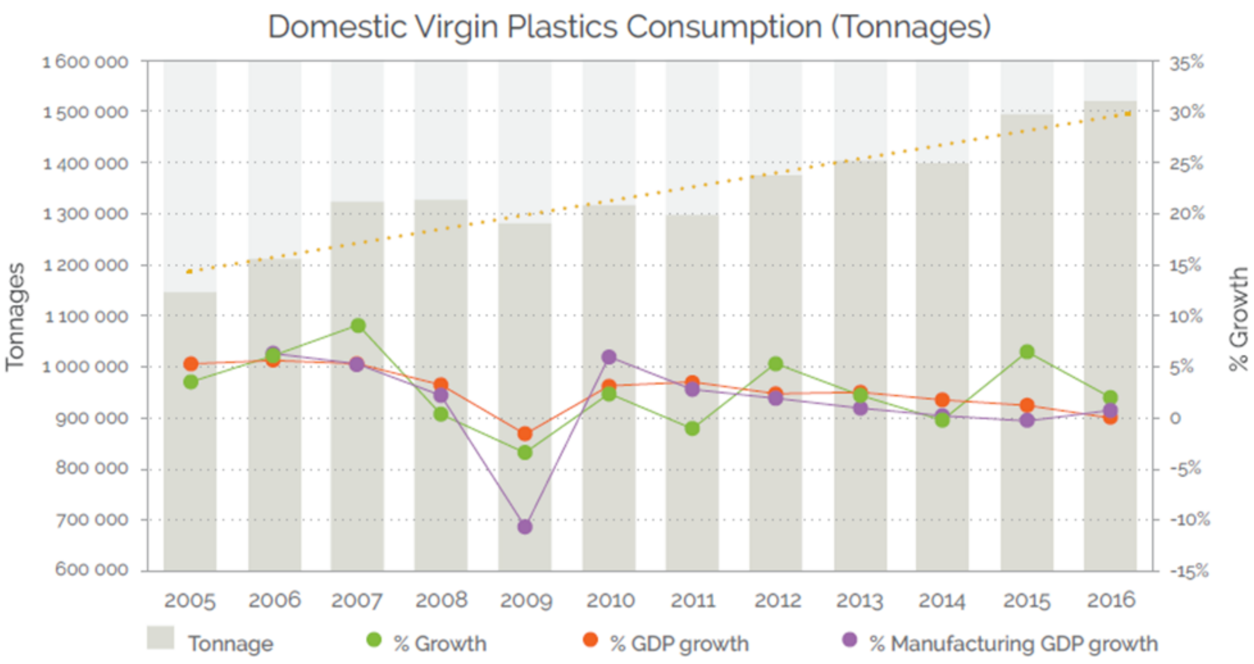



*Figure 2.3: South African plastic material consumption between 2005 and 2016 [25].*

Of the approximate 1.49 million tons of the plastic material that entered the South African market in 2015, more than 50% was used for packaging applications and approximately 13% for construction, followed by agriculture, electronic, automotive/transport and engineering applications, as shown in Figure 2.4 [25].

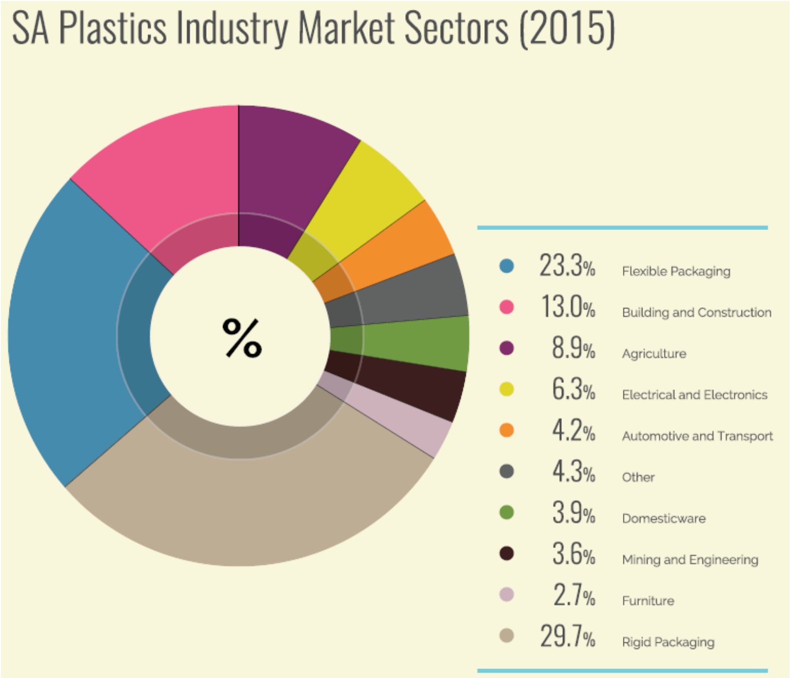



*Figure 2.4: South African plastic industry market sector during 2015 [25].*

Figure 2.5 shows that 36% of all plastic material processed in SA was through the IM process. Nearly all mass-produced plastic products (thermoset and thermoplastic polymers) are formed using dies and moulds. It is one of the most popular methods used to produce complex products in large quantities [11, 25]. Thermoplastics differ from thermosetting polymers that form irreversible chemical bonds during their curing process. In contrast, thermoplastic material becomes mouldable or pliable above specific temperatures and solidifies upon cooling. Plastic injection-moulded products, typically associated with thermoplastic polymers, can be found everywhere, making IM one of the most important processes used in the manufacturing of plastic products. Thermoplastic IM products are used in a vast range of industries such as the construction, automotive, aerospace, machine building, furniture, toy, packaging and medical industries [11, 22 & 23].

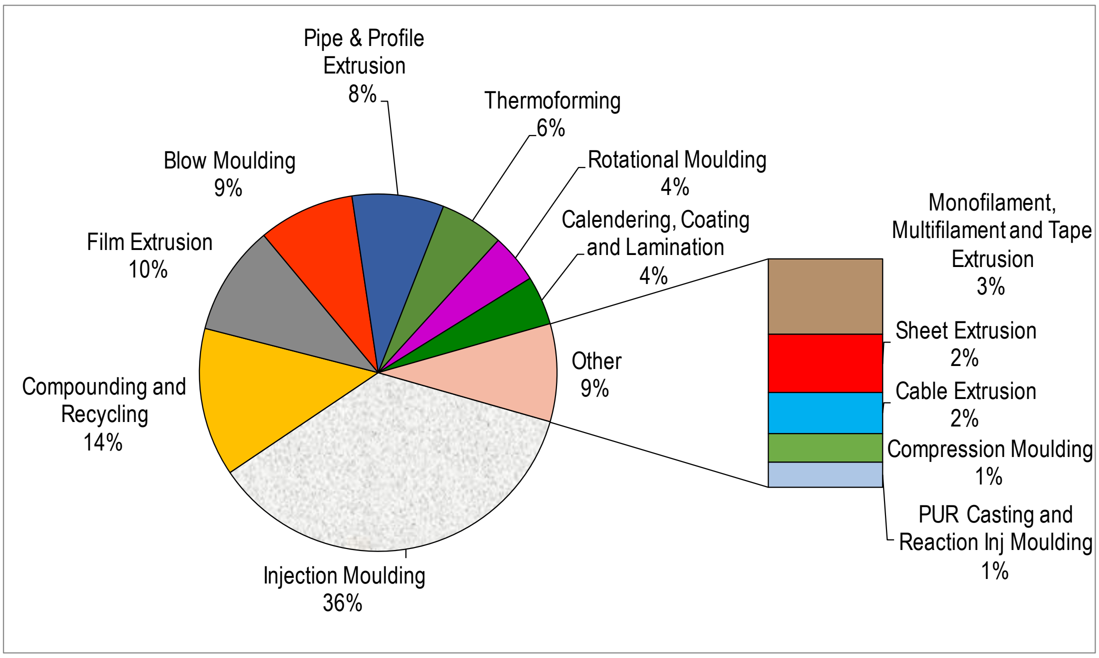



*Figure 2.5: Different methods of polymer processing in South Africa [26].*

## 2.4 Development of a thermoplastic injection-moulded product

The development process of an IM product requires complete and thorough knowledge of all the end-use requirements and specifications of the customer [27]. In order to successfully develop a thermoplastic IM product, the following need to be considered:

- **Uniform wall thickness.** The product should be designed with a uniform wall thickness. This will minimise residual stress, warping, volumetric shrinkage of the material, and it will also improve the cycle time [28, 29].
- **Corner radii.** All corners should have radii to avoid excessive stress concentrations. All of the features, such as ribs, bosses and the shut-offs where the mould seals, should have radii in order to reduce stresses. Sharp corners can lead to unexpected part failure and should be avoided [30, 31].
- **Ribs and gussets.** Ribs and gussets are used in regions to increase the structural integrity of the product where increased stiffness is required. Internal ribs should be placed in areas of stress instead of increasing the product's wall thickness. Avoid excessively thick, tall, thin and sharp cornered ribs and gussets where possible [29, 30].

- **Draft angles.** Draft angles assist in the removal of the product from the mould. Without the appropriate draft angle, parts may become trapped inside the cavity while the mould is in production and damage to the mould may occur. Draft angles are mostly between 1° and 2° depending on the material, geometry of the product and the desired surface finish [29, 30].
- **Undercuts.** Undercuts are features in the mould that prevent the manufactured product from being ejected from the mould or prevent the mould from opening. Undercuts can increase the cost and complexity of the mould because they will essentially require additional mechanisms to eject the part from the mould, for example, clip features [29, 30].
- **Surface finish.** Most thermoplastic part designs need a detailed surface finish or texture. These features can potentially increase the cost of the mould. Highly polished moulds require many hours of polishing to achieve the required finish and can be exponentially more expensive than the same mould with a rougher finish. Textured moulds can be very difficult and time-consuming to manufacture and may require expensive equipment and processes to achieve the required texture [30, 31].

## 2.5 Injection moulding process

The IM process is used to manufacture large quantities of products and in most circumstances IM products do not require any post-processing operations. Heated thermoplastic material (typically between 150 °C and 300 °C) in a malleable state is injected into a mould where it solidifies to the shape of the mould when cooled [11].

The basic IM cycle, as shown in Figure 2.6, consists of [32, 33 & 34]:

- Closing of the mould halves. The mould closes and is held together under pressure.
- Filling of the mould. Molten thermoplastic is injected into the mould under pressure to take the shape of the mould.
- Melt packing. Pressure is applied to the molten thermoplastic to ensure that all the cavities are filled to the desired density.
- Solidification of product. For the duration of the moulding cycle, water-cooling channels assist in cooling the mould and thermoplastic material until it solidifies.
- Ejection stage. The moulding cycle is completed when the mould opens and the solidified product is ejected.

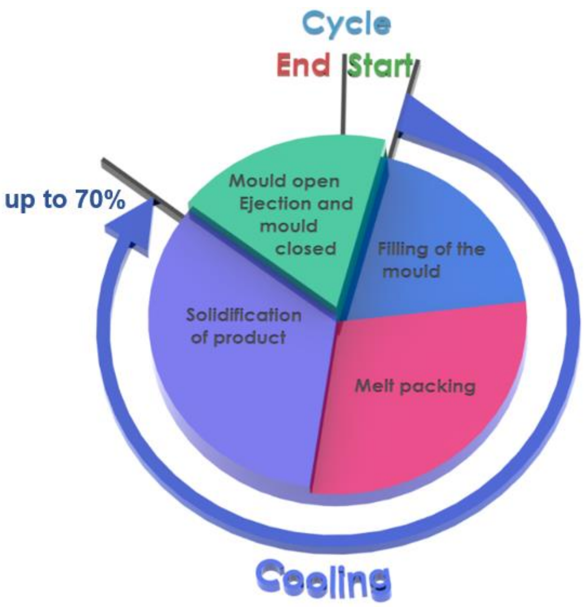



*Figure 2.6: Injection moulding cycle indicating the time taken for the cooling process.*

### 2.5.1 Injection moulding machines

IM machines are designed to process thermoplastic materials and consist of three elementary units, as shown in Figure 2.7 [11, 35]:

- **Plasticising or injection unit.** Melting of the raw thermoplastic material and injection into a mould under pressure. The plasticising unit consists of:
  - A barrel which is heated by electrical heater bands or a heating medium such as oil.
  - A reciprocating screw that can rotate and act as a plunger.
  - Feed hopper that delivers the raw material into the barrel.
- **Clamping unit.** The mould halves that are mounted onto the machine's platens are clamped together by the clamping unit. Its function is to keep the mould closed under the injection pressures of the molten thermoplastic [11, 35].
- **Mechanical drives and control units.** Hydraulics are mostly used in the clamping of an injection mould. It consists of a pump that delivers pressure to a network of pipes, valves and cylinders, which is controlled and regulated by the control unit [11, 35].

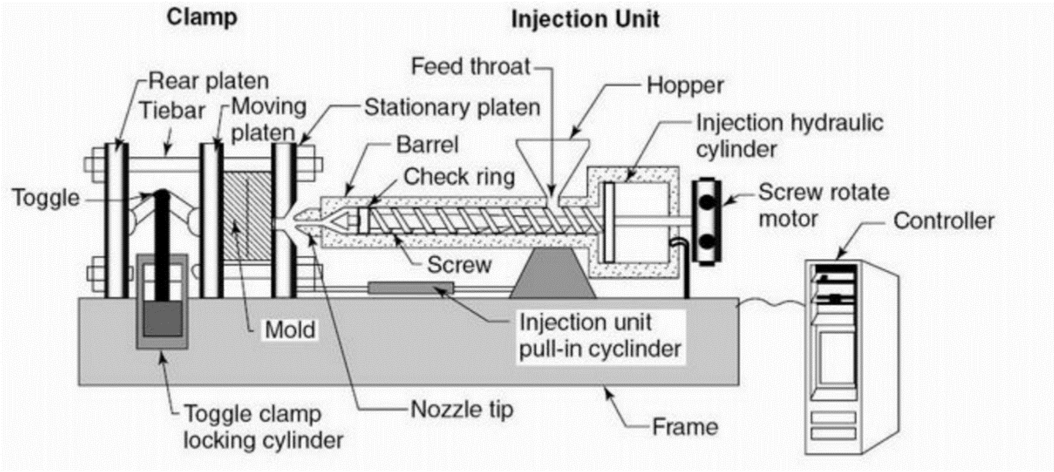



*Figure 2.7: A toggle clamp injection moulding machine displaying the different components [35].*

### 2.5.2 Injection mould

The thermoplastic injection mould is the most important element of the IM process. An IM generally consists of two halves, called the cavity and core. The cavity will normally form the external surfaces and the core the internal surfaces of the manufactured product [36]. Typically in a standard IM, the core and cavity will separate when the mould opens after the injected thermoplastic has been solidified. Its primary function is to convert raw material into a formed product. Cooling solidifies the molten material until it is rigid enough to be ejected from the mould [29, 36]. Figure 2.8 shows a standard two-plate mould base with two cavities [29, 37].

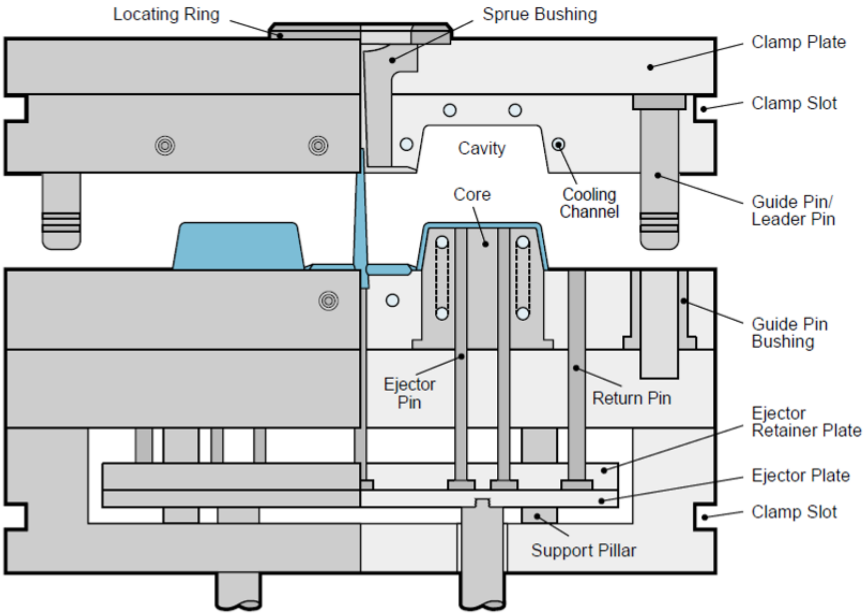



*Figure 2.8: Standard two-plate mould base with two cavities [37].*

The designing of a mould, manufacturing and the workmanship mainly determine the quality of the product and its production cost. During the design of an IM, the following need to be considered [36, 37 & 38]:

- Number of cavities in the mould. This determines the number of products that can be produced per cycle.
- Material used to manufacture the mould, e.g., steel, beryllium copper, tool steel, stainless steel, hardened steel. Mould material determines the cost, durability and function for which the mould is designed.
- Parting line, e.g., regular, irregular, two-plate mould, and three-plate mould. The parting line is determined by the product geometry and function.
- Method of manufacturing, e.g., machining, casting, electroplating, EDM machining or AM. The customer’s requirements and the product’s form and function will determine the methods used for mould manufacturing.
- Gating type and position, e.g., edge, restricted, submarine, sprue, ring, tab, flash or fan. Gating can have an impact on the cost per product, appearance of the product and the ability to manufacture a product.

- Runner system, e.g., hot runner, insulated runner or cold sprue. The runner system supplies the material to the mould cavity/cavities and is dependent on the product layout and gating required to produce the product.
- Method of ejection, e.g., knockout pins, stripper ring, stripper plate, unscrewing cam, removable insert, hydraulic core pull, and pneumatic core pull. Different methods can be used to eject a product after the thermoplastic material has been solidified inside the mould cavity. The method of ejection is dependent on several factors such as the material used for the product, the geometry of the product, appearance of the product, etc.

## 2.6 Manufacturing of injection moulds

When the mould design is completed the manufacturing process can commence. This involves numerous steps, most of which requires meticulous work of highly skilled mould makers and equipment. Manufacturing of an IM is a time-consuming process that requires skill, knowledge and attention to detail [37, 38].

The mould manufacturing process starts with preparing the mould material using machine tools, such as milling machines or lathes, to comply with the design specifications of the mould. Computer Aided Drawing (CAD) data of the mould are converted into a Computer Aided Manufacturing (CAM) program that generates numeric codes using algorithms for each of the mould components. This code describes tool paths for a computer numerical control (CNC) machine to follow by means of a Cartesian coordinates system. The prepared mould materials are machined with cutting tools to the predetermined design [37]. Part by part, all the mould components are produced using CNC and conventional manufacturing machines. Where features cannot be created through cutting tools, an EDM machine is used, either through the spark erosion or wire erosion process. When all the components of the mould are manufactured, the mould is assembled [35].

Venting channels can be added if necessary. This is done by grinding shallow channels on the shut-off surface or by allowing air or gas to escape through pins installed in the mould. Entrapped air or gas produced during the IM process can result in undesired burn marks on the product, or the mould cavity may not fill due to gas compression. Texturing or polishing of the mould cavities can be done to obtain the desired effect on the end product. Heat treatment of components can improve the durability of the mould, if required. After the manufacturing process, the mould is mounted into an IM machine where it is possible to produce products at a high production rate [37].

Improper cooling in an IM not only affects the cost to produce products but can also result in product defects such as warpage. Warpage is a defect caused by inconsistent internal stresses within the product due to uneven cooling throughout the product [33]. Cooling channels that are designed to conform to the shape of the product are also known as conformal cooling channels. These cooling channel designs can result in geometries that are not possible to produce using conventional mould manufacturing techniques. Modern mould manufacturing techniques, such as AM, make it possible to produce these complex components with conformal cooling structures [33].

## 2.7 Conclusion

This chapter presented a global drive to reduce the cost and lead-times of tooling while simultaneously improving the quality of products produced. This stimulates research to develop new technologies and processes that can improve cost, lead-times and product quality [11]. The rate at which IM products can be produced are determined by the rate that the thermoplastic material can be solidified inside the IM [32]. The time to cool down and solidify the product can take up to 70% of the total time to produce a product, as illustrated in Figure 2.6. If the heat transfer efficiency is increased within the IM process, then the rate of production will increase and thereby reduce the product manufacturing costs [32].

# 3 ADDITIVE MANUFACTURING AND RAPID TOOLING

## 3.1 Introduction

From the earliest inventions dating back to the 1960s, the first AM process, stereolithography, was commercialised in 1987 [39, 40]. Since those early days, AM has experienced continuous and increasing growth, establishing itself as an important manufacturing process [32]. The term AM was chosen by the American Society for Testing and Materials International (ASTM) committee because it clearly differentiates between the traditionally used manufacturing techniques [40, 41]. Unlike traditional or subtractive manufacturing processes, where material is removed by machining or drilling, AM consists of consecutive layers of material added upon each other to create the desired shape. AM processes were first used to rapidly produce physical prototypes using polymers and resins. With the recent advances in AM technology, it is not only used to produce functional prototypes but is now also able to produce end-use products [42, 43 & 44]. South Africa acquired their first AM system during 1991. Since then, industry awareness has grown with the help of application-specific research programmes driven by the Council for Scientific and Industrial Research (CSIR) and universities [45].

## 3.2 Additive manufacturing technologies

Several different AM processes are available, each with an appropriate material to suit the application it is intended for. Table 3.1 summarises the AM processes using the ASTM classification system [10, 40 & 46]. It also indicates the different technologies and materials that can be processed for each category.

*Table 3.1: Classification of AM processes by ASTM international [10, 40 & 46].*

| Categories | Technologies | Process Materials | Power source | Characteristics |
|---|---|---|---|---|
| **Binder jetting** | Indirect inkjet printing | Polymer powder, Ceramic powder, Metal powder, Plaster, Resin | Thermal energy | • Full-colour objects<br>• Require infiltration during post-processing<br>• Wide material selection<br>• High porosities on components |
| **Directed energy deposition** | Laser Engineered Net Shaping (LENS)<br>Electronic Beam Welding | Metal powder,<br>Metal wire,<br>Molten metal | Laser beam | • Repair damaged/ worn parts<br>• Functional material<br>• Require post-processing |
| **Material extrusion** | Fused Deposition Modelling (FDM)<br>Contour crafting | Thermoplastics, Ceramic slurries, Metal pastes | Thermal energy | • Cost effective<br>• Multi materials<br>• Limited part resolution<br>• Poor surface finish |
| **Material jetting** | Polyjet/Inkjet printing | Photopolymer, Wax | Thermal energy, | • Multi-materials |

| | | | | |
|---|---|---|---|---|
| | | | Photo-curing | • High surface finish<br>• Low-strength components |
| **Powder bed fusion** | Selective Laser Sintering (SLS)<br><br>Direct Metal Laser Sintering (DMLS)<br><br>Selective Laser Melting (SLM)<br><br>Electron Beam Melting (EBM) | Polymer powders,<br><br>Atomised metal powders,<br><br>Ceramic powder | High-power laser beam,<br><br>Electron beam | • High accuracy<br>• Fully dense parts<br>• High specific strength and stiffness<br>• Extensive powder handling<br>• Support structures necessary |
| **Sheet lamination** | Laminated Object Manufacturing (LOM) | Plastic film,<br><br>Metallic sheet,<br><br>Ceramic tape | Laser beam | • High surface finish<br>• Low costs; materials, machine, process<br>• De- cubing issues |
| **Vat photopolymer-isation** | Stereolithography | Photopolymers, Ceramics | Ultraviolet laser | • High cost of materials and supplies<br>• Process issues due to over-curing |

### 3.2.1 Binder jetting

In the binder jetting process, a liquid bonding agent is selectively deposited onto a bed of powder. Once the bonding agent droplets have infiltrated the powder surface, a new layer of powder is deposited through a mechanical mechanism. This process is repeated to produce a bonded powder component [40, 46]. Components produced by binder jetting requires an infiltration post-process to obtain sufficient strength.

### 3.2.2 Directed energy deposition

Directed energy deposition (DED) is an AM process in which material in the form of metal wire or powder is fed directly into a focused energy source as the molten material is being deposited [40]. The energy source used to fully melt the material is either an electron beam or a laser beam. The DED process can achieve a theoretical part density of up to 99.9% and parts built by this process usually show 30% higher strengths than parts produced through metal casting [46].

### 3.2.3 Material extrusion

The material extrusion AM process deposits material selectively through a nozzle or an orifice onto a surface. Fused deposition modelling (FDM) is an AM material extrusion process that creates three-dimensional objects by mechanically layering a wide variety of extruded engineering plastics such as ABS, PLA, etc. [47]. The inexpensive, reliable and easy-to-operate FDM process has made this AM technology commonly recognised and is used by many consumers, industry and academia. Research and development sectors continuously develop new materials and improve on the AM process. Material extrusion is used increasingly for fabricating functional parts and prototypes in engineering applications [10].

### 3.2.4 Material jetting

Material jetting is like inkjet technology that transfers ink droplets to paper drop by drop. In the material jetting AM process, photopolymer or wax droplets are directly deposited onto a substrate layer by layer and thereafter heated or photo cured. The applied heat or photo curing causes the jetted droplets to change phase, creating the component.

### 3.2.5 Powder bed fusion

Powder bed processes selectively join thin layers of powder using an energy source such as a laser or electron beam. Selective Laser Sintering (SLS), Direct Metal Laser Sintering (DMLS), Selective Laser Melting (SLM) and Electron Beam Melting (EBM) are the most popular techniques used in the powder bed fusion AM processes, using materials such as polymers or metals. Figure 3.1 below illustrates the manufacturing procedure of the powder bed fusion process.

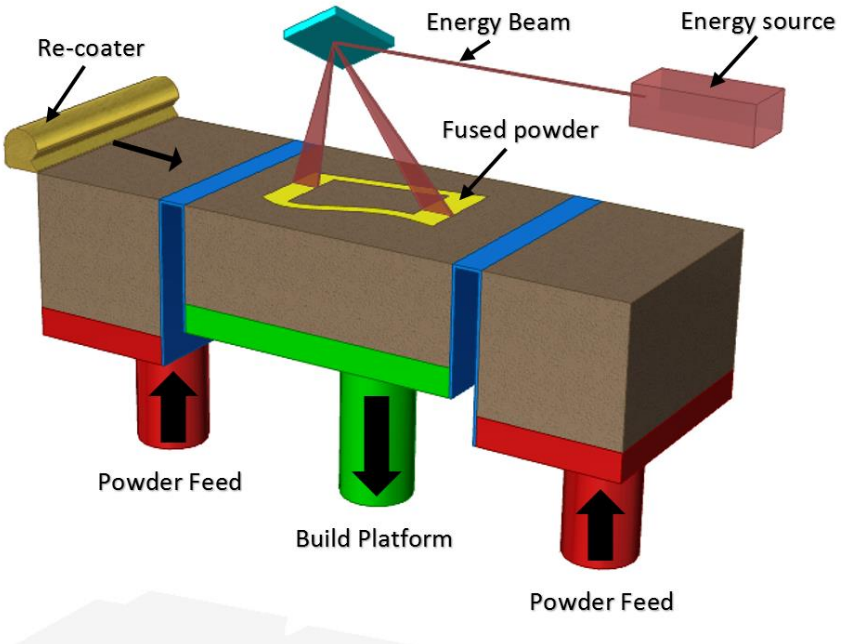



*Figure 3.1: Powder bed fusion process [40].*

Product data created by CAD software are sliced into layers by dedicated slicing software such as EOS RP$^{TM}$. This software generates tool paths for the energy beam to fuse the powder particles together. A mechanism called a re-coater is used to deposit powder on top of each scanned region, allowing the part to be manufactured layer by layer. This process is repeated until the product is completed [40, 41].

### 3.2.6 Sheet lamination

Sheet lamination is an AM process in which sheets of material are bonded together to form an object. With relatively low machine-, process- and material costs, sturdy components with minimal internal tension can be produced through the sheet lamination AM process [40].

### 3.2.7 Vat photopolymerisation

In the vat photopolymerisation AM process, a photopolymer liquid in a container is selectively cured through light-activated polymerisation. The stereolithography (SLA) process uses an ultraviolet laser to selectively polymerise ultraviolet curable resins in a layered method to produce a three-dimensional component. High costs of photopolymer materials and supplies, as well as process errors due to over-curing, are some disadvantages of the vat photopolymerisation process [40].

## 3.3 AM workflow

The creation of an AM component from CAD data consists of three phases, as shown in Figure 3.2. The three phases consist of pre-processing followed by building and post-processing. The CAD data of the component to be created are converted to a Stereolithography (STL) file format. The STL file converts the surface geometry of the CAD into a triangulated surface which does not include features of the model such as texture or colour. Thereafter, the STL file is sliced into constant layers with a constant thickness. The sliced data set is transferred to an AM system where the component is produced, followed by post-processing. Depending upon the AM process, post-processing involves cleaning, infiltration, machining, heat-treatment or curing [10, 40].

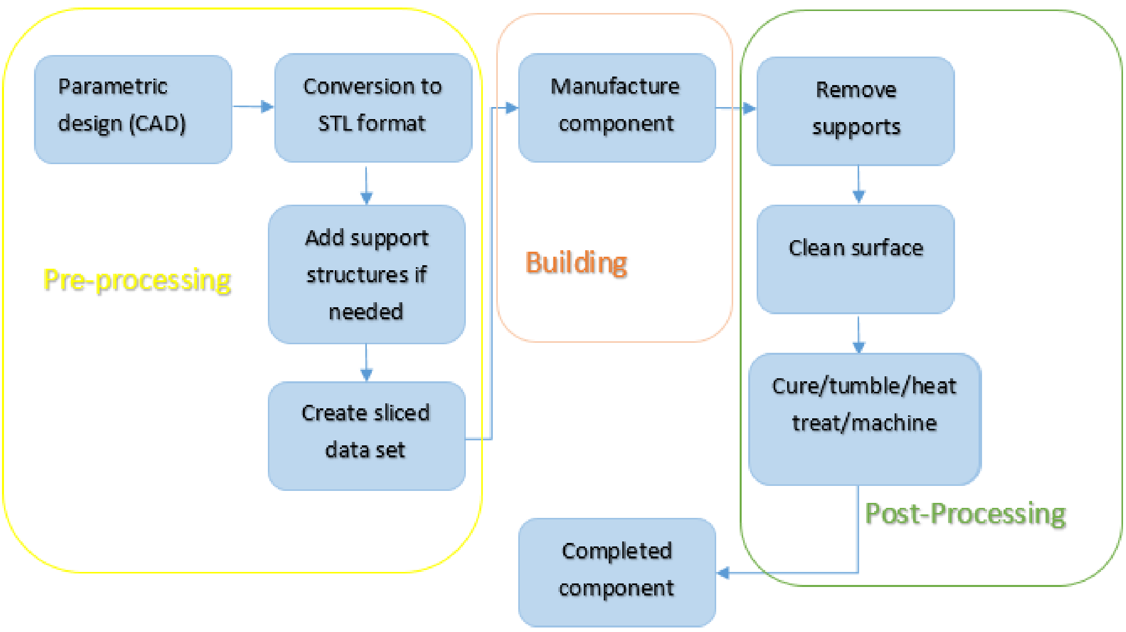



Figure 3.2: AM work flow to create an AM component from CAD data [10].

## 3.4 AM advantages

Because the AM process produces components directly from CAD data, it is possible to create complex geometries that are normally difficult or even impossible to produce using traditional manufacturing or mould-based manufacturing methods [48]. The cost and time to produce a complex part is similar as that of a less complex part with the same dimensions using AM technologies [8, 10 & 49].

The benefits of AM are well-established and include unique capabilities such as [10, 40]:

- **Design flexibility.** A layered fabrication approach enables the creation of complex geometrical shapes in contrast with traditional manufacturing processes with constraints, such as the need for tooling, fixtures, patterns, etc., when fabricating complex geometries.
- **Cost of complexity.** Geometrical complexity comes at no additional cost when employing AM when compared to traditional manufacturing techniques such as IM where the cost of the mould has a relationship to the complexity of the component produced by it. Product complexities that are possible to produce through AM include:
  - Variable thicknesses, undercuts and deep channels in product features.
  - Abnormally-shaped holes, twisted shapes, lattices, internal structures and topologically optimised organic structures in geometries.
  - No need for assemblage. AM processes can create geometries that would otherwise require assembly of multiple components produced by traditional techniques [8].
- **Prototype parts can be produced quickly** for validation, measurement and actual trials. The AM process can be a major cost-saver, allowing the designer or manufacturer to see what a product will look like during early development stages. AM also allows for highly complex designs to be produced and rapid design changes to be implemented during the development stage [40].

When conventional mould manufacturing methods are used, frequent changes of a product or multiple revisions thereof are not always possible or cost effective and should be avoided. Contrary to conventional manufacturing methods, AM can reproduce 3D objects efficiently without additional time or costs, by only changing the design.

## 3.5 AM disadvantages

One of the shortcomings of AM is the high raw material cost which results in a higher unit cost of the prototype or component. Another disadvantage of a prototype produced through AM is that the mechanical properties of the prototype do not correspond to a product manufactured using conventional manufacturing processes (i.e. forming, IM, etc.) [10, 40].

There is a need in the industry to produce representative prototypes that are manufactured in the actual production material using the final production process planned to manufacture the component, such as IM. These representative prototypes, manufactured in the correct material are required for testing purposes such as SABS, VESA, or clinical trials. Using AM to produce components for tooling enables the user to produce end products through the correct process in the required material [18]. This method is called rapid tooling (RT).

## 3.6 Rapid tooling

RT techniques were developed to produce prototypes or products faster and more cost effectively by reducing lengthy mould-manufacturing lead-times and costs. Cost as well as time savings of 50% are possible when RT techniques are used [18]. The possibility of significant savings as well as the potential for faster response to changing market demands makes RT technologies an effective means in product manufacturing [10, 50].

RT using AM technologies can produce IM inserts comprising complex geometries that are difficult or even impossible to manufacture through conventional tooling methods. This can be done in parallel with conventional tooling methods used for the manufacturing of less complex geometries. Also, RT technologies can be beneficial to manufacturing processes that use plastics, metals, ceramics and other materials [6]. For plastic processing, these processes include IM, compression moulding, vacuum casting or forming, blow moulding, extrusion and processes such as glass-reinforced plastic layup. For metal processing, these processes include metal casting patterns or moulds (sand- and investment casting), forming dies (sheet metal), die- casting and forging processes (hot and cold forging). Processing of ceramic materials include processes such as powder compaction (isostatic forming as well as in presses) and slip casting [6, 50]. RT methods can be classified in three different categories, as shown in Figure 3.3 [50].

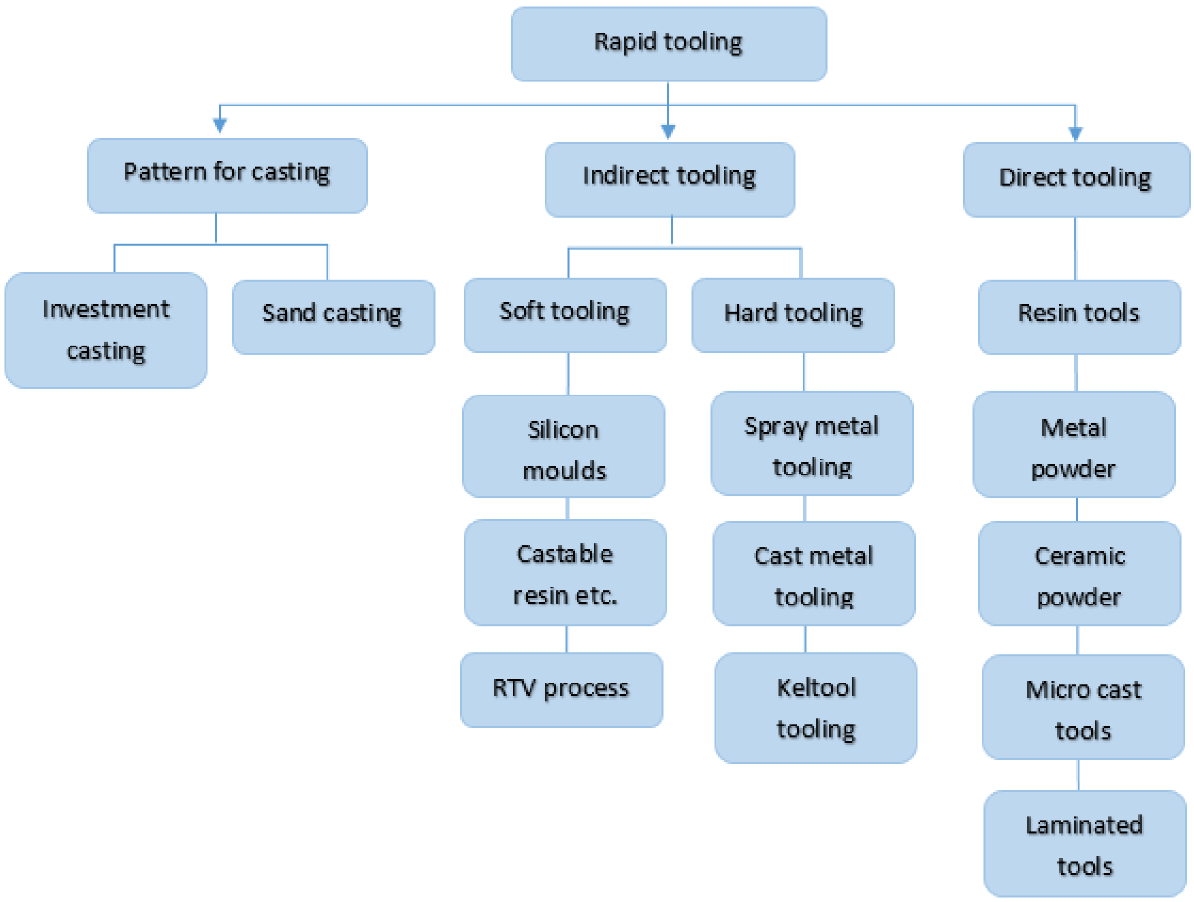



*Figure 3.3: Classification of different RT methods [50].*

### 3.6.1 Patterns for casting

Making use of AM technologies to produce parts (patterns or mould components for metal casting) without the use of tooling promotes the rapid manufacturing of metal components [6]. Cost and time required to develop parts are reduced by eliminating conventional manufacturing methods associated with metal casting processes. It is possible with AM processes to create an entire sand-casting mould or mould components (such as cores) directly from CAD data [50].

RT can also be beneficial in the investment casting process were tooling is traditionally used to produce sacrificial patterns. These sacrificial patterns can be produced through AM, eliminating the need for tooling.

### 3.6.2 Indirect tooling

Indirect tooling consists of soft or hard tooling. The durability and stiffness of the mould is determined by the material from which the mould is manufactured.

Soft tooling is created from a master or a positive pattern. Examples of soft tooling include room temperature vulcanizing (RTV), silicon moulds (typically used for wax patterns), vacuum casting moulds, spin casting, as well as castable ceramics [50]. The expected lifespan of these moulds varies from one hundred to three hundred cycles. Figure 3.4 shows the assembly of a soft tool manufactured from silicon for a urethane casting.

*Figure 3.4: Assembly of a soft tool manufactured from silicon [51].*

Hard tooling is used for tooling applications where high production volumes are expected. The lifespan of a hard tool can vary between hundreds to hundreds of thousands of cycles depending on the product geometry and mould design. Hard tooling is more expensive and time-consuming to produce compared to soft tooling. Hard tooling can withstand higher temperatures compared to soft tooling, making it suitable for certain high-temperature processes and materials [51]. Various techniques are used to create hard tooling. These methods include:

- **Spray metal moulds which** are mostly used for low-pressure processes such as rotational moulding and vacuum forming. This process can also be used in high-pressure processes such as IM for low-volume prototypes [6].
- **Cast metal tooling which i**s used to produce mould components in metal through AM-produced patterns or moulds. These metal mould components may require post-processing, such as machining, before they are used to produce the end product [6].

- **Keltool$^{TM}$ process,** a method of producing cost effective tooling quickly. In this process, a master pattern (typically produced through AM) is used to manufacture a mould that is used to produce a Keltool mould, suitable for IM applications.

### 3.6.3 Direct tooling

Direct tooling involves tooling components being produced directly by AM technologies. Resin tooling, ceramic powder tooling, laminated metal tooling, as well as metal powder tools, can be produced directly through AM. DMLS is a direct tooling method that can produce mould inserts suitable for high-pressure processes such as high pressure die casting and plastic IM. Shortcomings of existing RT techniques include high material and equipment costs associated with most AM processes. Dimensional restrictions of the machine build envelope limit the size of inserts that can be manufactured through the AM processes [49].

## 3.7 Hybrid tooling

Hybrid tooling is a term used to describe different manufacturing technologies used to manufacture a mould. Hybrid tooling combines the benefits of AM and conventional manufacturing methods. Complex features are manufactured using AM while the more easily machinable features are produced through traditional manufacturing methods. This results in a reduction of the required AM insert size, which resolves the problem of size limitations of AM machines as well as the related costs. Figure 3.6 shows examples of hybrid tooling moulds manufactured for the IM process [18, 52].

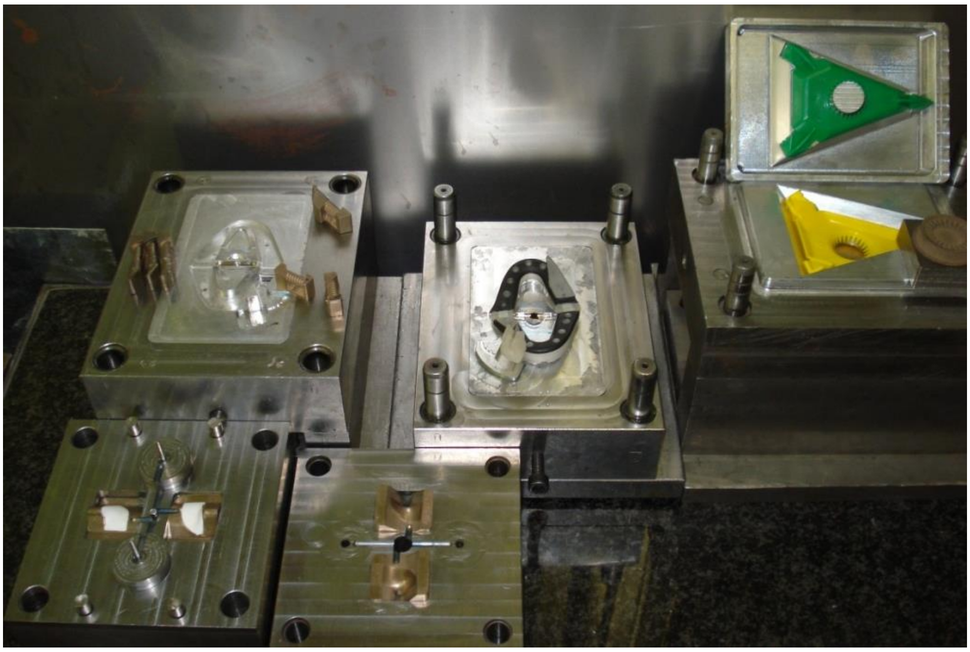


*Figure 3.5: Injection moulds manufactured using hybrid tooling techniques.*

Figure 3.6 illustrates how AM technologies and conventional tooling techniques can occur concurrently to produce a hybrid tool that can potentially reduce tool manufacturing lead-times.

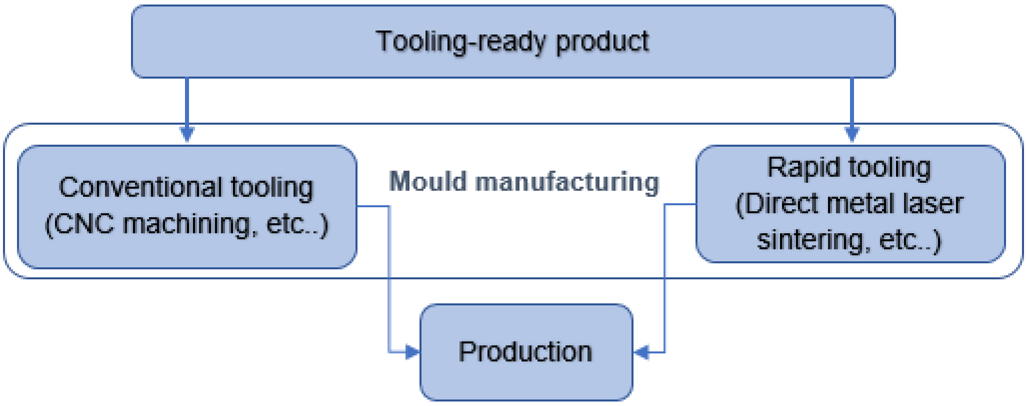



*Figure 3.6: Concurrent manufacturing possibility through hybrid tooling.*

### 3.7.1 Hybrid tooling for injection moulding applications

Recent advances in technologies and powder developments for AM processes made it possible to produce AM mould inserts suitable for high-volume production [49]. Table 3.2 summarises the achievable quantities for high-volume production tools as well as for prototype and low-volume production, as classified by the Society of Plastic Industry (SPI) [1].

*Table 3.2: SPI mould classification system [1].*

| SPI class designation | IM machine size (ton) | Estimated number cycles | Mould description |
|---|---|---|---|
| 101 | >400 | >1 x $10^6$ | Extremely high production |
| 102 | >400 | <1 x $10^6$ | Medium to high production |
| 103 | >400 | <1 x $10^5$ | Medium production |
| 104 | >400 | <1 x $10^5$ | Low production |
| 105 | >400 | <1 x $10^2$ | Prototype only |
| 401 | <400 | >1 x $10^5$ | Extremely high production |
| 402 | <400 | <1 x $10^5$ | Medium to high production |
| 403 | <400 | <1 x $10^5$ | Low to medium production |
| 404 | <400 | <1 x $10^2$ | Prototype only |

Maraging Steel MS1 by EOS GmbH Electro Optical Systems (EOS), is an example of a recent powder development which is suitable to produce tooling inserts for high-volume IM applications [1, 53]. The mechanical properties of Maraging Steel MS1 combined with the advantages that the DMLS process offers results in mould inserts that are suitable for high-volume production applications for the IM process [49].

### 3.7.2 Maraging Steel MS1

Maraging steel is a low-carbon, high-strength, martensitic (Mar-) metallurgical process (- aging) as the name suggests. It has been traditionally used in aerospace, military and tooling applications. Maraging steels offer good weldability, excellent mechanical properties and superior machinability that make them well-suited for tooling applications [53]. Maraging steels fall in a special class of ultra-high strength steels. The ultra-high strength of maraging steels are obtained from precipitation of intermetallic compounds and do not involve carbon-like conventional steels [54]. The chemical composition of maraging steel 300 (18Ni-300 steel), or *werkstoffnummer*: 1.2709, is shown in Table 3.3 below.

*Table 3.3: Chemical composition of maraging steel 300 (18Ni-300 steel) [55]*

| Alloying element | Fe | Ni | Co | Mo | Ti | Al | Cr | C | Mn,Si | P,S |
|---|---|---|---|---|---|---|---|---|---|---|
| wt % | rest | 17-19 | 8.5-9.5 | 4.5-5.2 | 0.6-0.8 | 0.05-0.15 | <0.5 | <0.03 | <0.1 | <0.01 |

Maraging Steel MS1 consists of the same chemical composition as maraging steel 300 [53, 54]. Using the Maraging Steel MS1 material in the DMLS process makes it possible to produce complex internal structures that can be beneficial for tooling applications such as conformal cooling channels [49].

Benefits of using DMLS Maraging Steel MS1 in tooling applications include [49]:

- Ability to produce DMLS components concurrently with conventionally manufactured mould components.
- Freedom of design when designing for AM. (unconstrained by conventional manufacturing methods).
- The possibility of implementing conformal cooling channels in tooling inserts that can extract heat more efficiently from a mould during the IM cycle. This can result in a reduction in IM cycle times and improved product quality.

## 3.8 Heat transfer in an injection mould

Cooling channels are essential for heat transfer during the IM process, where molten plastic must be solidified to produce a product. The more efficiently heat is transferred from the molten plastic to the cooling medium of the mould, the more efficient the IM cycle becomes [5, 7]. Heat transfer can take place through conduction, radiation or convection, where conduction is the method where most of the heat transfer takes place in an IM. Heat from the molten plastic is transferred by conduction through the mould material to the cooling medium (usually water) inside a cooling channel. Conduction is a form of heat transfer that takes place when energy is transferred through a material due to atomic/molecular vibrations of a solid, or movement of molecules in liquids and gasses [56].

Conduction of heat transfer depends upon [56]:

- The area through which heat transfer takes place.
- Temperature differences of the faces through which the heat is transferred.
- Time taken for the heat transfer to take place.
- Material thickness through which heat is transferred.
- Material properties, such as the coefficient of thermal conductivity.

Baron Jean-Baptiste-Joseph Fourier determined that heat transfer is proportional to the area through which the heat is transferred and temperature difference on the faces through which heat is transferred. He also determined that heat transfer is inversely proportional to the thickness of the material through which heat is passed. [56].

Fourier derived the following formulas based upon Figure 3.7.

$$\dot{Q} = \frac{-kA(t1-t2)}{x}$$ *Equation 1: Fourier's equation*

This formula is known as Fourier's equation:

Where:

$k$ = Coeffiecient of thermal conductivity, (W/mK)

$A$ = Area of transfer, ($m^2$)

$t_1$ = Inlet surface temperature, (°C)

$t_2$ = Exit surface temperature, (°C)

$x$ = Thickness of material, (m)

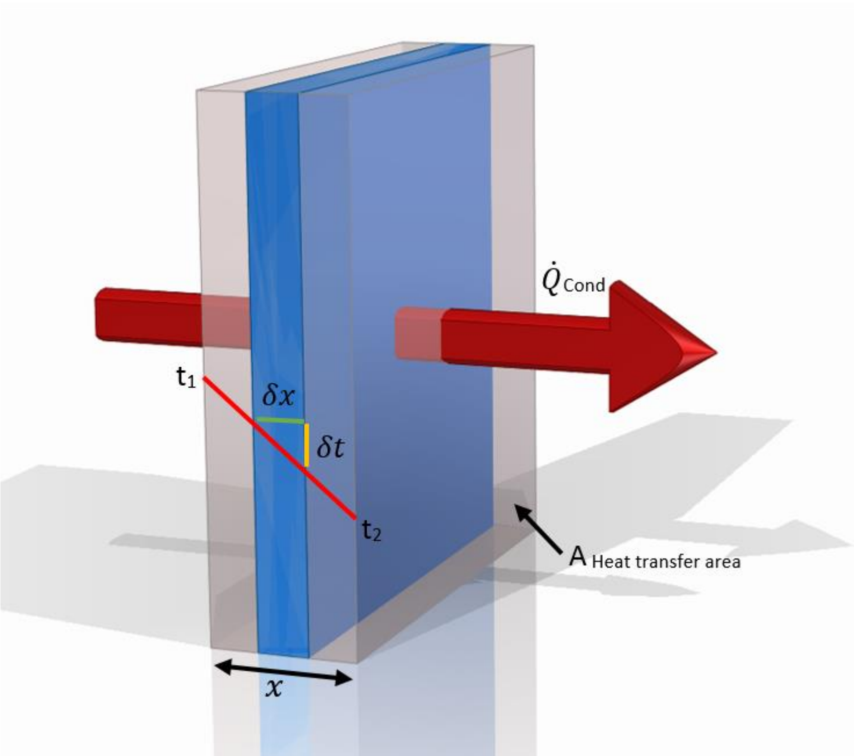



*Figure 3.7: Conduction through material according to Fourier's law.*

For optimal cooling of an IM, the following need to be considered during the design phase of an injection mould or insert [57]:

i. Determine the total shot weight of moulded product and runner system

The volume and density of the moulded product is used to determine the shot weight.

$$M = V \times \rho$$

Where M = mass of product or (shot weight), (kg).

V = Volume of product and feed system, ($m^3$)

$\rho$ = Density of plastic material to be used, ($kg/m^3$)

ii. Determine the amount of heat content to be removed for each IM cycle

The amount of heat energy to be removed is calculated using the specific heat capacity of the plastic material from which the product is manufactured and the temperature difference between the molten plastic material and the IM. Table 3.4 summarises the amount of heat energy to be removed per unit mass for different engineering plastics.

*Table 3.4: Heat content to be removed for different engineering plastic materials [57].*

| | Melt temperatures $(T1)$ | Mould temperatures $(T2)$ | Difference in temperatures $(\Delta T)$ | Specific heat content $(Cp)$ | Heat to be removed |
|---|---|---|---|---|---|
| **Material abbreviation** | °C | °C | K | $\frac{J}{kg.K}$ | $\frac{J}{g}$ |
| **PET** | 240 | 60 | 180 | 1570 | 282.6 |
| **POM** | 205 | 90 | 115 | 3000 | 345 |
| **PC** | 300 | 90 | 210 | 1750 | 367.5 |
| **ABS** | 240 | 60 | 180 | 2050 | 369 |
| **PS** | 220 | 20 | 200 | 1970 | 394 |
| **HIPS** | 240 | 20 | 220 | 1970 | 433.4 |

| | | | | | |
|---|---|---|---|---|---|
| **PA6** | 250 | 80 | 170 | 3060 | 520.2 |
| **PA66** | 280 | 80 | 200 | 3075 | 615 |
| **LDPE** | 210 | 30 | 180 | 3180 | 572.4 |
| **HDPE** | 240 | 20 | 220 | 3640 | 800.8 |
| **PP** | 240 | 50 | 190 | 2790 | 530.1 |

iii. <u>Calculate the flow rate of the cooling medium through the mould.</u>

The formula below describes the mass flowrate of the cooling medium, (typically water) needed to remove the heat per cycle. This is obtained using the heat energy to be removed per cycle and the specific heat content of the cooling medium. A difference in temperature of 4 $^{o}$C or 4 Kelvin can be assumed for $\Delta T$ during calculations [57].

$$\therefore \quad \dot{m} = \frac{\dot{Q}}{Cp \ \Delta T}$$ *Equation 2: Mass flowrate*

Where $\dot{Q}$= Heat to be removed, (W)

$\dot{m}$ = Mass flowrate of cooling medium used through the mould, ( $\frac{kg}{hour}$)

$Cp$ = Specific heat content of cooling medium used through the mould, ($\frac{J}{kg.K}$)

$\Delta T$ = Temperature difference of the inlet and outlet of the cooling channel medium, (K)

iv. <u>Selection of the diameter of the cooling channel to be used</u>

Figure 3.8 below shows a section of a mould base. It illustrates how conduction transfers heat from the moulded product through the mould base into the cooling channels.

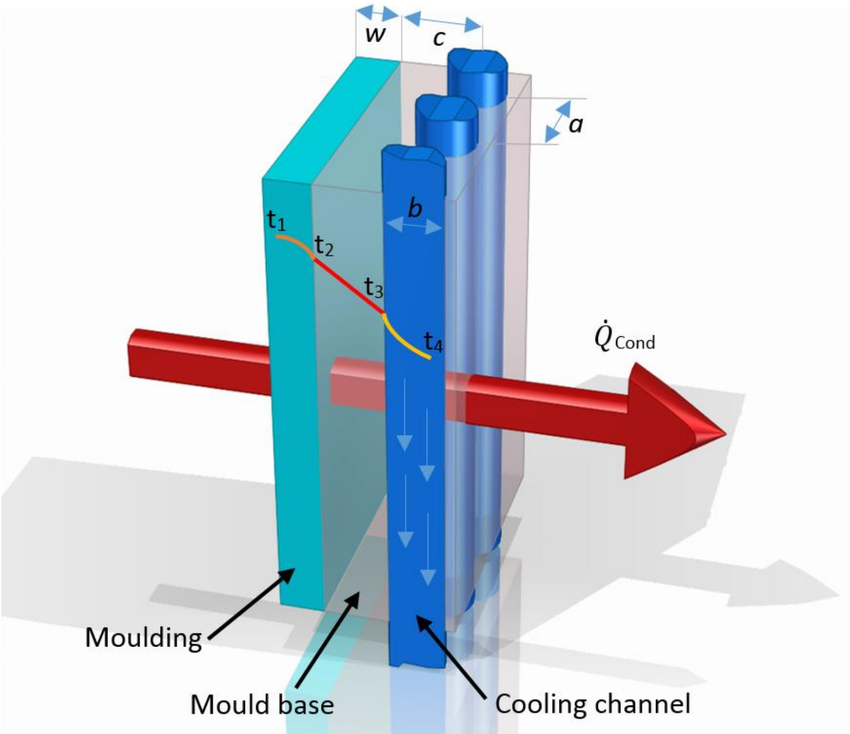



*Figure 3.8: Transfer of heat through conduction from a moulding to the cooling channels.*

The three important parameters for successful cooling channel designs are:

- The cooling channel diameters ***(b).***
- The distance between cooling channels and cavity ***(c).***
- The distance between cooling channels ***(a).***

These parameters are illustrated in Figure 3.9 and the relationship between the parameters is summarised in Table 3.5.

*Table 3.5: Cooling channel design guide derived from Fourier's equation [58].*

| Wall thickness of product (mm) | Hole diameter (*b*) in mm | Centre-line distance between holes (*a*) | Distance between holes and cavity (*c*) |
|---|---|---|---|
| **0 to 2** | 4 to 8 | 2 to 3 times dimension (b) | 1.5 to 2 times dimension (b) |
| **2 to 4** | 8 to 12 | 2 to 3 times dimension (b) | 1.5 to 2 times dimension (b) |
| **4 to 6** | 12 to 14 | 2 to 3 times dimension (b) | 1.5 to 2 times dimension (b) |

The distance of the cooling channels from the cavity ***(c)*** should be as small as possible and the values of ***(a)*** and ***(b)*** are dependent on each other.

v. Calculate number of cooling channels required to accommodate the flow rate and cooling medium.

To calculate the number of cooling channels required, the total length of the cooling channel needs to be calculated using Equation 3. The number of cooling channels are determined by considering the total length of the cooling system inside the mould base.

$$L = \frac{2 \times a \times \dot{Q}}{k \times \pi \times b \times \Delta T}$$

*Equation 3: Total length of cooling channel*

Where:

*a* = Distance between cooling channels, (m)

$\dot{Q}$ = The calculated heat content to be removed from the plastic material, (W)

$k$ = The coefficient of thermal conductivity, (W/mK)

$b$ = The diameter of the cooling channel, (m)

$\Delta T$ = The temperature difference between the plastic to the mould, (K)

## 3.9 Cooling channel geometries

Cooling channels that conform to the product geometry have the potential to improve the heat transfer effectiveness of an insert when compared to the heat transfer achieved in traditionally produced channels. Conformal cooling channels can reduce the cycle time in an IM process while simultaneously increasing part quality (eliminating warpage and other defects) by means of a uniform heat transfer from the product [48].

Figure 3.9 illustrates conformal cooling channels applied to an IM insert. Conformal cooling channels can reduce the cost of plastic IM parts by reducing the cooling time required. Conformal cooling channel case studies, published by EOS, showed a reduction in IM cycle times of up to 60% and an increase in product quality [58].

*Figure 3.9: Example of conformal cooling channels designed by Pole European de la Plastyrgie [5].*

According to Fourier's law, heat transfer is inversely proportional to the thickness of the material the heat is passing through. Thus, if the cooling channel conforms to the shape of the mould cavity, the thickness of the material through which the heat needs to flow can be minimised resulting in improved cooling of the cavity. This is not possible with conventional manufacturing techniques which are limited to straight-line drilling and slotting.

Benefits of conformal cooling over conventional cooling in an injection mould include [48, 59]:

- Heat is extracted more evenly which reduces product deformation (such as warpage).
- Heat from the mould is extracted quicker resulting in a reduction of IM cycle times, consequently saving time and money during the production of the product.
- Conformal cooling channels can reach areas of the mould that would not be possible with conventionally manufactured cooling channels.
- Product quality can be improved by eliminating defects (such as warpage and heat sinks), associated with inadequate cooling of an IM.

## 3.10 Conclusion

Tooling plays a significant role in the product manufacturing process. It can be time-consuming as well as extremely expensive. By increasing the complexity of an IM, mould-manufacturing times and costs increase. This results in many plastic product developments not being commercialised due to the high costs associated with it.

AM technologies and materials have improved during the last few years and it is now possible to produce IM inserts suitable for high-volume production. Traditional tool manufacturing methods can occur in parallel with RT techniques to reduce tooling manufacturing costs and lead-times. Through AM inserts, conformal cooling channels can be manufactured which can reduce the cycle time of an IM process and improve the part quality through efficient heat transfer.

Well-designed IM cooling is essential to produce quality IM components economically. IM design is experience-based and depends upon the competence of the designer. It is important that the designer understands the relationship between theory and practice to develop a functional mould design with the manufacturing processes intended to be used in mind. The introduction of AM technologies suitable for tooling applications, such as RT technologies, provide more freedom for mould designers. Therefore, more efficient cooling channel designs are possible which are not constrained by the limitations of traditional manufacturing processes. The creation of complex geometries and internal structures, such as conformal cooling channels, is one such example.

# 4 EXPERIMENTAL APPROACH AND RESULTS

## 4.1 Introduction

To evaluate the influence of different cooling channel designs of an insert on the IM value chain, a four-phase approach was followed. During Phase 1, two DMLS inserts with different conformal cooling channel designs were evaluated using Computer Aided Engineering (CAE) and Computational Fluid Dynamics (CFD) to identify the most efficient design.

During Phase 2, the conformal cooling channel design selected during Phase 1 was compared to an insert with cooling channels designed for conventional manufacturing techniques. Formulas described in Section 3.6 were used to optimise the design and layout of the conventionally manufactured cooling channels.

Phase 3 consisted of the manufacturing of the selected AM insert using the DMLS process and the conventional insert using conventional manufacturing techniques. During Phase 3, IM trials were conducted with the inserts and the experimental results were compared to the simulated results.

During Phase 4, the results of the previous phases were applied to an industry-specific case study. The study involved analysing a conformal and conventional insert design and to determine the feasibility of using an AM insert in a plastic IM application.

Figure 4.1 illustrates the four-phased approach schematically.

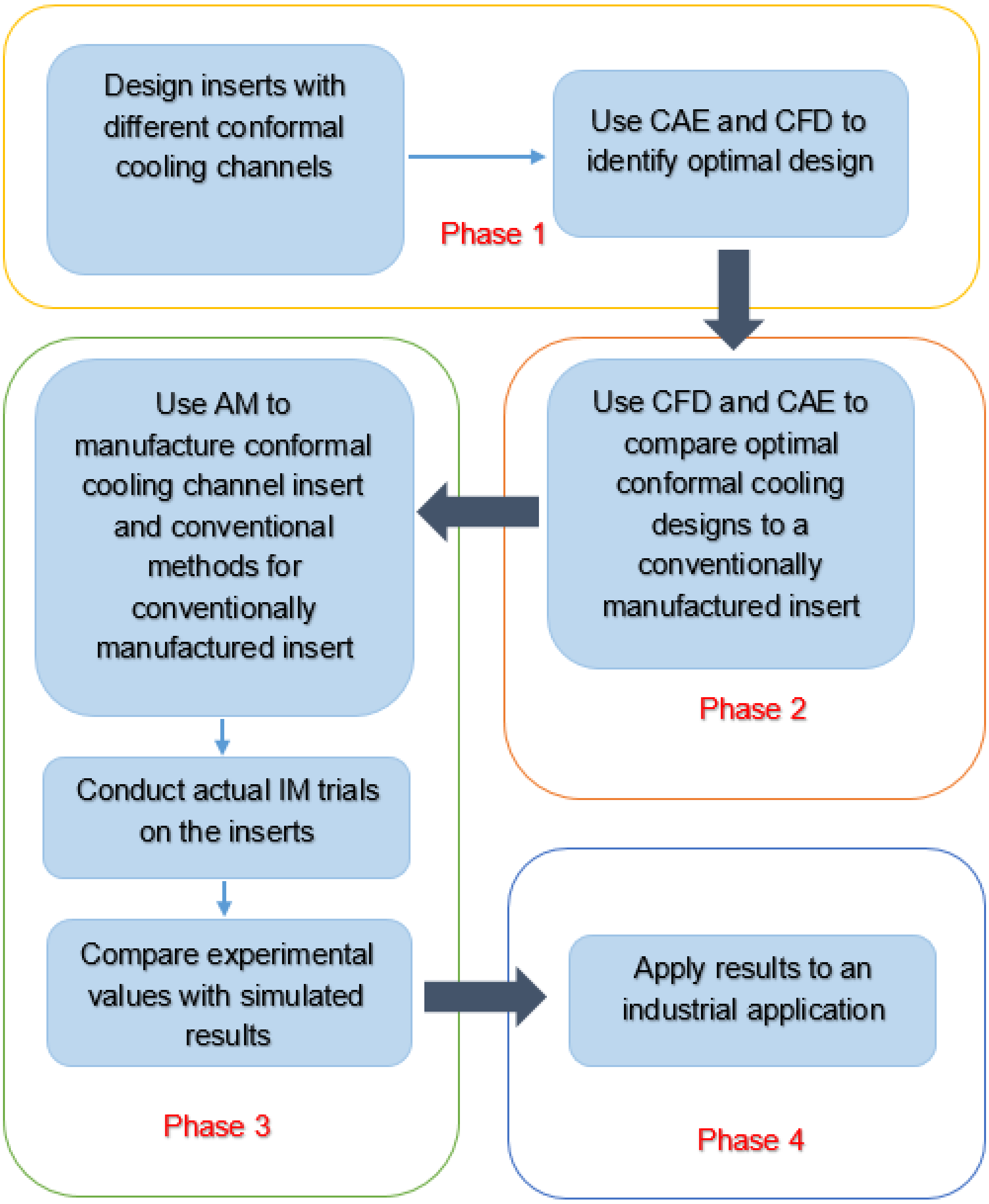



*Figure 4.1: Representation of the four-phased approach to determine the influence of different cooling channel designs of an insert on the IM value chain.*

An interlocking floor tile product shown in Figure 4.2, with outer dimensions of 150 mm x 150 mm x 4 mm, with a maximum wall thickness of 2 mm designed for an industrial application, was used to evaluate the different cooling channel designs during Phases 1 to 3.

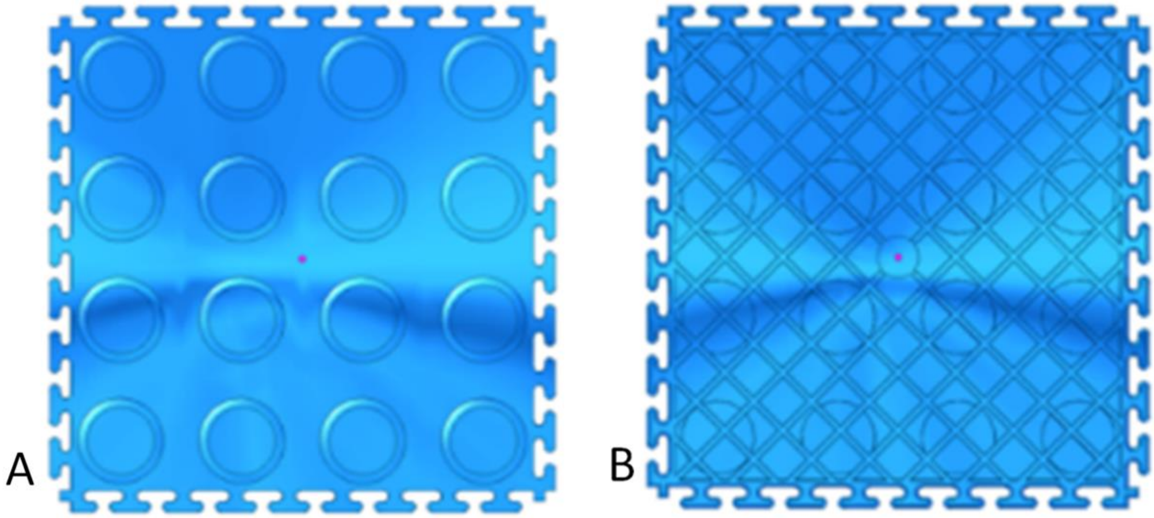



*Figure 4.2: Top (A) and bottom (B) view of the interlocking floor tile product used during the evaluation of Phases 1 to 3 [49].*

## 4.2 Phase 1: Evaluation of conformal cooling channel designs

During Phase 1, two different conformal cooling channel designs, a spiral and meander, were applied to an AM insert for the interlocking floor tile product. A comparison between the two different conformal cooling channels was conducted with simulation software to obtain the best possible heat transfer through the AM insert to the cooling medium inside the cooling channels. The layout of Phase 1 is schematically shown in Figure 4.3.

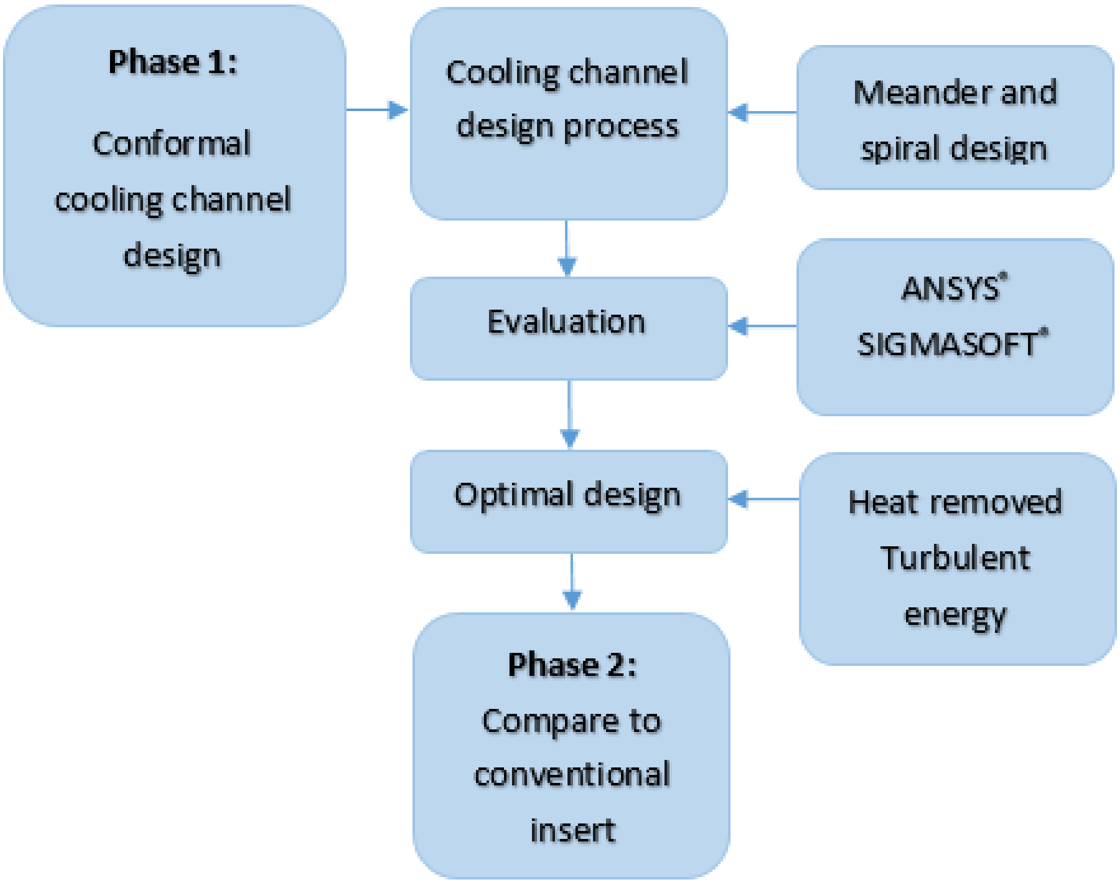



*Figure 4.3: Schematic representation of Phase 1.*

Different cooling channel designs were considered and two were chosen as the most appropriate designs for the DMLS process based upon:

- The removal of unsintered powder from the cooling channels of the AM insert after the laser sintering process.
- The ability of the conformal cooling channels to access difficult-to-reach regions of the insert (e.g. behind screw holes) where heat can accumulate inside the mould resulting in mould hot spots that cannot be accessed by conventional cooling channels.

ANSYS®, a high-performance CFD software and SIGMASOFT®, a virtual moulding simulation software, were used to simulate the heat transfer and flow characteristics of the cooling fluid inside the cooling channels of the two designs. ANSYS® was used to solve complex fluid flow-related physics of the cooling channels, and SIGMASOFT® was used to simulate the heat transfer between the plastic melt, mould inserts and the mould base during consecutive IM cycles.

For optimal cooling of the AM insert, the cooling channel dimensions were based upon the design specifications derived from Fourier's equation summarised in Table 3.5. According to Table 3.5, the interlocking floor tile with a maximum wall thickness of 2 mm requires cooling channels with a diameter between 4 and 8 mm. A cooling channel with an elliptical geometry (with primary and secondary axis dimensions of 5.6 mm and 4 mm respectively), with the same cross-section as a diameter 4.75 mm cooling channel was used. This resulted in a centre distance of 12 mm between the cooling channels based upon the design specifications of Table 3.5. An elliptical geometry was used due to the increased strength of the cooling channel in the direction of the applied pressure during an IM cycle. The elliptical shape also reduces the possible distortion of the cooling channel due to unsupported overhangs during the DMLS manufacturing process of the cooling channel profile. This shape also allowed the cooling channels to be spaced closer to each other while avoiding insert features such as screw and ejector pin holes.

The physical properties of the fluid used as the cooling medium will determine the heat transfer characteristics of the cooling channels. When laminar flow occurs inside a cooling channel, there is no separation of the boundary layer from the wall of the cooling channel and heat is transferred only through conduction to the cooling fluid. When there is turbulent flow inside a cooling channel, intermixing between the boundary layer and the bulk of the fluid occurs, resulting in a more efficient heat transfer through conduction and convection. Thus, a higher turbulent intensity inside a cooling channel will result in a more effective cooling.

### 4.2.1 AM insert with spiral conformal cooling channels

A spiral conformal cooling channel design with an elliptical geometry was designed for an AM insert to manufacture the interlocking floor tile product. Simulation software was used to determine the heat transfer from the AM insert to the cooling channels as well as the flow characteristics of the cooling channel design.

### Procedure

A spiral conformal cooling channel was designed in such a manner that the cooling fluid entered the insert from the outside and spiralled towards the centre of the product, exiting the insert near the centre as shown in Figure 4.4. The flow orientation was chosen to gradually heat up the cooling fluid as it flows towards the centre where the plastic melt is injected into the cavity. A higher cavity temperature near the injection point will assist with the flow of the injected molten polymer, preventing the polymer from solidifying before the cavity is filled.

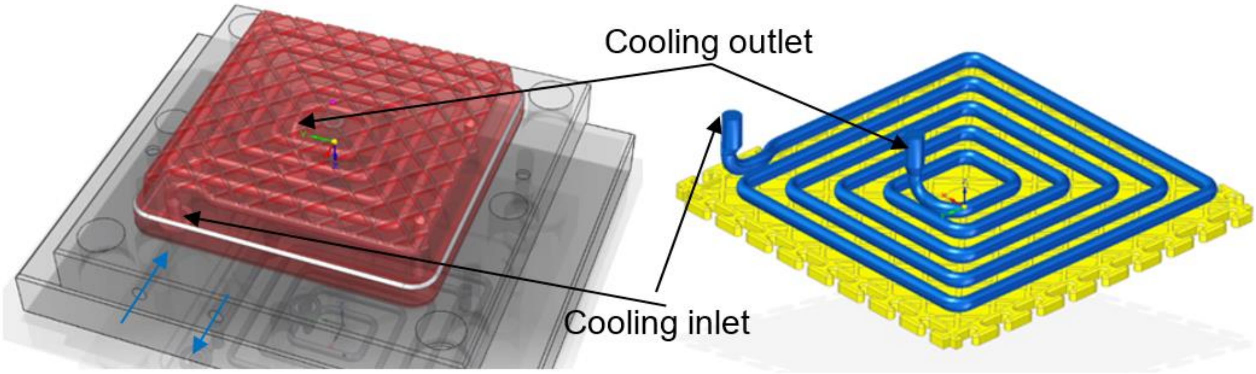



*Figure 4.4: Layout of the spiral conformal cooling channel.*

The centre distances between the cooling channels and the distance from the cavity surface used during the design of the spiral conformal cooling channel (shown in Figure 4.5) were based on the design specifications of Table 3.5.

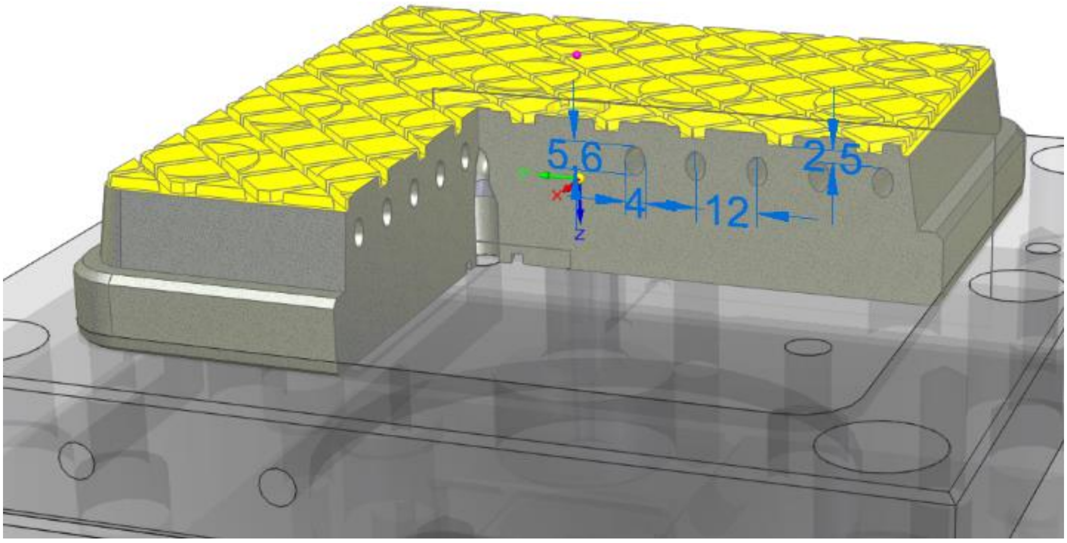



*Figure 4.5: Spacing used during the design of the spiral conformal cooling channels for the interlocking floor tile product.*

The mould with the AM spiral conformal cooling channel insert was set up in SIGMASOFT® and ANSYS® simulation software using the parameters summarised in Table 4.1. The processing parameters used during the simulations were based upon the specifications and capability of the IM machine used during the actual IM trials.

*Table 4.1: Simulation parameters used during the SIGMASOFT® and ANSYS® simulations of the conformal cooling channels for the AM inserts.*

| Parameter | Value |
|---|---|
| **Ambient temperature** | 20 ºC |
| **Polymer material** | PPC 7650 thermoplastic elastomer, Kraiburg |
| **Insert material (conventional)** | X38CrMo16 or (1.2316) |
| **Insert material (AM)** | X3NiCoMoTi 18-9-5 or (1.2709) |
| **Cooling fluid** | Water |
| **Heat capacity of cooling medium** | 4.187 kJ/kg K |
| **Cooling medium mass flow rate** | 0.133 kg/sec |
| **Cooling medium inlet temperature** | 20 ºC |
| **Melt temperature of injected polymer material** | 220 ºC |
| **Initial mould temperature** | 26 ºC |
| **Packing pressure** | 580 bar |
| **Filling time** | 1.5 s |
| **Packing time** | 3.5 s |
| **Mould closing time, after injection** | 14 s |
| **Total cycle time** | 27 s |
| **Number of cycles** | 25 |

## *Results*

Figure 4.6 shows the temperature distribution inside the cooling channel as ribbon streamlines, from inlet to outlet. Water entered the spiral cooling channel design at 293 K and exited at a higher temperature of 337 K. From the streamlines, it is visible that the flow was more turbulent at the corners, as shown by label A in Figure 4.6, while the flow in the straight sections of the channel was laminar, as shown by label B.

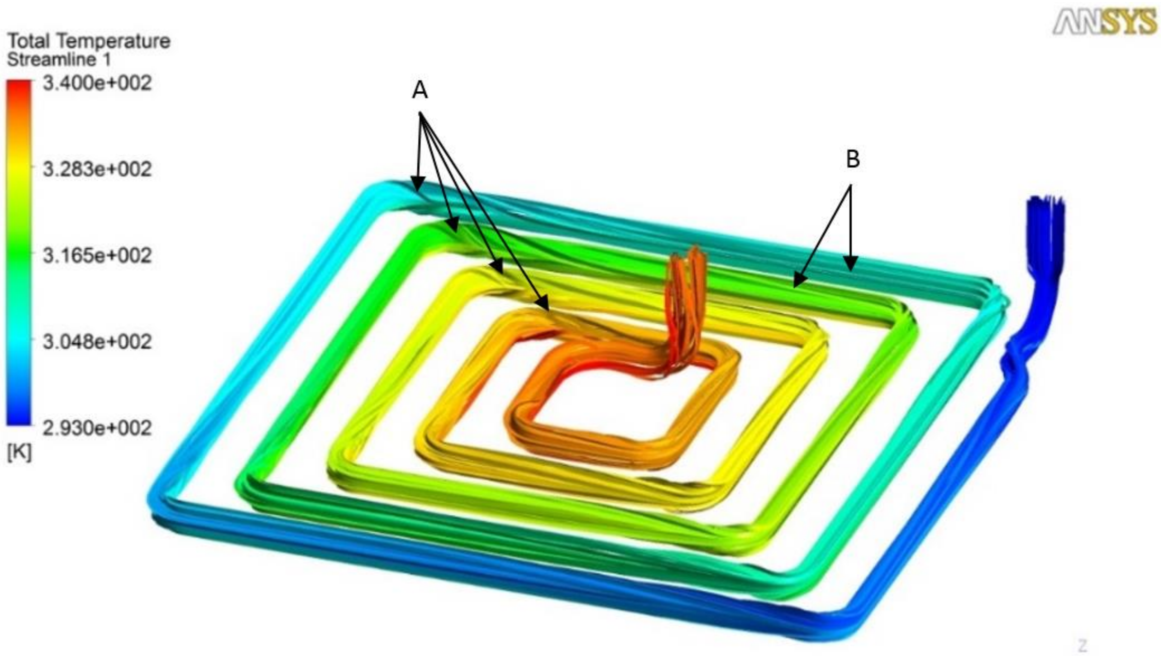



*Figure 4.6: Streamline temperature for the spiral cooling channel design indicating turbulent flow at the corners (A) and laminar flow (B).*

The enlarged section of Figure 4.7 shows a greater increase in the water temperature as it flowed around a corner compared to a straight section of the cooling channel. This was caused by the turbulent flow induced at a corner inside the cooling channel, resulting in an increased heat transfer to the cooling channel.

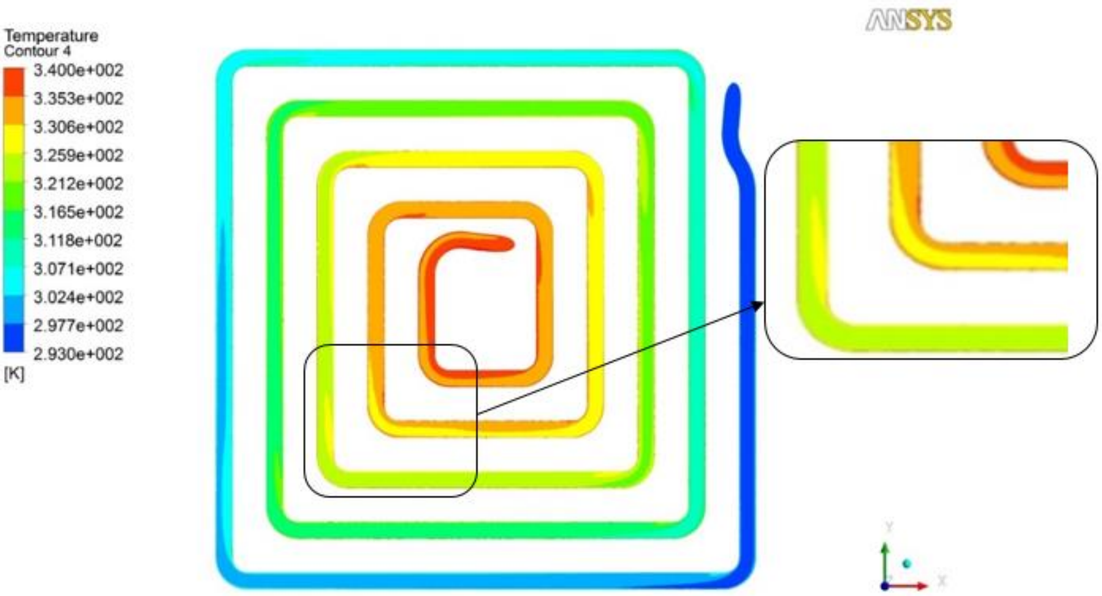



*Figure 4.7: Mid-plane temperature distribution of the spiral conformal cooling channel design indicating the increase in the water temperature as it flows around a corner.*

Figure 4.8 shows a section view of the AM insert, illustrating the temperature distribution through the insert. The temperature of the cooling channels on the outside of the insert (shown by label D) was lower than the channels on the inside (shown by label C). This was due to the flow direction of the cooling channel layout where cooler water entered the insert from the outside (D) and as it flowed towards the centre of the insert (C), where the molten polymer is injected into the cavity, the water temperature increased due to the heat transferred from the AM insert to the cooling water.

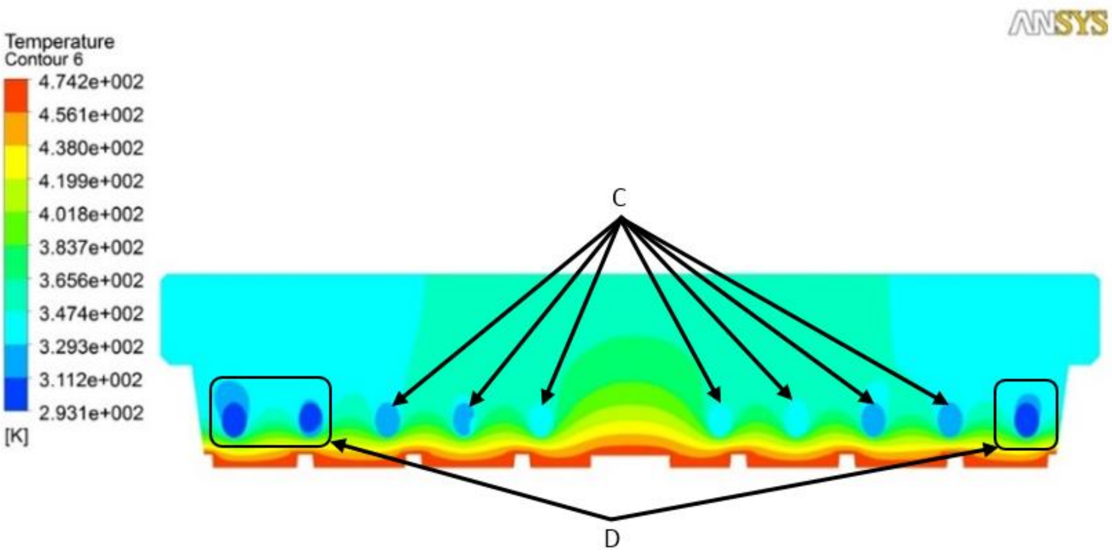



*Figure 4.8: Temperature distribution of the cooling medium from the outside (D) to the inside (C) of the spiral conformal cooling channel design.*

During ANSYS® simulations, basic heat transfer principles were used to determine the amount of heat energy that can be removed from a constant heat source at 200 ºC by the cooling channel. The heat source was applied to the surface of the AM insert where the product would be formed. Because the path of each water particle flowing through the cooling channel was not similar, heat flow results could not be calculated and compared accurately. Therefore, five equally spaced particles were evaluated and a graph of the temperature against time was obtained from the results for each particle, as shown in Figure 4.9. The area under each curve was calculated using the trapezium rule, and the calculated area divided by the total time for a particle to flow through the channel was used to determine the average temperature for each of the five particles. The average temperature was used to calculate the total heat absorbed by each particle flowing through the channel.

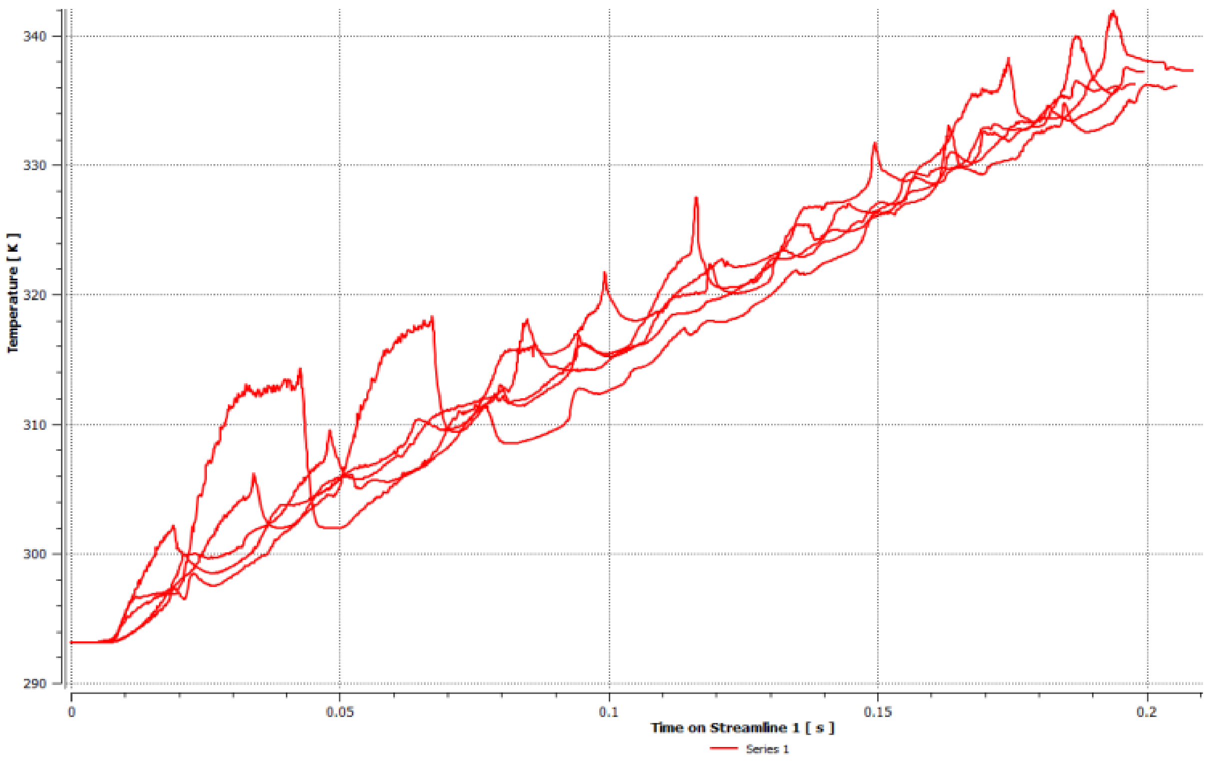



*Figure 4.9: Temperature-against-time graph of the five particles flowing through the spiral conformal cooling channel.*

The peaks of the graph shown in Figure 4.9 indicate higher temperatures around the corners due to the increased heat absorption caused by the higher turbulent flow at the corners. The heat is then transferred by conduction to the bulk of the fluid (shown by the decrease in temperature) while it flows through the straight sections of the cooling channel.

The average heat absorbed by the cooling channel was calculated using the average temperature of each particle considered in the simulation from the inlet to the outlet of the cooling channel. The average heat absorbed for the spiral cooling channel design was calculated as follow:

$$Q = \dot{m}C_p\Delta T$$

$$Q = 0.133(4.187)(341.281 - 293.15)$$

$$Q = 26.802 \text{ kJ}$$

The area under each curve was calculated and divided by the total time to obtain the average temperature for each particle as it flowed through the cooling channel. This procedure was repeated for each particle and the total average temperature was obtained from the average temperatures of each particle. Table 4.2 summarises the average temperature of each particle flowing through the cooling channel.

*Table 4.2: Average calculated temperatures of the five particles flowing through the spiral conformal cooling channel.*

| Particle | Average temperature [K] |
|---|---|
| **Particle 1** | 315.957 |
| **Particle 2** | 315.841 |
| **Particle 3** | 318.048 |
| **Particle 4** | 316.008 |
| **Particle 5** | 315.272 |
| **Average (total)** | 316.225 |

Through ANSYS® simulations using direct numerical simulation, the turbulence intensity was obtained for the spiral conformal cooling channel. The turbulence intensity indicates the amount of intermixing occurring in the fluid. The maximum turbulence kinetic energy obtained from the simulated results for the spiral conformal cooling design was 2.90503 $m^2.s^2$.

### 4.2.2 AM insert with meander conformal cooling channels

#### *Procedure*

An insert with a meander conformal cooling channels was designed using the same parameters and dimensions as the spiral conformal cooling channels discussed in Section 4.2.1. The layout of the meander cooling channel is shown in Figure 4.10.

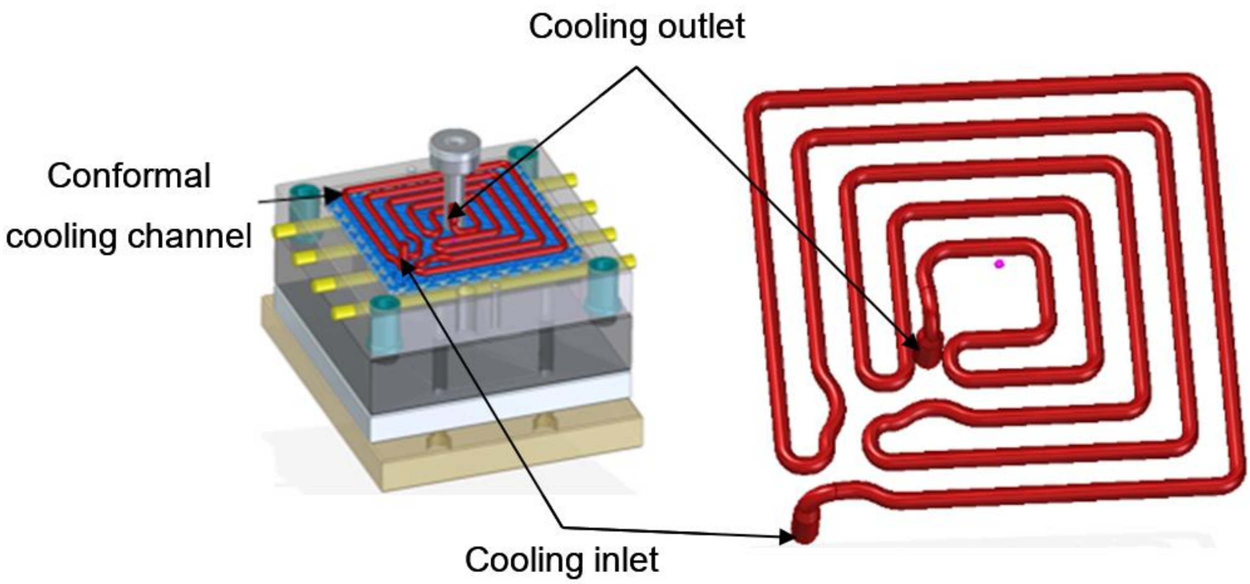



*Figure 4.10: Meander conformal cooling channel layout of the AM insert to manufacture the interlocking floor tile.*

The parameters used during the SIGMASOFT® and ANSYS® simulations of the meander conformal cooling channel design are summarised in Table 4.1. The cooling fluid entered the insert from the outside and meandered towards the centre of the product, exiting the insert near the centre, as shown in Figure 4.10.

#### *Results*

Figure 4.11 shows the temperature distribution of the cooling channel as ribbon streamlines, from inlet to the outlet. Water entered the meander conformal cooling channel design at 293 K and exited at a higher temperature of 340 K. From the streamlines it is visible that at the regions shown by label A in Figure 4.11, intermixing of the fluid occurred due to turbulent flow compared to the regions shown by label B where laminar flow occurred.

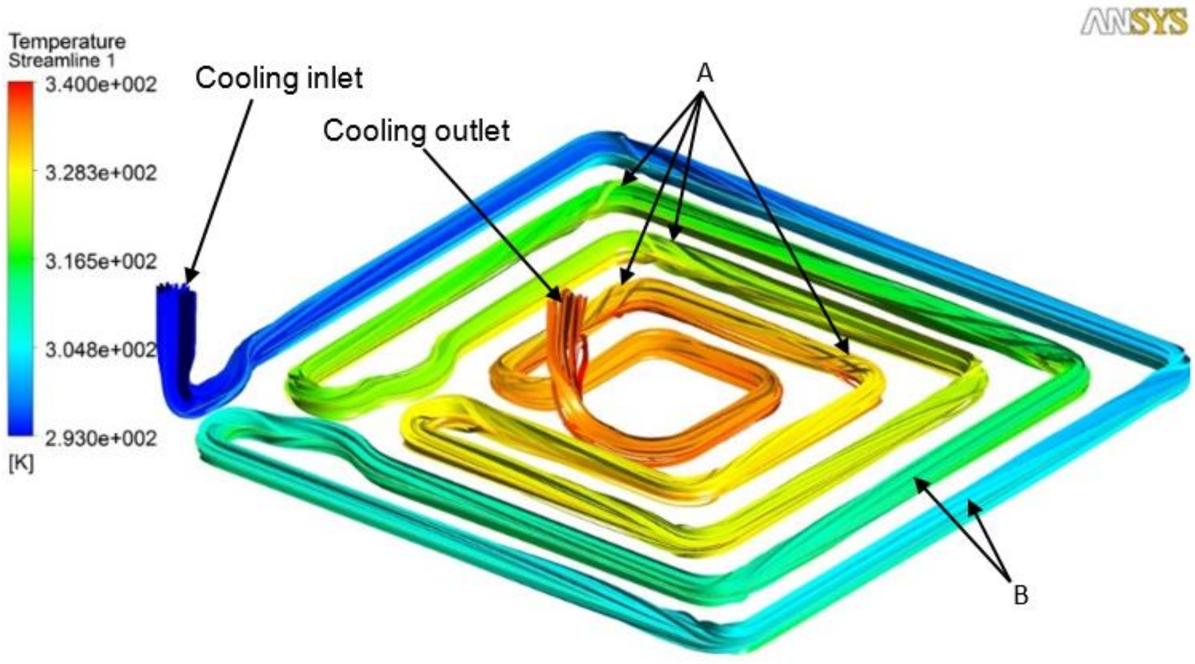



*Figure 4.11: Streamline temperature for the meander cooling channel design indicating turbulent flow at the corners (A) and laminar flow (B).*

The temperature distribution of the cooling medium inside the cooling channel, shown in Figure 4.12, indicates that the turbulent flow around the corners improved the heat absorption, resulting in an increase in temperature, as shown by the enlarged section.

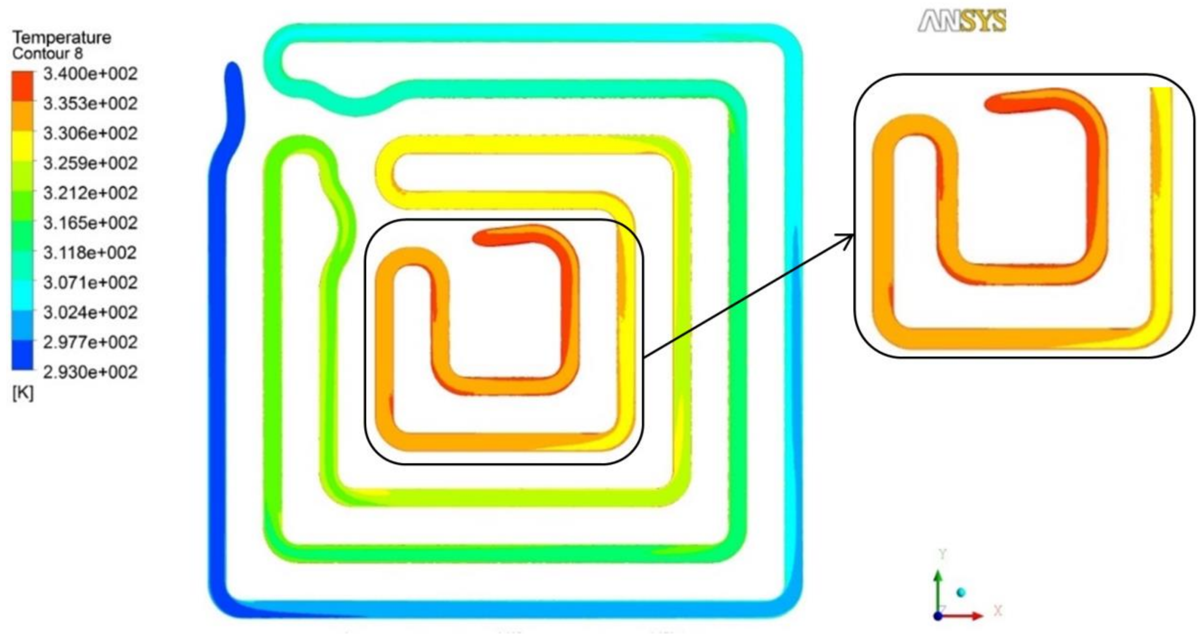



*Figure 4.12: Meander spiral mid-plane temperature distribution of the cooling fluid as it flows through the insert.*

Figure 4.13 shows a section view of the AM insert, illustrating the temperature distribution through the insert. The temperature of the cooling channels on the outside of the insert was lower than the channels on the inside. This is due to the direction of flow in the cooling channel. Cooler water entered the insert on the outside and as it flowed towards the centre of the insert the water temperature increased due to heat transferred from the AM insert to the cooling water.

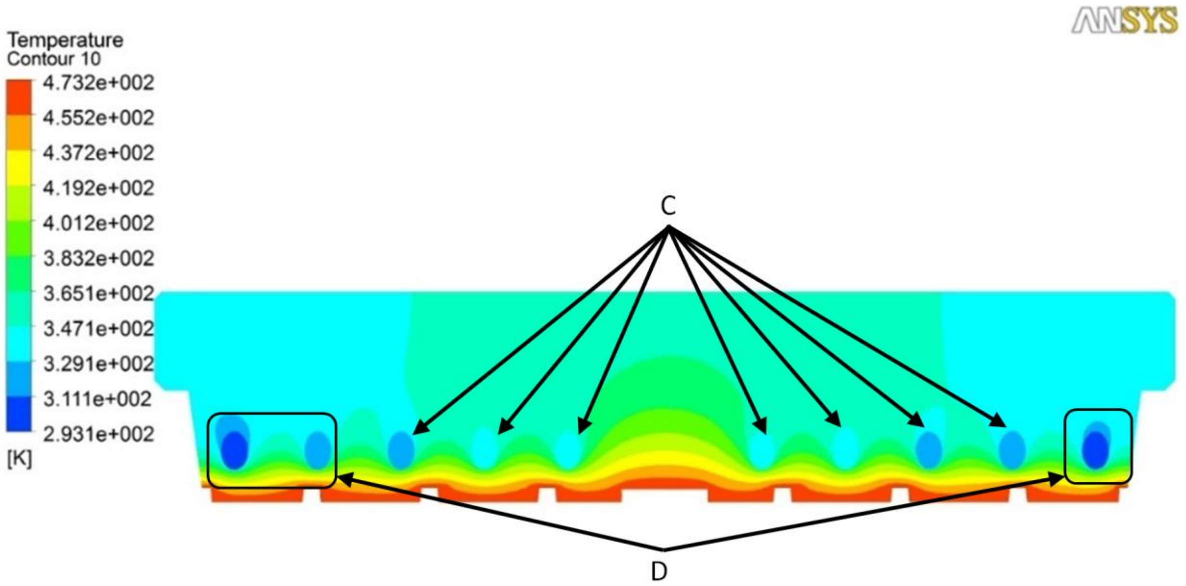



*Figure 4.13: Temperature distribution of the cooling medium from the outside (D) to the inside (C) of the meander conformal cooling channel design.*

Figure 4.14 shows a graph of temperature against time for five randomly spaced particles flowing through the meander conformal cooling channel.

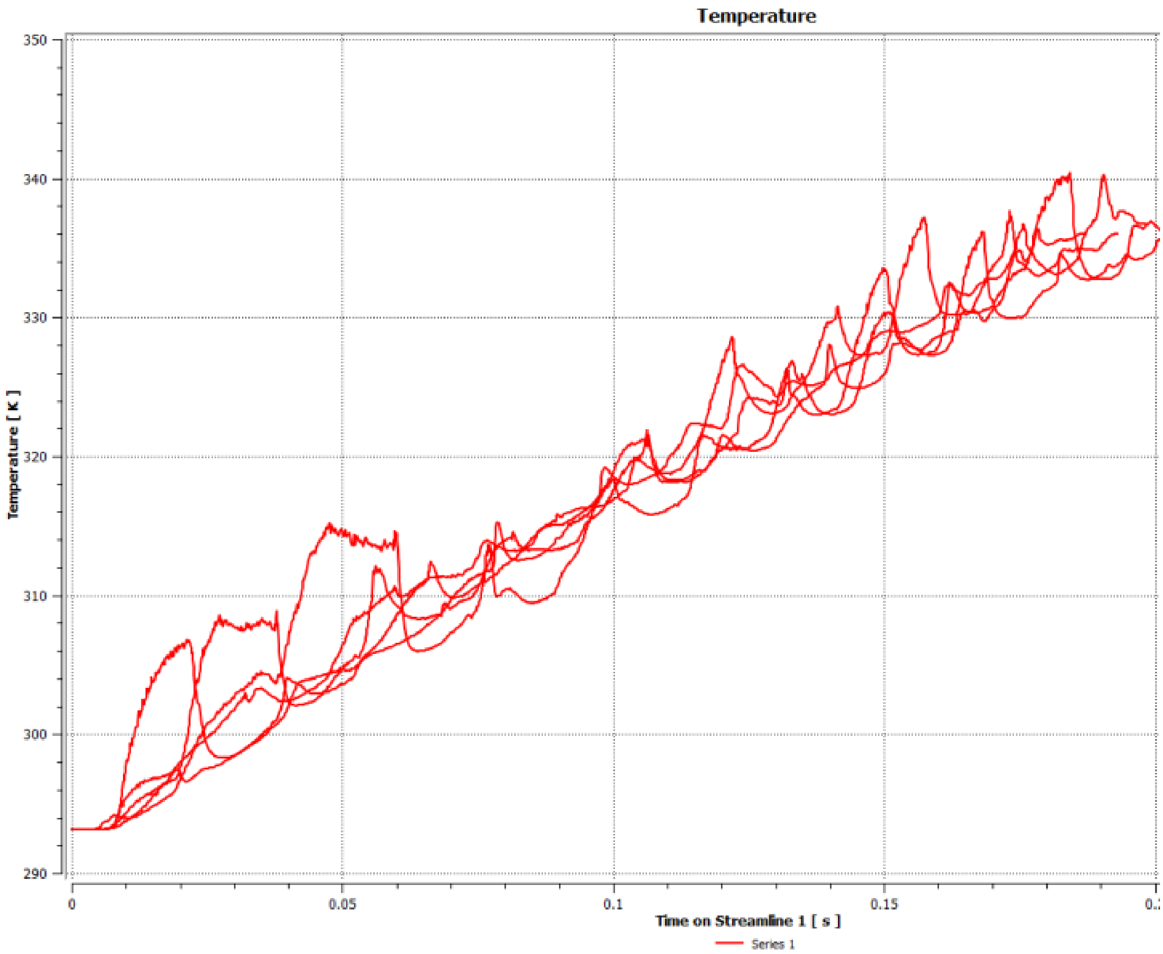



*Figure 4.14: Temperature vs time results for the meander AM insert.*

The peaks indicate higher temperatures around the corners. The heat is then transferred by conduction to the bulk of the fluid (shown by the decrease in temperature) while it flows through the straight sections of the cooling channel.

The average heat absorbed by the cooling channels was calculated from the inlet and outlet temperatures obtained from the graph as follows:

$$Q = \dot{m}C_p\Delta T$$

$$Q = 0.133(4.187)(340.928 - 293.15)$$

$$Q = 26.606\ kJ$$

The area under each curve was calculated and divided by the total time to obtain the average temperature for each particle. The total average temperature of the cooling channel was calculated from the five particles' average temperatures, as shown in Table 4.3

*Table 4.3: Average calculated temperatures of the five particles flowing through the meander conformal cooling channel.*

| Particle | Average temperature [K] |
|---|---|
| Particle 1 | 317.363 |
| Particle 2 | 315.862 |
| Particle 3 | 316.551 |
| Particle 4 | 316.629 |
| Particle 5 | 315.745 |
| Average | 316.430 |

The maximum turbulence kinetic energy obtained from the simulated results for the meander conformal cooling design was 3.13247 $m^2.s^2$.

### *Discussion of results*

The simulated results summarised in Table 4.4 showed that the meander cooling channel induced a higher turbulent flow compared to the spiral cooling channel. The spiral cooling channel design had a maximum turbulence kinetic energy of 2.905 $m^2.s^2$ compared to the 3.132 $m^2.s^2$ of the meander cooling channel design. This was because the meander cooling channel design changed direction more often than the spiral cooling channel, resulting in a higher intermixing of the fluid (turbulence), improving the heat absorption of the water inside the cooling channel. The higher number of peaks in the temperature-time graph (Figure 4.14) also indicates that more heat was absorbed by the meander cooling channel design compared to the spiral cooling channel design.

*Table 4.4: Simulated results of the spiral and meander conformal cooling channels.*

| Variable | Spiral channel | Meander channel | Variation (%) |
|---|---|---|---|
| Outlet temperature [K] | 341.281 | 340.928 | 0.1% |
| Maximum turbulence kinetic energy [$m^2.s^2$] | 2.905 | 3.132 | 7.2% |
| Heat transfer [kJ] | 26.803 | 26.606 | 0.7% |
| Average water temperature [K] | 316.225 | 316.429 | 0.06% |

The percentage variation of the outlet temperature, heat transfer and average water temperature between the spiral and meander cooling channels was less than 1%, as shown in Table 4.4. The meander cooling channel design had a 7% higher maximum turbulence kinetic energy compared to the spiral cooling channel design. This variation could be due to the different flow patterns caused by the cooling channel layout.

Based on the results of Table 4.4, the meander cooling channel design was selected as the most efficient design due to the higher turbulence kinetic energy. The meander cooling channel design will be manufactured and compared to the conventionally manufactured insert during Phase 2.

## 4.3 Phase 2: Compare and evaluate meander AM insert design with a conventionally manufactured insert.

During Phase 2, a conventionally manufactured insert was designed with cooling channels according to the design specifications of Table 3.5, considering mould constraints and manufacturing limitations. Simulations were conducted with ANSYS® and SIGMASOFT® using the conventionally manufactured cooling channel design. The same simulation parameters were used for the conventional cooling channel design as indicated in Table 4.1. Figure 4.15 schematically illustrates the layout of Phase 2.

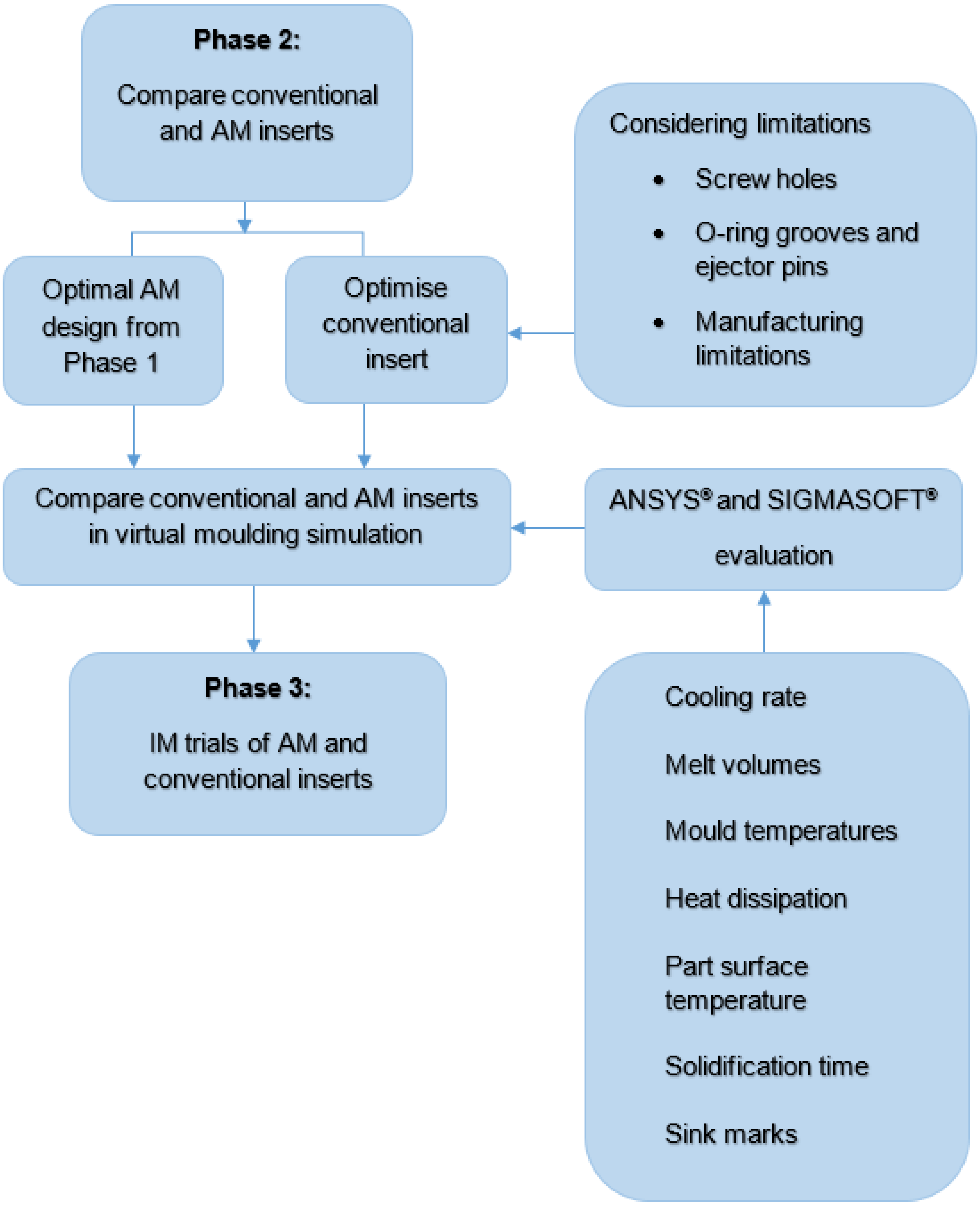



*Figure 4.15: Schematic representation of Phase 2.*

### 4.3.1 Insert with conventionally manufactured cooling channels

During the design of the cooling channel layout, conventional manufacturing techniques such as straight-line drilling, slotting and grooving were considered while avoiding mould features such as screw holes and ejector pins holes, as shown in Figure 4.16. Due to the fit, form and function of the insert, it was not possible to drill cooling channels into the insert, thus the channels were machined into the rear face by slotting a groove accompanied by a smaller groove necessary for an O-ring seal.

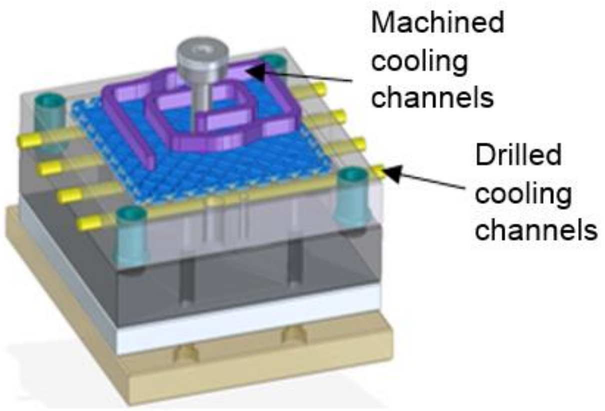



*Figure 4.16: Cooling channel layout of the conventionally manufactured insert.*

### 4.3.2 Comparison between AM and conventionally manufactured inserts

The same simulation parameters were used, as shown in Table 4.1, to compare the conventional insert to the AM insert with meander conformal cooling channels. The first twenty-five IM cycles were simulated using SIGMASOFT® virtual moulding simulation software. From the SIGMASOFT® simulation results the following were compared:

- Heat flow
- Melt volumes
- Mould temperature
- Insert surface temperature
- Solidification time
- Sink marks

The cooling rate and mould temperatures during an IM cycle were recorded at ten seconds after the start of the cycle when the injection of the polymer was completed and after 27 seconds before the mould opened for the first and the 25$^{th}$ IM cycle. The melt volumes were recorded after 16 seconds for the first and the 25$^{th}$ IM cycle. The cycle time for each insert was determined by measuring the time taken to obtain the same amount of solidification inside the cavity after the runner and/or sprue had frozen off.

### 4.3.3 Results

***Heat flow***

After the first IM cycle, more heat was absorbed by the conformal cooling channel design, resulting in a lower mould temperature. The total amount of heat removed by the conventional and AM inserts after the first and 25th cycles are shown in Table 4.5.

*Table 4.5: Total amount of heat removed by the conventional and AM inserts after the first and 25th cycles.*

| | Heat flow (kJ) | |
|---|---|---|
| **Cycle number** | 1st IM cycle | 25th IM cycle |
| **AM insert** | 6.788 | 8.917 |
| **Conventional insert** | 0.737 | 6.323 |

Figure 4.17 illustrate the heat flow in joule against time per IM cycle for the conformal and conventional cooling channels.

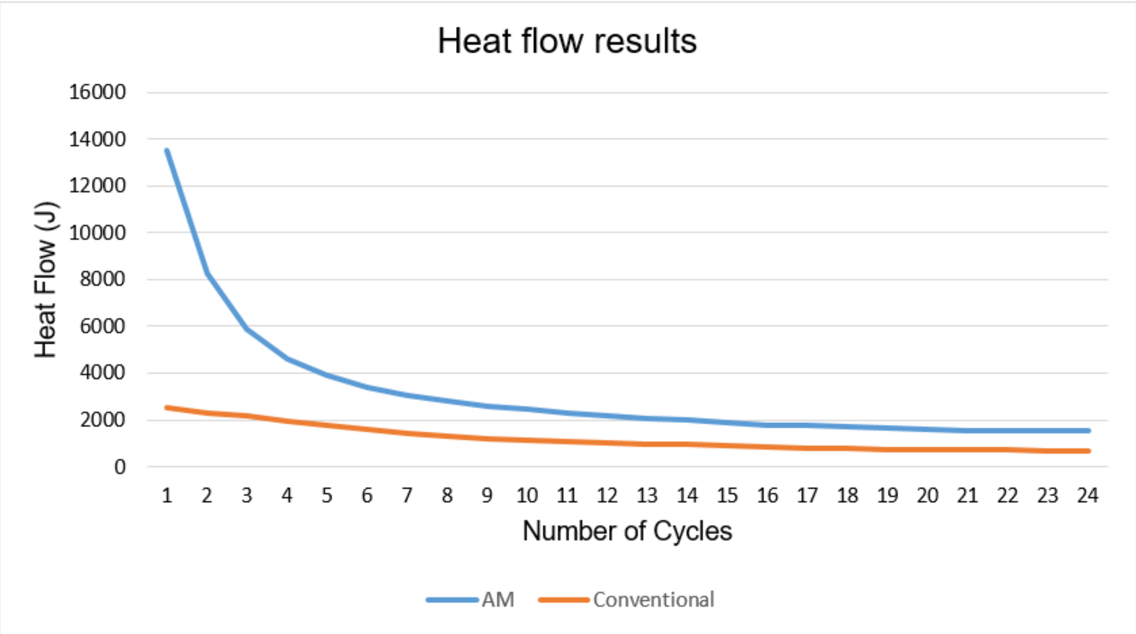



*Figure 4.17: Simulated heat flow results of the AM insert with conformal cooling channels and the conventionally manufactured insert during 25 IM cycles.*

### *Melt volume*

Figure 4.18 shows the melt volumes of the AM and the conventional inserts after 16 seconds during the 25th IM cycle. The regions indicated in red are still feedable through the runner, regions indicated in blue are frozen from the runner, while the transparent regions indicate solidified material.

From the comparison shown in Figure 4.18, it can be seen that there were less regions with flowable material (indicated in blue and red) in the part manufactured by the insert with conformal cooling channels (Figure 4.18 A) than in the part manufactured by the insert with conventional cooling channels (Figure 4.18 B).

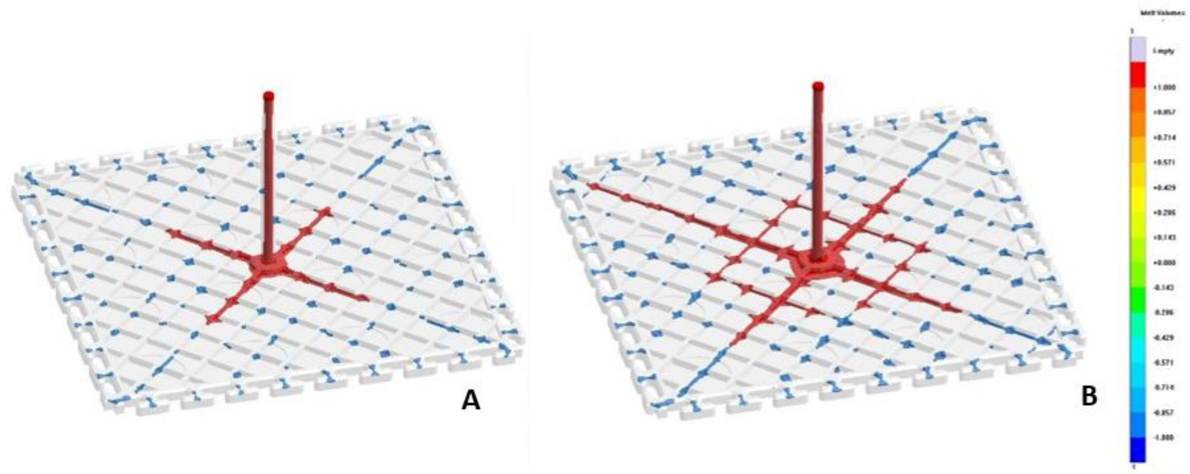



*Figure 4.18: Melt volumes after 16 seconds during the 25th cycle for the AM insert (A) and conventionally manufactured insert (B).*

### *Mould temperature*

The temperature distribution inside the mould is shown in Figure 4.19. After 27 seconds into the 25th IM cycle, the conformal cooling channels (Figure 4.19 A) absorbed more heat than the conventional cooling channels (Figure 4.19 B), preventing the heat from conducting through to the mould components, resulting in a shorter cycle time. The maximum mould temperature after 27 seconds during the 25th IM cycle was 38.9 °C in the conformal cooling channel mould compared to 49.2 °C in the conventional cooling channel mould.

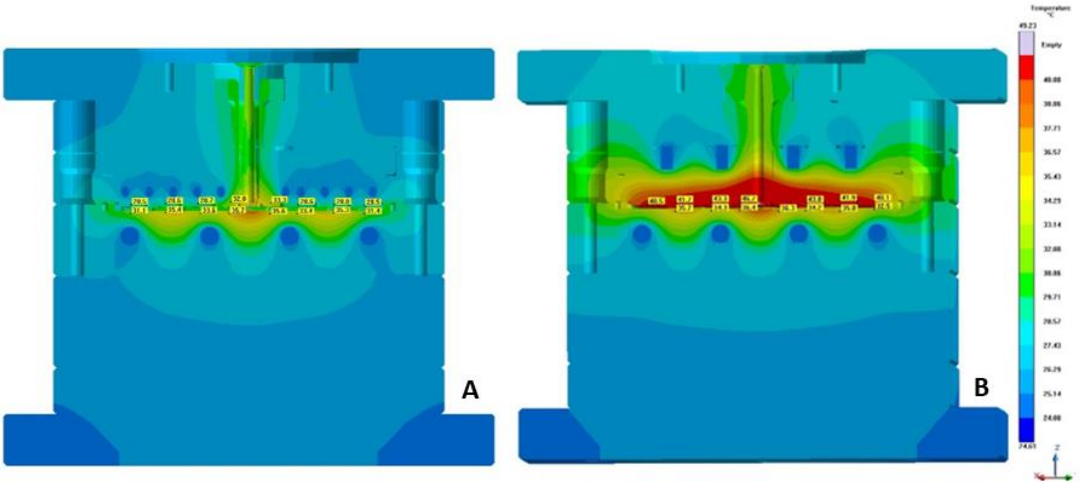



*Figure 4.19: Internal mould temperatures after 27 seconds during the 25th IM cycle for the AM insert (A) and the conventionally manufactured insert (B).*

### Insert surface temperature

Simulated results show that after 25 IM cycles, the insert with conformal cooling channels (Figure 4.20 A) had a lower surface temperature compared to the insert with conventional cooling channels (Figure 4.20 B). The average temperature difference between the AM insert and the conventional insert after the first IM cycle was about 6 °C and 12 °C after the 25th IM cycle.

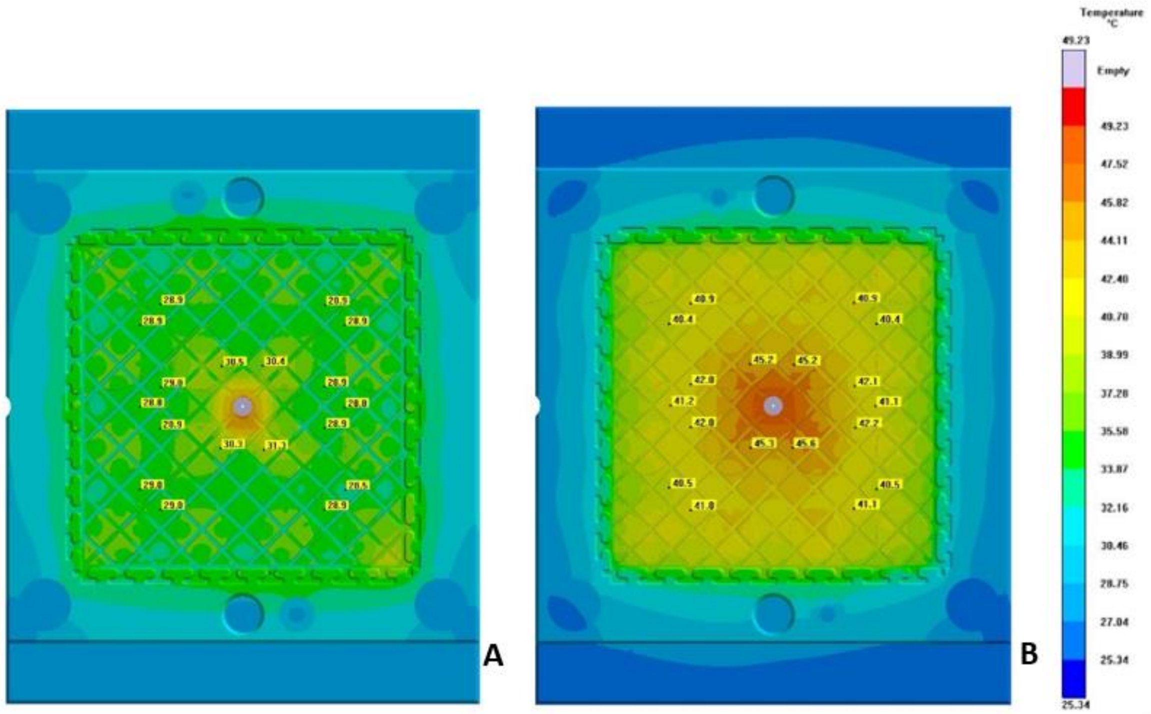



*Figure 4.20: Insert temperatures during the 25th cycle for the AM insert (A) and the conventionally manufactured insert (B).*

### *Solidification time*

The difference in solidification time was more noticeable after the 25th IM cycle compared to the first IM cycle due to the insert surface temperature difference between the two inserts as shown in Figure 4.21. The difference in time to reach the same amount of solidification after 25 IM cycles was 1.8 seconds between the two inserts. This resulted in the part manufactured by the AM insert being ejected 1.8 seconds earlier than the part manufactured by the conventionally manufactured insert.

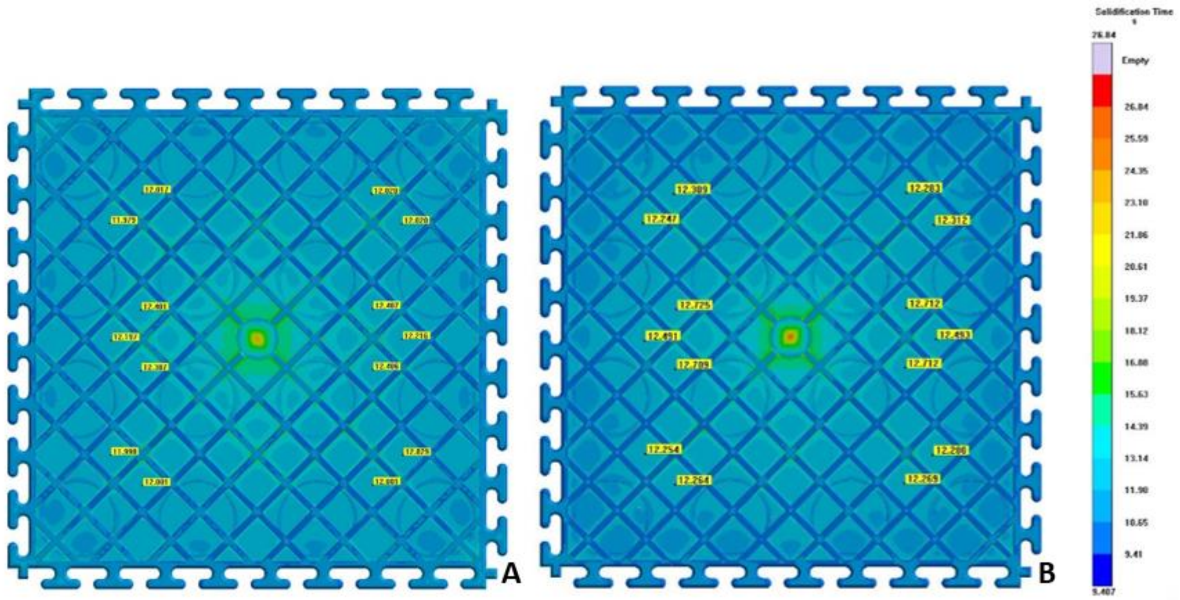



*Figure 4.21 A and B: Solidification time during the 25th cycle after 27 seconds for the AM insert (A) and the conventionally manufactured insert (B).*

### *Sink marks*

From the simulated results, there was not any noticeable difference between the maximum displacement of the sink marks between the two different cooling channel designs, as shown in Figure 4.22.

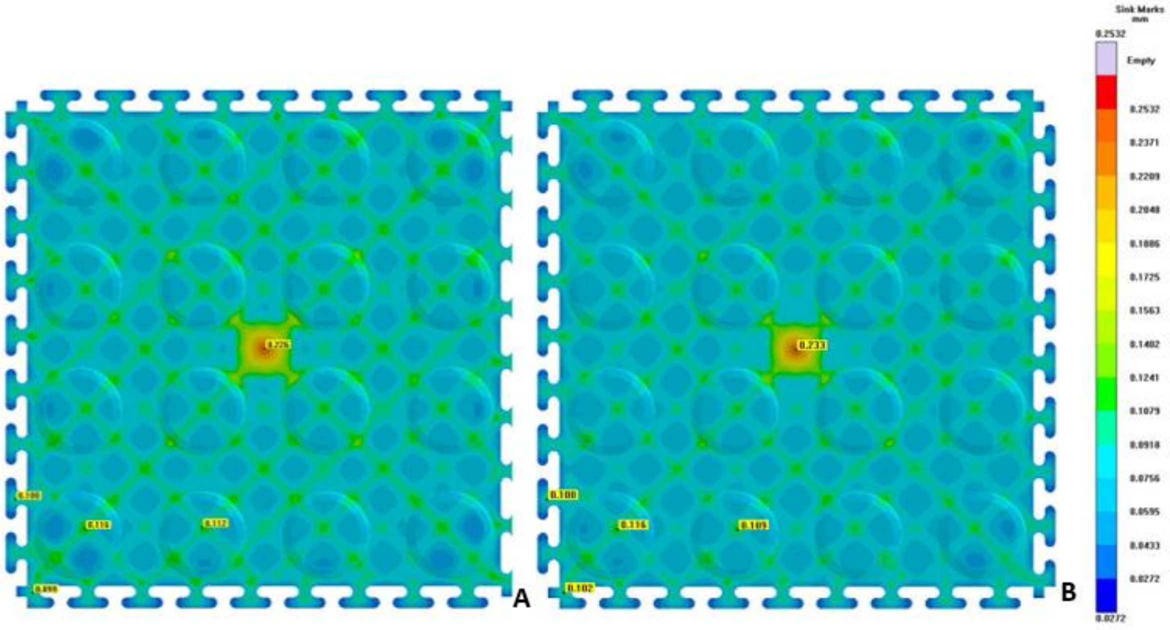



*Figure 4.22: Maximum displacement of the sinks marks after 25 IM cycles for the AM insert (A) and the conventionally manufactured insert (B).*

### 4.3.4 Discussion of results

The maximum values for cooling rates, mould temperatures, solidification times and sink marks are summarised in Table 4.6 for the AM insert and the conventionally manufactured insert during the first and 25th IM cycles.

*Table 4.6: Simulated results for cooling rates, mould temperatures, solidification times and sink marks for the AM and conventionally manufactured inserts.*

| Variable | Conformal | Conventional | Variation (%) |
|---|---|---|---|
| Maximum cooling rate (Cycle 1, t = 10 s) | 116 [°C/s] | 116 [°C/s] | 0.0% |
| Maximum cooling rate (Cycle 25, t = 10 s) | 113.3 [°C/s] | 111.7 [°C/s] | 1.4% |
| Maximum cooling rate (Cycle 1, t = 27s) | 5.4 [°C/s] | 5.4 [°C/s] | 0.0% |
| Maximum cooling rate (Cycle 25, t = 27s) | 5.4 [°C/s] | 5.5 [ºC/s] | 1.8% |
| Maximum mould temperature (Cycle 1, t = 27s) | 35.7 [°C] | 39.9 [°C] | 10.5% |
| Maximum mould temperature (Cycle 25, t = 27s) | 38.9 [°C] | 49.2 [°C] | 20.9% |
| Maximum solidification time (Cycle 1, t = 27s) | 24.4 [s] | 25.4 [s] | 3.9% |
| Maximum solidification time (Cycle 25, t = 27s) | 25 [s] | 26.8 [s] | 6.7% |
| Maximum sink marks (Cycle 1, t = 27s) | 0.25 [mm] | 0.25 [mm] | 0.0% |
| Maximum sink marks (Cycle 25, t = 27s) | 0.25 [mm] | 0.25 [mm] | 0.0% |

The AM insert had a larger maximum cooling rate, especially after 25 IM cycles, compared to the conventional insert, as shown in Table 4.6. The cooling rate during the first IM cycle is the same for both inserts because the mould was still cold and most of the heat was absorbed by the mould components. The 1.8 second difference between the solidification times occurred due to a more efficient heat energy transfer by the AM insert compared to the conventionally manufactured insert. This resulted in a shorter cycle time, increasing the production rate of the AM insert by 6.7% compared to the conventionally manufactured insert.

The heat flow from the molten plastic to the cooling channel through the mould is shown in Figure 4.23 for the first and 25th IM cycles for both the AM and conventional manufactured inserts. The amount of heat absorbed by the inserts during the first IM cycle was higher than the 25th IM cycle, the reason being that as the mould was heated during consecutive IM cycles, less heat was absorbed as the system reached a quasi-equilibrium state after 25 IM cycles. The AM insert can absorb and transfer heat more efficiently compared to the conventionally manufactured insert, as seen in Figure 4.23 below.

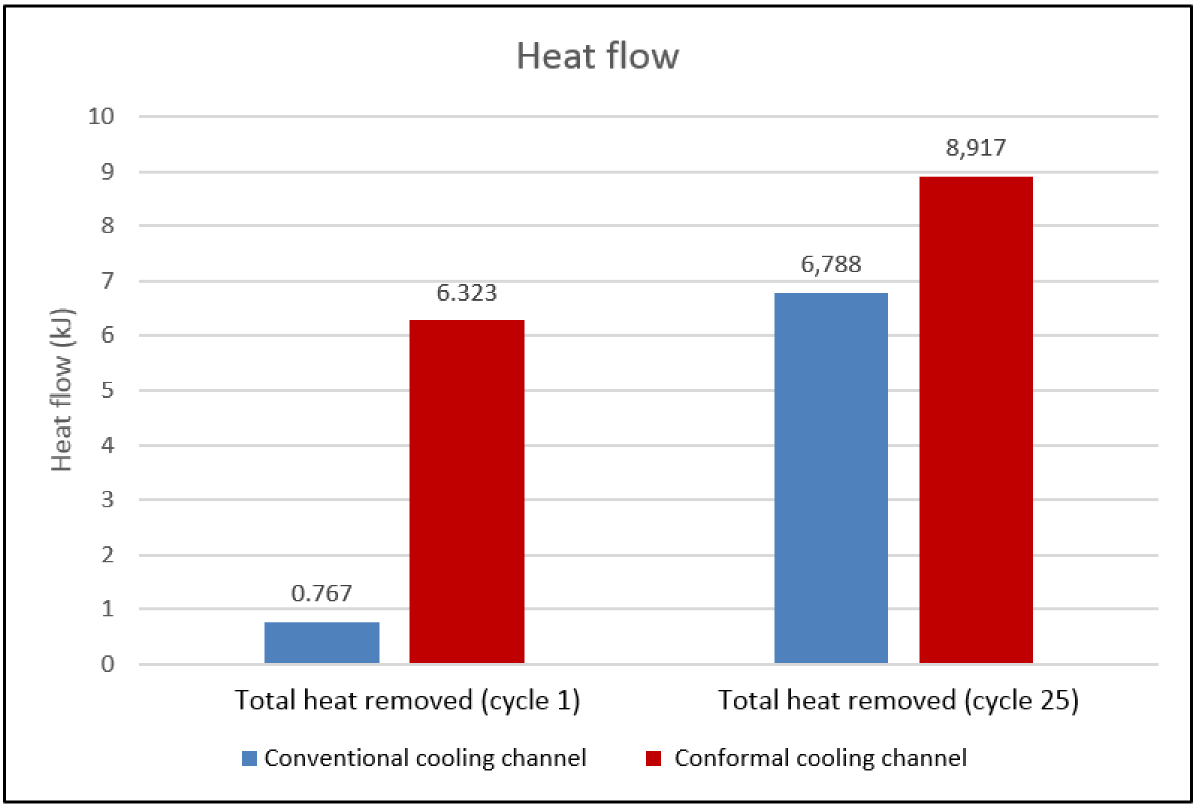



*Figure 4.23: Heat absorbed by the conventional and conformal cooling channels designs during the first and 25th IM cycles.*

## 4.4 Phase 3: IM trials of AM and conventionally manufactured inserts

During Phase 3, IM trials were conducted with the AM and conventionally manufactured inserts. Probes were placed inside the inserts to record the actual temperatures of the inserts during the first 25 IM cycles. These values were compared to the simulated results using virtual probes placed at the same locations as the actual probes. Figure 4.24 illustrates the layout of Phase 3 schematically.

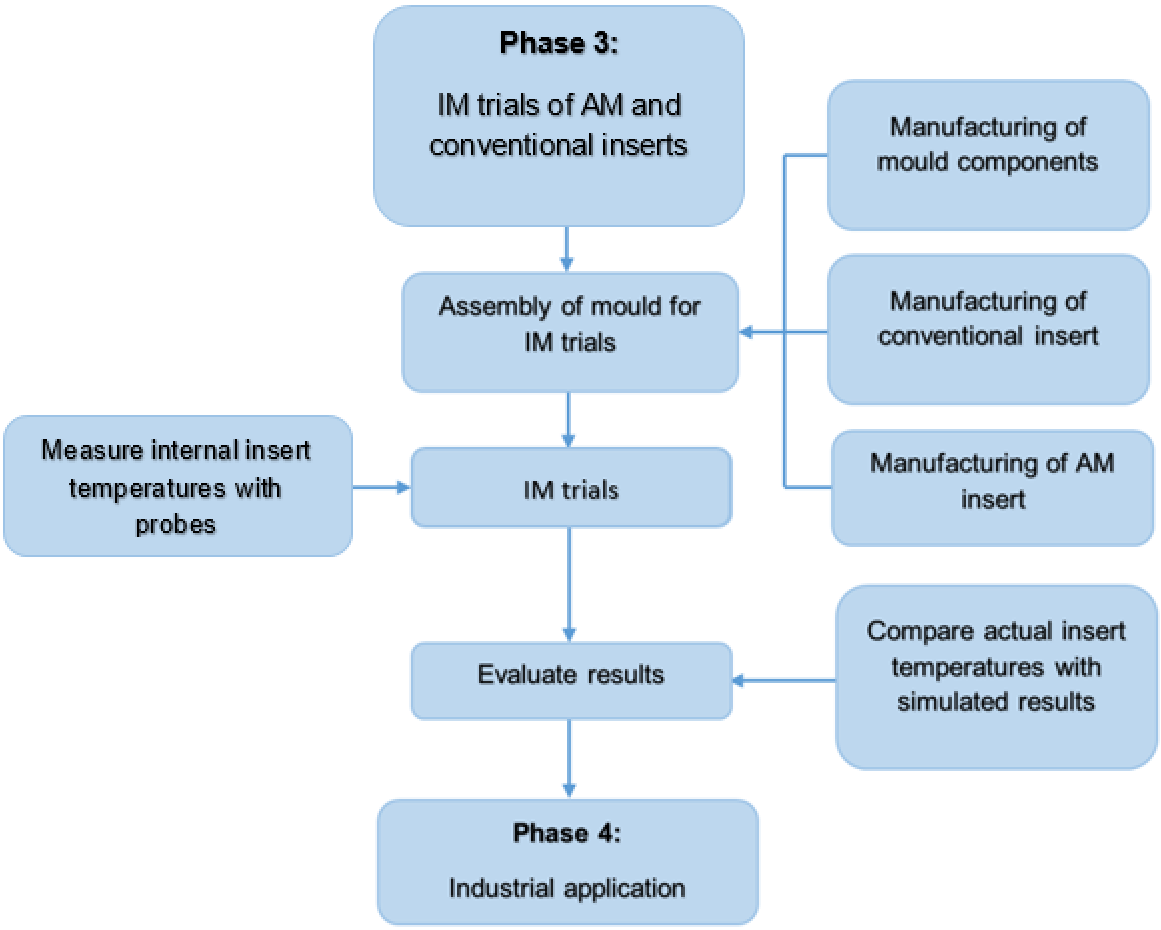



*Figure 4.24: Schematic representation of Phase 3.*

### 4.4.1 Procedure

A mould was designed to accommodate the two different versions of inserts. This allowed for the internal temperatures to be measured inside the inserts during the IM process using similar process conditions. The mould components were manufactured by subtractive manufacturing through CNC machining. Machine tool paths were created and converted into Numerical Control (NC) codes using EdgeCam 2014 R1, CAM software. The mould components were manufactured using a Jyoti VMC850 vertical CNC machining centre, as shown in Figure 4.25.

*Figure 4.25: Jyoti VMC850 vertical CNC machine used to manufacture the mould components.*

### 4.4.2 Manufacturing of AM insert

An AM insert was manufactured through the DMLS process, using an EOSINT M280 DMLS machine, from Maraging Steel MS1, as shown in Figure 4.26. Layer thicknesses of 50 μm were used, and additional material stock of 0.5 mm was also added to all the external faces of the insert to make provision for possible distortions during the AM process. The material added to the insert was removed during a post-processing procedure through CNC machining.


*Figure 4.26: EOSINT M280 AM machine used to manufacture the AM insert from Maraging Steel MS1.*

### 4.4.3 Manufacturing of the conventional insert

The cooling channels for this insert were designed to suit conventional manufacturing techniques. Because the external features of the two inserts were the same, existing holes and features of the insert were taken into consideration during the cooling channel design. The cooling channel and O-ring grooves were manufactured by machining slots into the bottom of the insert, as shown in Figure 4.27.

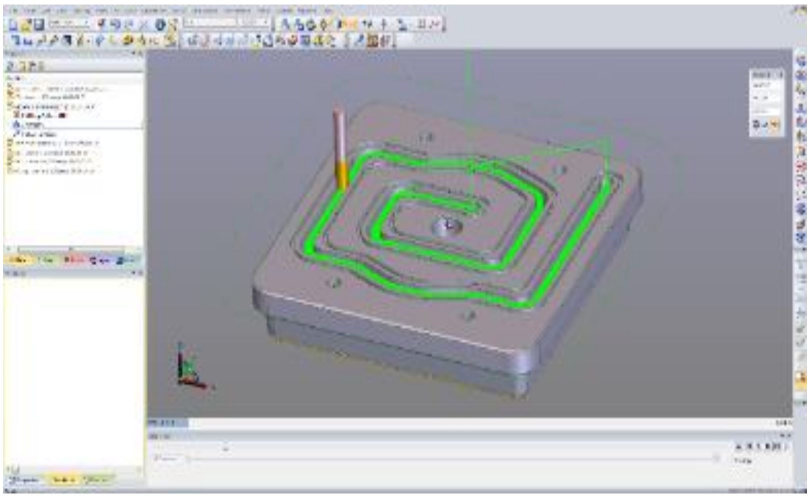


*Figure 4.27: NC toolpaths program created by EdgeCam 2014 R1 for the manufacturing of the conventional cooling channels.*

### 4.4.4 IM trials

A Dr BOY 22-ton IM machine was used for the IM trials of the mould with the AM and conventionally manufactured inserts, as shown in Figure 4.28.

*Figure 4.28: Dr Boy IM machine used during the IM trial with the PC interface used to record the temperatures of the mould.*

Both inserts were fitted with temperature probes to record the temperatures inside the inserts during the IM process. A microcontroller (Arduino uno) with a PC interface (developed by the Research Group in Evolvable Manumation Systems within the Department of Electrical, Electronic and Computer Engineering at CUT) was used to record and display the temperatures during the IM trials. Figure 4.29 shows the locations of the simulated probes (A) and the corresponding locations of the actual probes (B) inside the inserts.

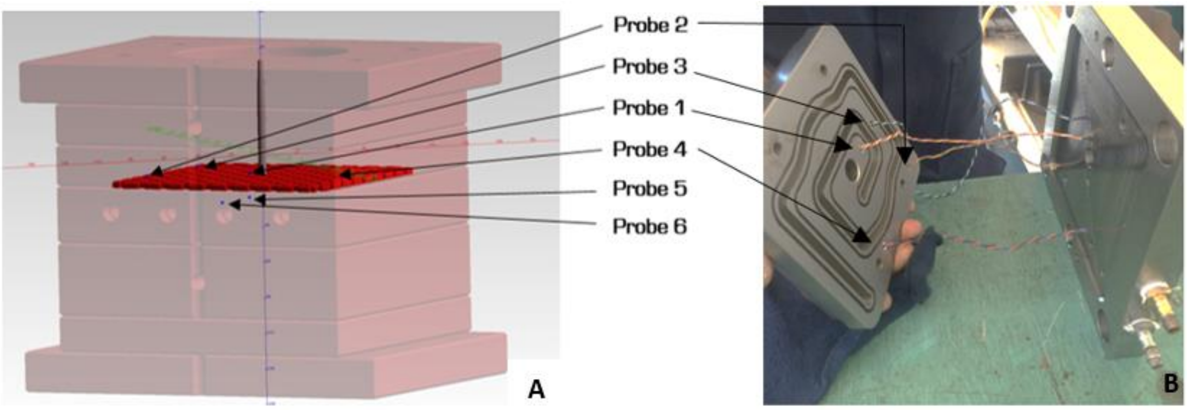
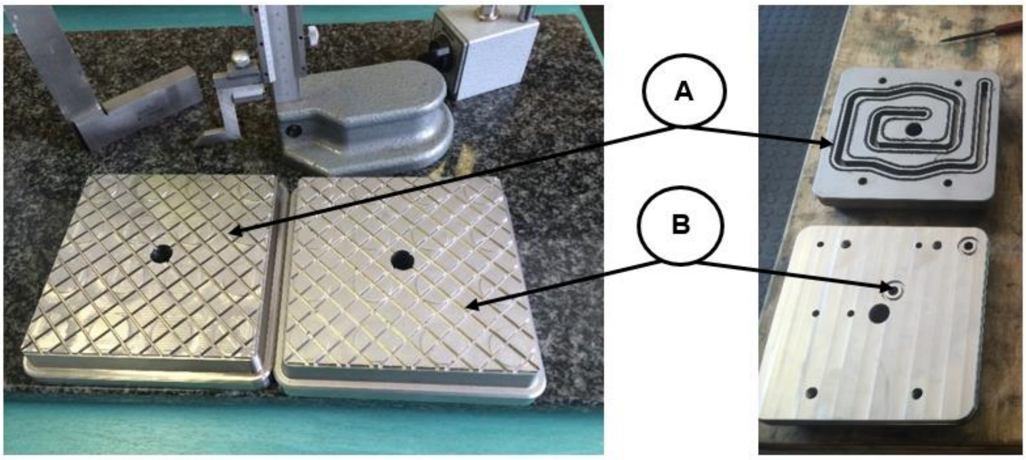



*Figure 4.29: Locations of the simulated probes (A) and the corresponding locations of the actual probes (B) placed inside the inserts.*

Figure 4.30 shows the manufactured conventional (A) and AM (B) inserts that were used during the actual IM trials.




A = Conventional manufactured insert with cooling channels machined from bottom of insert

B = AM insert with conformal cooling channels (inlet and outlet of cooling channel visible)

*Figure 4.30: Conventionally manufactured (A) and AM insert (B) used during the actual IM trials.*

### 4.4.5 Results

The temperature results for the first 25 IM cycles of both cooling channel designs were compared to the simulated results. The temperature-against-time graph for Probe 2, shown in Figure 4.31, shows the measured and the simulated temperatures of the conventionally manufactured insert from the first to the 25$^{th}$ IM cycle. Probe 2 was selected because of its placement closest to the part surface where the polymer material is injected into the cavity. This placement should give an overall representation of both inserts' temperatures and the conduction of heat through the material during the IM cycle. Due to the placement of the probe inside the AM insert, the starting temperature for both the actual and simulated values were slightly higher than those of the conventionally manufactured insert.

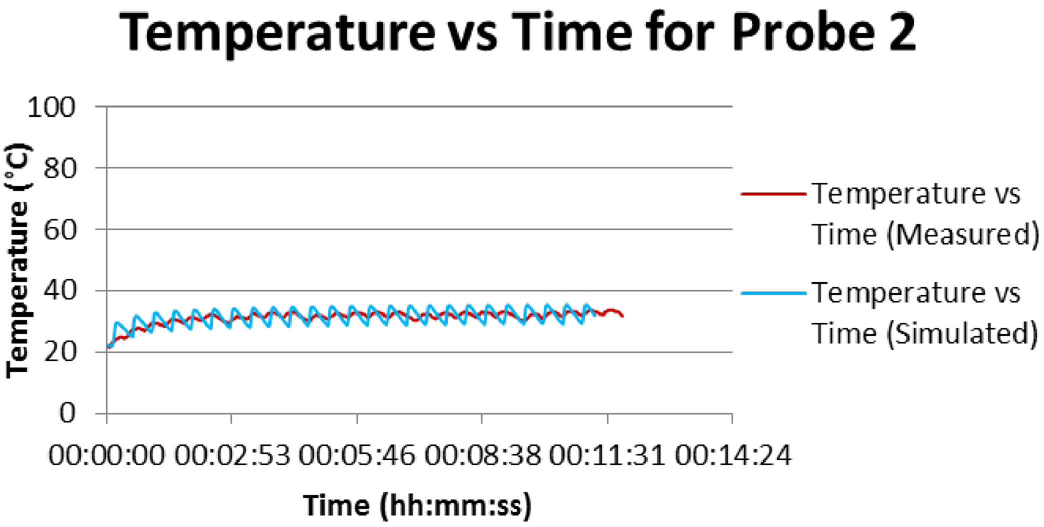



*Figure 4.31: Measured and simulated temperatures of the conventionally manufactured insert from the first to the 25th IM cycle for Probe 2.*

Table 4.7 below shows a comparison between simulated and actual probe temperatures for the conventionally manufactured insert.

*Table 4.7: Actual and simulated probe temperatures of the conventionally manufactured insert.*

| | Measured average temperature (°C) | Simulated average temperature (°C) | Variation (%) |
|---|---|---|---|
| **Probe 1** | 37.06 | 34.84 | 5.98 |
| **Probe 2** | 31.30 | 31.47 | 0.54 |
| **Probe 3** | 34.69 | 32.58 | 6.08 |
| **Probe 4** | 25.71 | 26.43 | 2.73 |
| **Probe 5** | 29.14 | 27.48 | 5.69 |
| **Average** | **31.58** | **30.56** | **4.21** |

For the conventionally manufactured insert, the average temperature of the simulated probes was within 4.21% of the average temperature values measured during the IM trials. The deviation between the simulated results and the experimental results could be because the simulated results were based on theoretical internal temperatures compared to the experimental results, which depended upon a variety of real-world factors such as the difference in conductivity between the mould components and the probes. Figure 4.32 shows the measured as well as simulated temperatures of the conformal cooling insert during the first to $25^{th}$ IM cycle.

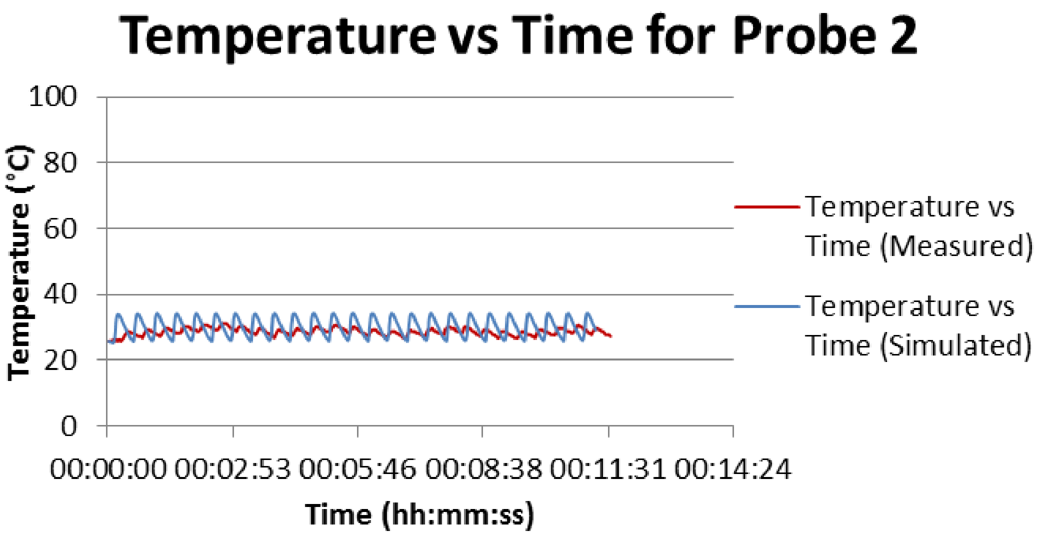



*Figure 4.32: Measured and simulated temperatures of the AM insert from the first to the 25th IM cycle for Probe 2.*

Table 4.8 below shows a comparison between simulated and actual probe temperatures for the AM insert.

*Table 4.8: Actual and simulated probe temperatures of the AM insert.*

| | Measured average temperature (°C) | Simulated average temperature (°C) | Variation (%) |
|---|---|---|---|
| **Probe 1** | 29.83 | 31.30 | 4.69 |
| **Probe 2** | 28.74 | 30.11 | 4.55 |
| **Probe 3** | 28.81 | 30.33 | 5.01 |
| **Probe 4** | 30.65 | 31.43 | 2.48 |
| **Probe 5** | 34.67 | 34.52 | 0.43 |
| **Average** | **30.54** | **31.54** | **3.43** |

## 4.5 Conclusion

It is possible to use CAE and CFD software to analyse conformal cooling channel designs to identify the most efficient design for the transfer of heat from the insert to the cooling fluid. This can be used to obtain the most effective cooling channel design before major capital is invested to produce an AM insert with conformal cooling for the IM process.

The total heat removed during the first and the 25$^{th}$ IM cycles for the conventionally manufactured and AM inserts shows that the AM insert can remove more heat energy per unit of time compared to the conventionally manufactured insert. This is because the conformal cooling channel geometry and layout is not constrained by the AM process used to manufacture the insert. It is evident that a conformal cooling channel design can remove heat more efficiently from the mould compared to a conventional cooling channel design. This is an important advantage of AM inserts for the IM process because it can influence the rate at which plastic components can be produced.

# 5 CASE STUDY: INDUSTRIAL APPLICATION

To study the feasibility of DMLS inserts for production tooling, the knowledge gained during Phases 1 to 3 were applied to an industrial application during Phase 4. An AM insert with conformal cooling channels and a conventionally manufactured insert with conventional cooling channels were designed for the industrial application. The two insert designs were evaluated comparing the manufacturing costs and lead-times of the different insert manufacturing techniques. A virtual IM simulation was conducted to determine the performance of the two inserts during the IM process. The schematic layout of Phase 4 is illustrated in Figure 5.1.

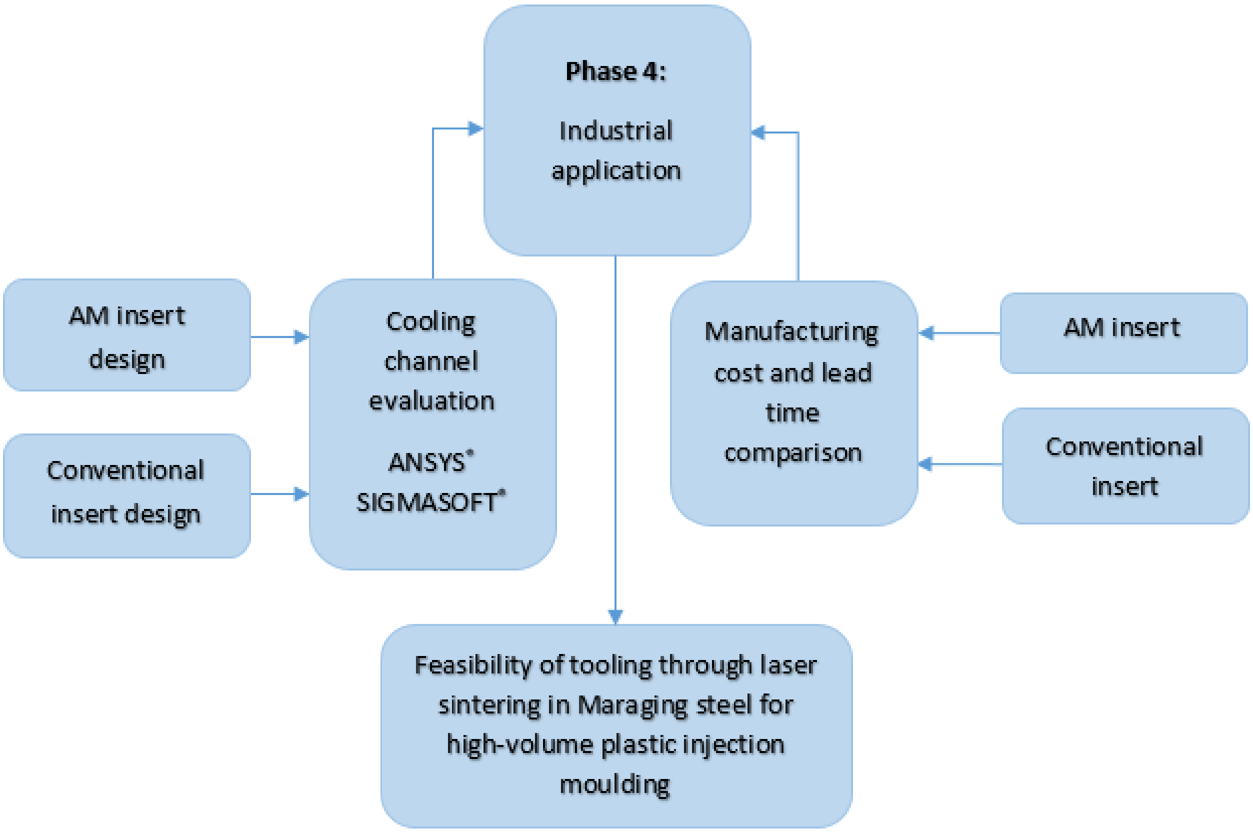



*Figure 5.1: Schematic representation of Phase 4.*

## 5.1 Industrial application: Triga mould

Two components to be manufactured through the IM process were developed for Triga, a company specialising in display systems. A family mould configuration, shown in Figure 5.2 A and B, was designed to manufacture the different components. An AM insert was considered for the product, shown in blue in Figure 5.2 C, due to the large number of geometrical features requiring secondary conventional manufacturing techniques such as EDM machining.

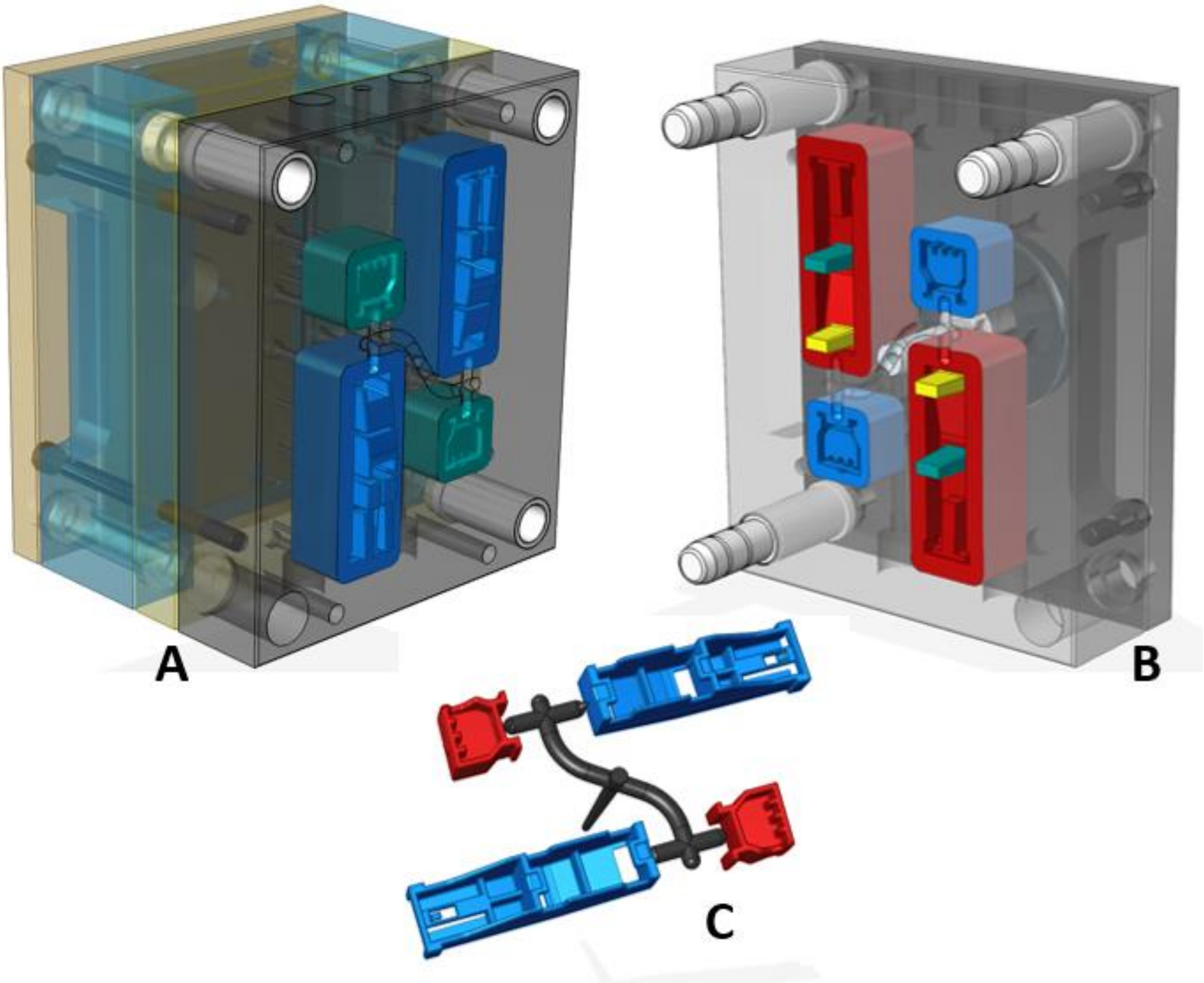



*Figure 5.2: CAD image of the moving (A), and fixed half (B) of the family mould as well as the products (C) for the Triga project.*

### 5.1.1 Procedure

An IM and inserts were designed following a similar design methodology as discussed in Section 3.6. AM inserts with conformal cooling channels were designed, to be manufactured through the DMLS process using Maraging Steel MS1 material, as shown in Figure 5.3.

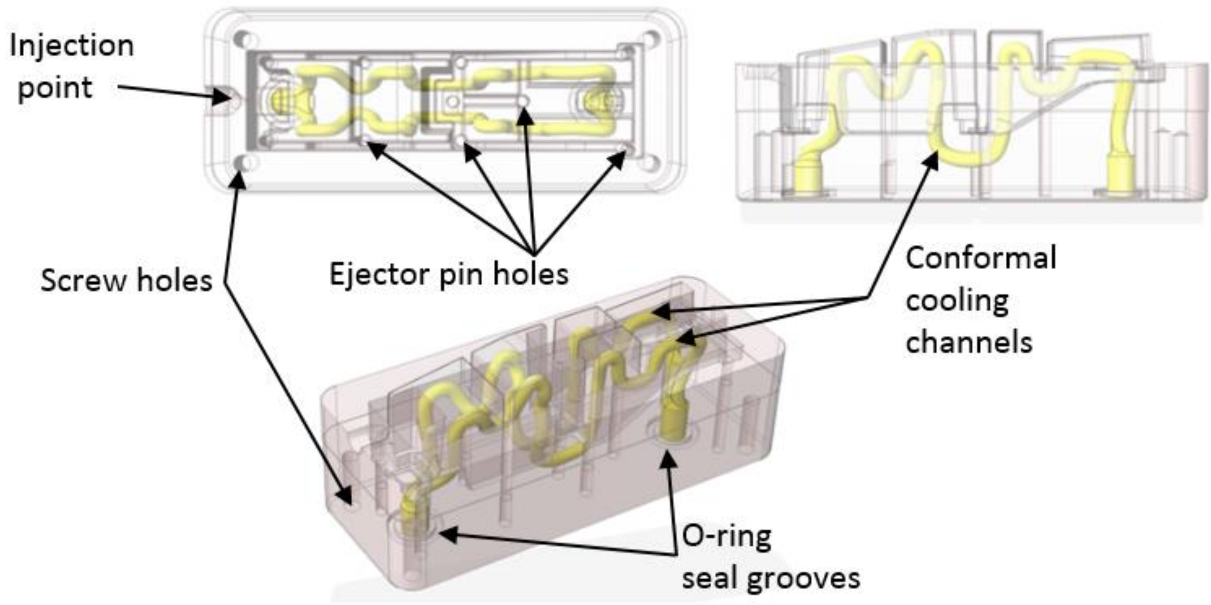



*Figure 5.3: CAD design of the DMLS insert with conformal cooling channels.*

A conventionally manufactured insert, shown in Figure 5.4, was designed considering the limitations of conventional manufacturing techniques such as straight-line drilling and slotting.

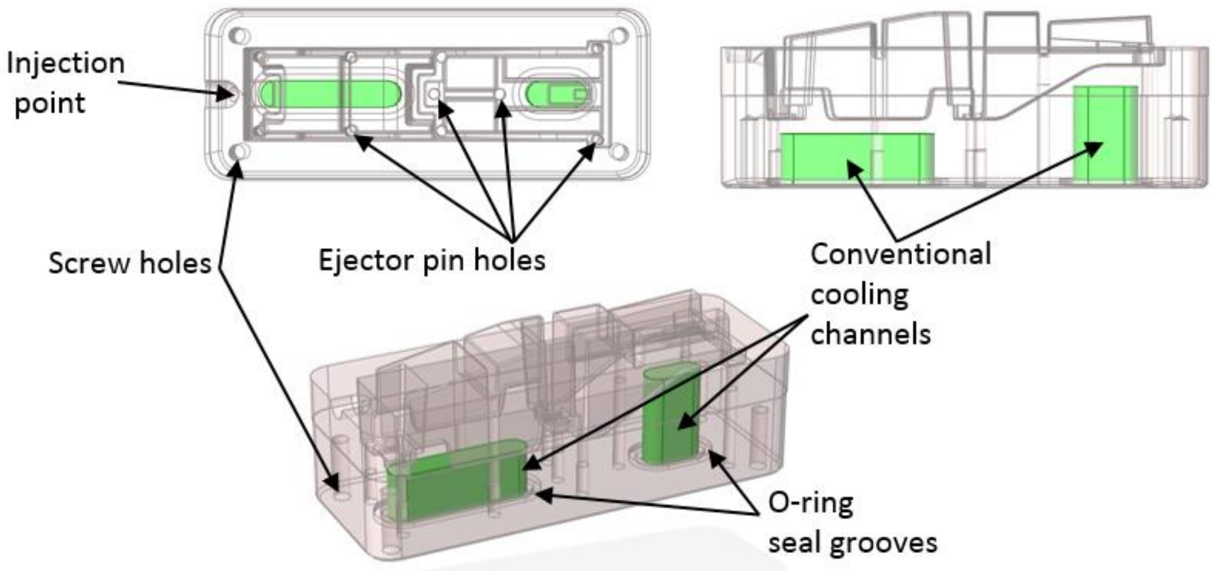



*Figure 5.4: CAD design of the conventionally manufactured insert with cooling channels.*

Figure 5.5 shows the influence of the different manufacturing techniques on the design of the cooling channels. Features such as ejector pins and screw holes influenced the cooling channel design of the conventional insert whereas the design freedom of AM allowed the cooling channels of the AM insert to follow the contours of the product more closely.

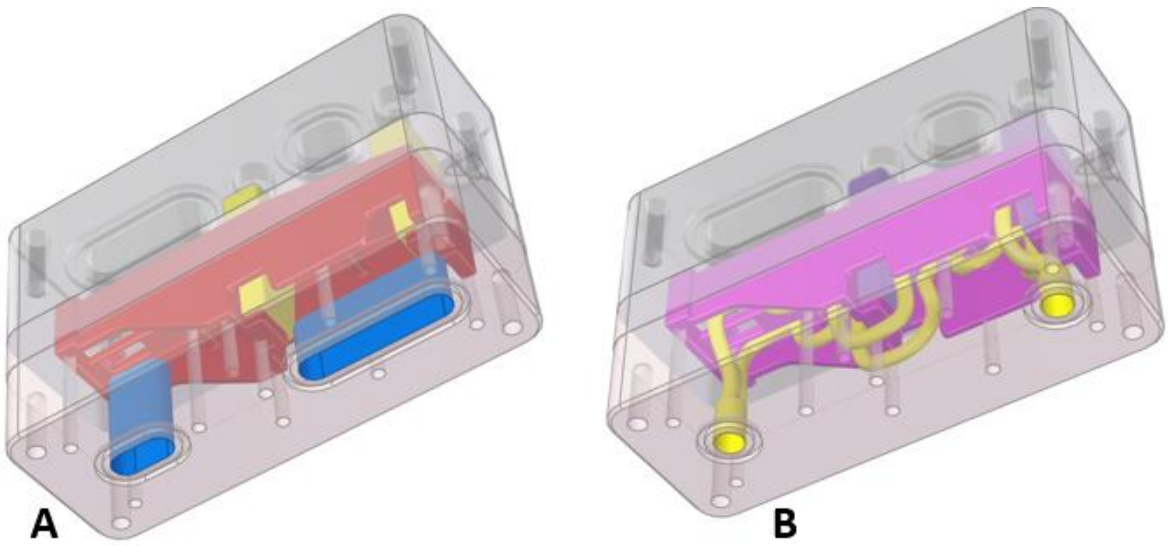



*Figure 5.5: Difference in the cooling channel design due to the different manufacturing techniques; conventional insert (A) and AM insert (B).*

Both cooling channel designs (conformal and conventional) were compared using simulation software ANSYS® and SIGMASOFT®. ANSYS® software was used to analyse the water flow and temperature increase within the cooling channels, while SIGMASOFT® mould flow simulation software was used to simulate the IM process.

### *Simulation process parameters*

The parameters used during the simulations were based upon the specifications and capability of the IM machine to be used to produce the components. Assumptions were made for the heat transfer coefficients and ambient temperatures during the SIGMASOFT® simulation, and the component was assumed to be isothermal for the ANSYS® simulation. The parameters used during the simulations are summarised in Table 5.1.

*Table 5.1: Simulation parameters used during the SIGMASOFT® and ANSYS® simulations for the Triga project.*

| Parameter | Value |
| --- | --- |
| **Ambient temperature** | 20 ºC |
| **Polymer material** | ABS Terluran GP22 (BASF) |
| **Polymer melt temperature** | 250 ºC |
| **Initial mould temperature (conventional and conformal)** | 25 ºC |
| **Insert material (conventional)** | 40CrMnMoS8-6 or (1.2312) |
| **Thermal conductivity (conventional insert)** | 20 [W/m °C] |
| **Specific heat capacity (conventional insert)** | 450 [J/kg °C] |
| **Insert material (AM)** | EOS Maraging Steel MS1 |

| | X3NiCoMoTi 18-9-5 or (1.2709) |
|---|---|
| **Thermal conductivity (conformal insert)** | 20 [W/m °C] |
| **Specific heat capacity (conformal insert)** | 450 [J/kg °C] |
| **Cooling fluid** | Water @ 25 ºC |
| **Cooling fluid mass flow rate (per channel)** | 1.2 [kg/min] |
| **Mould service time** | 10 s |
| **Filling pressure** | 80 bar |
| **Packing pressure** | 80% of filling pressure |
| **Filling time** | 2 s |
| **Packing time** | Until part ejection |
| **Mould closing time, after injection** | 40 s |
| **Total cycle time** | 52 s |
| **Number of cycles** | 20 |
| **Heat transfer coefficient (part-mould interface)** | 800 $[\frac{W}{m^2K}]$ |
| **Heat transfer coefficient (mould – cooling channel interface)** | 10000 $[\frac{W}{m^2K}]$ |
| **Heat transfer coefficient (mould – ejector pin interface)** | 10000 $[\frac{W}{m^2K}]$ |
| **Heat transfer coefficient of mould (moving half – fixed half interface)** | 10000 $[\frac{W}{m^2K}]$ |

The following simulation results were compared during the 20$^{th}$ IM cycle, when the mould had reached a quasi-equilibrium thermal state between the two different cooling channel designs:

- Cooling rate
- Part surface temperature
- Melt volumes
- Sink marks
- Warpage
- Heat dissipation
- Mould temperature
- Cooling channel turbulence

### 5.1.2 Results

#### *Cooling rate*

*Figure 5.6* below shows centre-section views of both designs during the IM process indicating in which manner the heat was transferred from the injected molten plastic through the inserts to the cooling medium. The encircled regions of *Figure 5.6* indicate a noticeable temperature difference inside the conformal and conventional cooling channel inserts after 30 seconds into the 20th IM cycle.

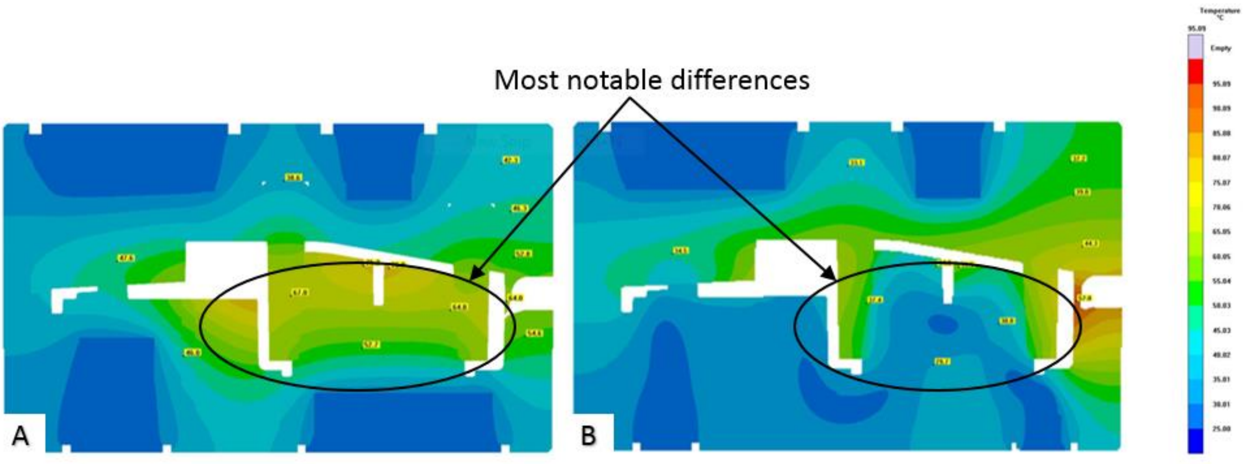



*Figure 5.6: Mould temperatures inside the conventional cooling (A) and conformal cooling (B) insert designs after 30 seconds during the 20th IM cycle.*

### Part surface temperature

Figure 5.7 and Figure 5.8 show the part surface temperatures of the two designs after 30 seconds into 20th IM cycle. From these figures it is evident that the conformal cooling channel design cooled the component more evenly compared to the conventional cooling channel design.

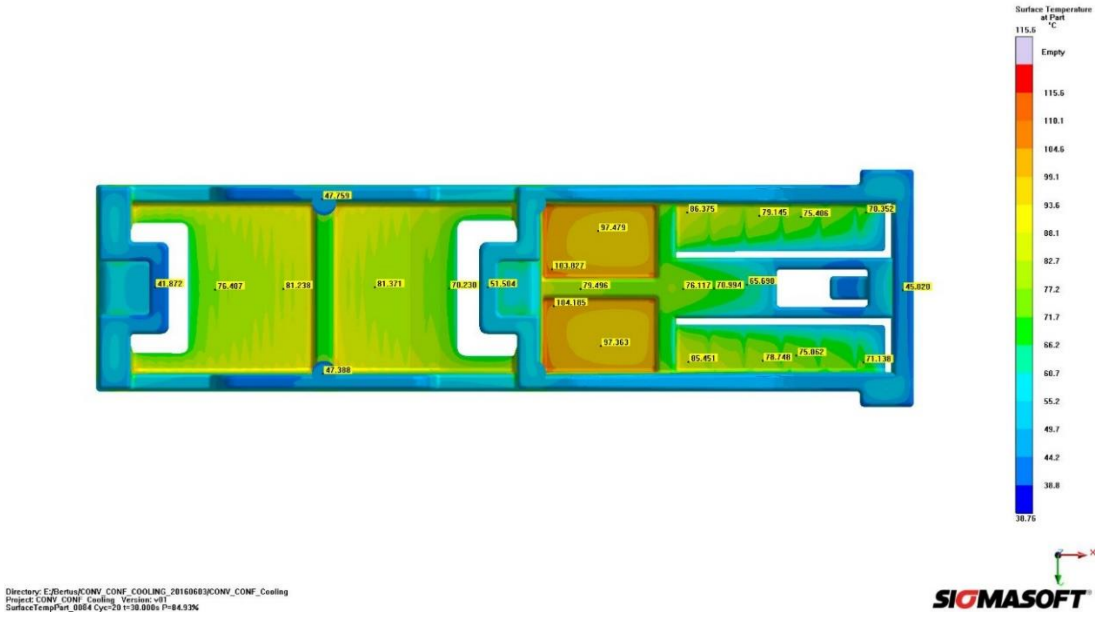



*Figure 5.7: Part surface temperature for the conventional cooling channel design after 30 seconds during the 20th IM cycle.*


*Figure 5.8: Part surface temperature for the conformal cooling channel design after 30 seconds during the 20th IM cycle.*

### *Melt volumes*

Hot spots inside the component are the result of poor heat transfer from the part to the mould that could cause defects in the product and should be avoided. Figure 5.9 shows the distribution of the hot spot time of a product manufactured using AM and conventionally manufactured inserts. The hot spot time is the time required for the molten material to completely solidify and is shown as coloured regions inside the part. The colour indicates the time it will take for that specific region to solidify and therefore has a direct effect on the IM cycle time. The larger hot spot times (indicated in warmer colours such as yellow, orange and red) in the conventional insert design (Figure 5.9 A) indicate that this design was less effective in transferring heat energy to the cooling medium compared to the conformal cooling channel insert.

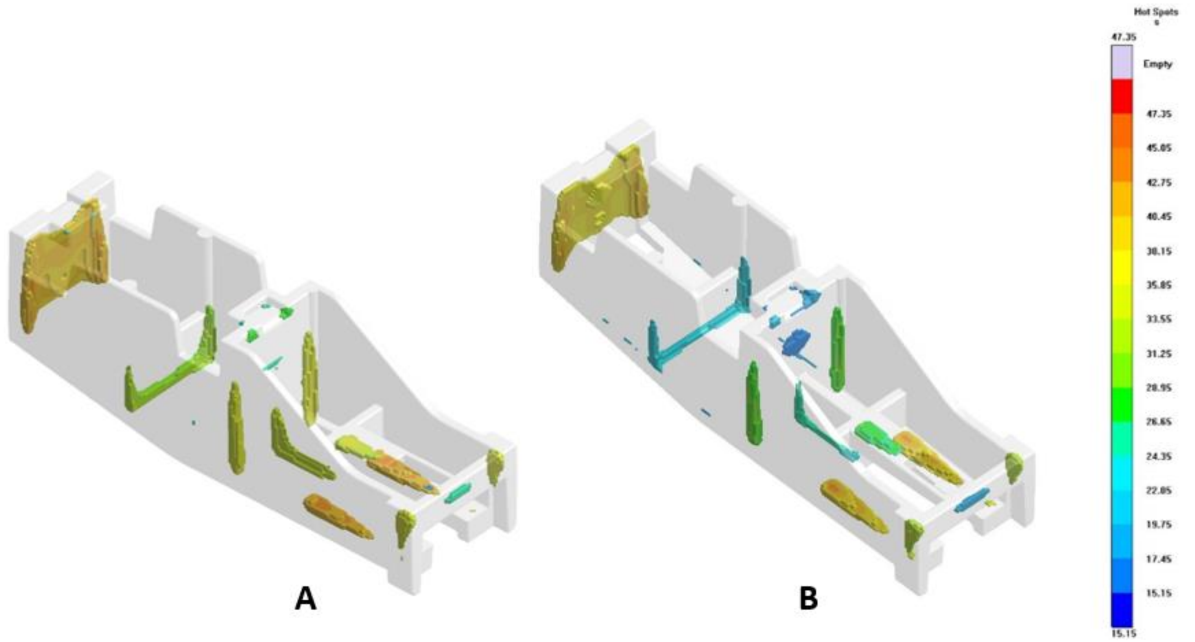



*Figure 5.9: Hot spot time for the conventional cooling channel insert (A) and the conformal cooling channel design (B) at 30 seconds during the 20$^{th}$ IM cycle.*

### Sink marks

Figure 5.10 and Figure 5.11 show the volumetric shrinkage of a product for the two different insert designs. The product was manufactured during the 20$^{th}$ IM cycle and allowed to cool down in atmospheric conditions at an ambient temperature of 20 ºC for one hour and fifty seconds after it has been ejected from the mould. The simulated results showed a minimal difference in the sink marks between the two cooling channel designs.

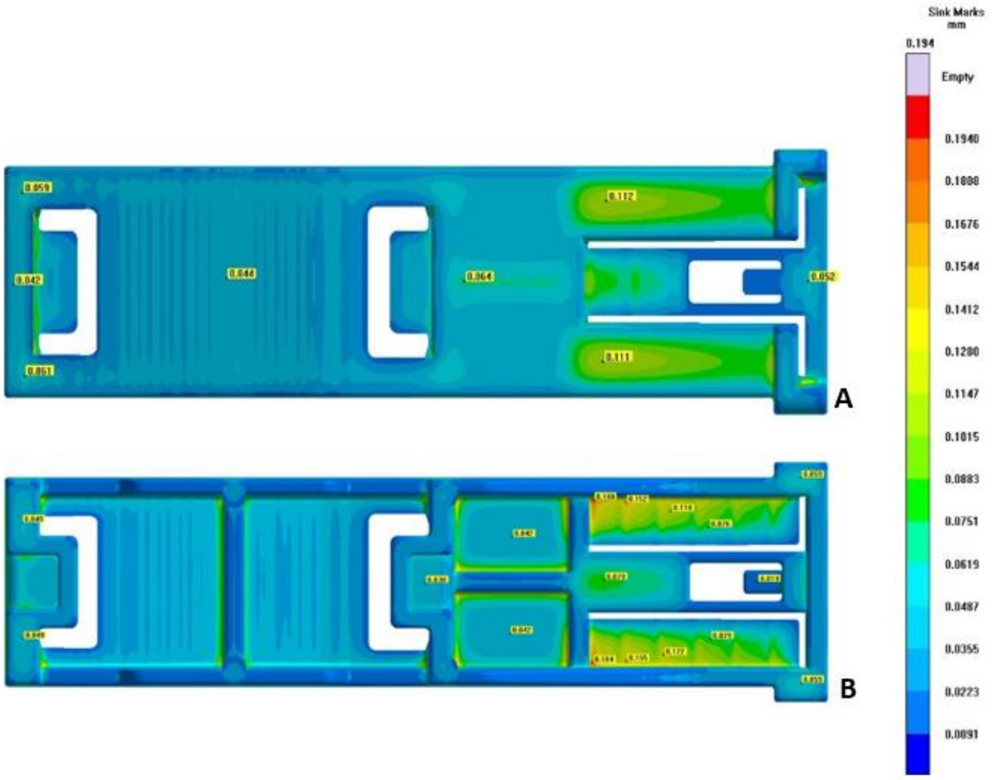



*Figure 5.10: Bottom view (A) and top view (B) of the sink marks on a product manufactured by an insert with conventional cooling channels.*

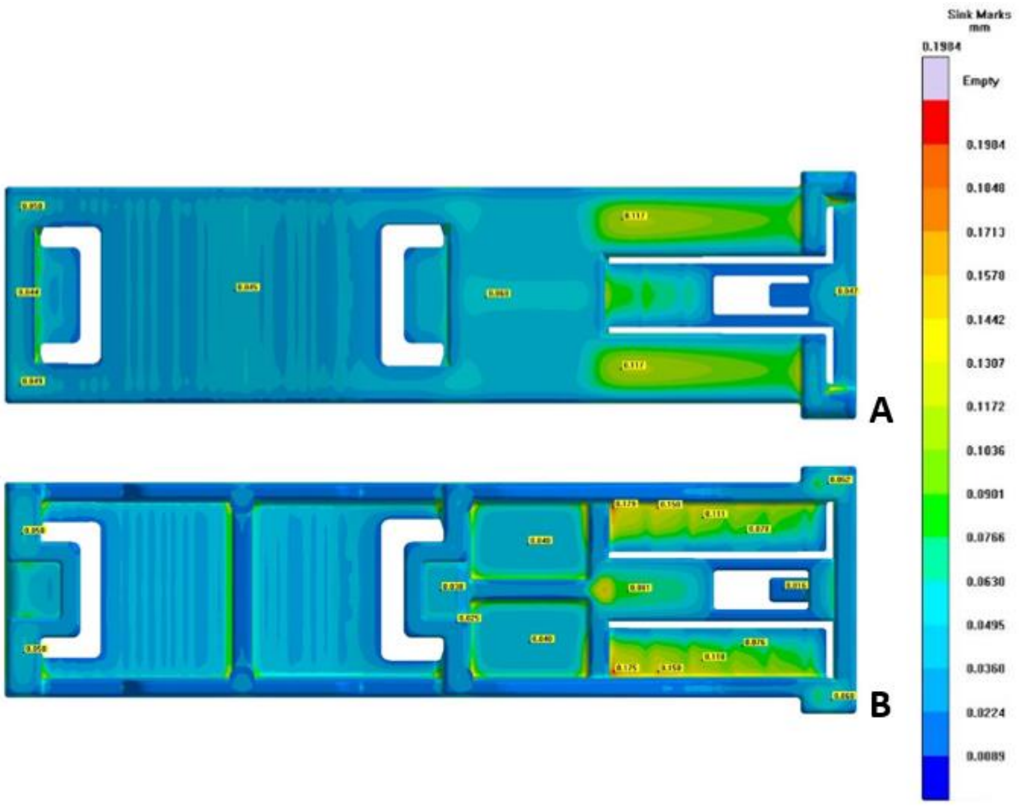



*Figure 5.11: Bottom view (A) and top view (B) of the sink marks on a product manufactured by an insert with conventional cooling channels.*

## Warpage

The effect of warpage on a product manufactured during the 20th IM cycle is shown for the conventional and conformal cooling channel designs in Figure 5.12 and Figure 5.13. The simulated results were exaggerated by the software to make the warpage more visible. From the simulated results it can be concluded that there was not any significant noticeable warpage between the product manufactured by the conventional and the conformal cooling channel designs.

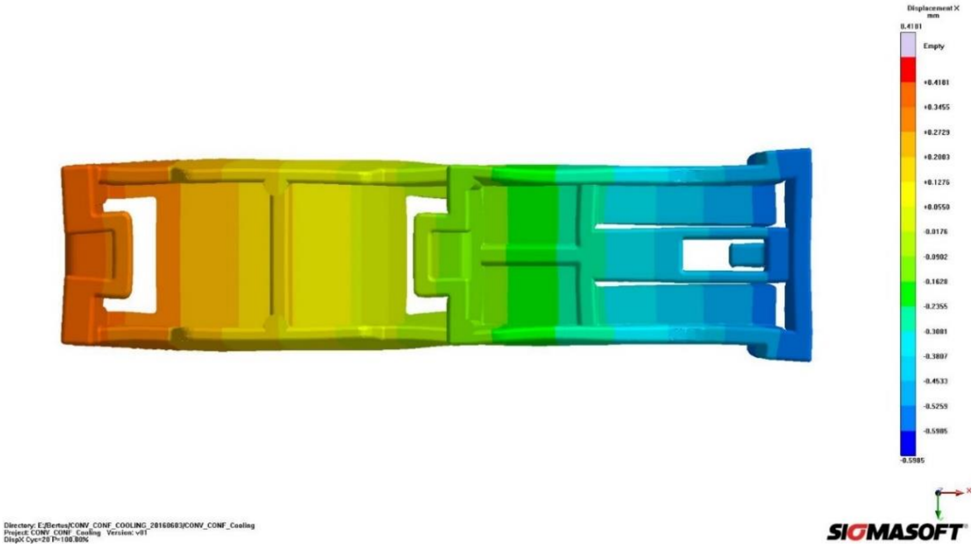



*Figure 5.12: Simulated warpage of the product manufactured by the insert with conventional cooling channels.*

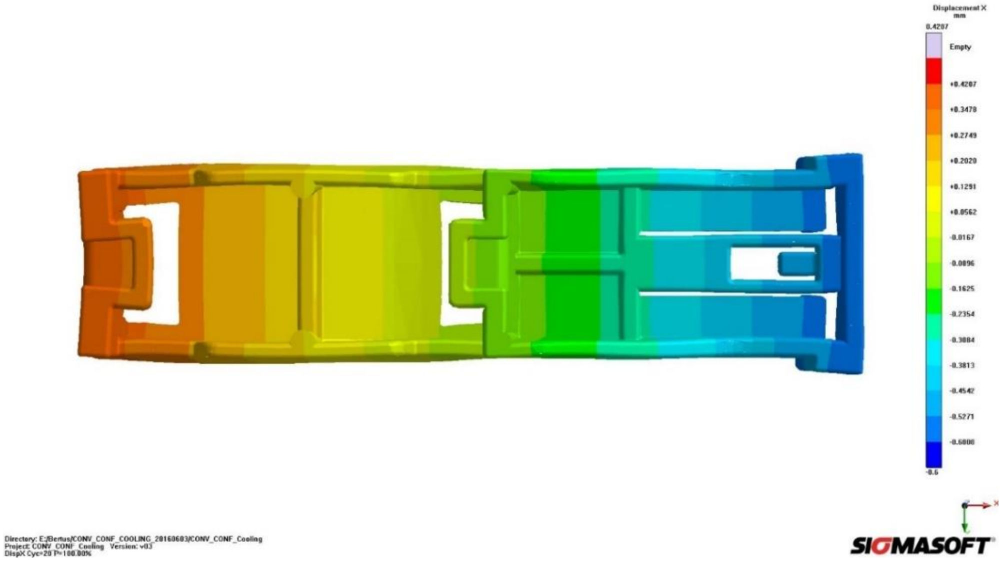



*Figure 5.13: Simulated warpage of the product manufactured by the insert with conformal cooling channels.*

### *Heat dissipation*

The heat balance summary is the amount of heat absorbed by the mould during the IM cycles. Figure 5.14 showed that the heat absorbed by the mould decreased as the mould reached a quasi-equilibrium state after 20 IM cycles. During the first IM cycle, a large amount of heat was absorbed by the mould, but during consecutive IM cycles less heat was absorbed as the mould was heated. The AM insert with conformal cooling channels absorbed heat at a higher rate compared to the insert with conventional cooling channels.

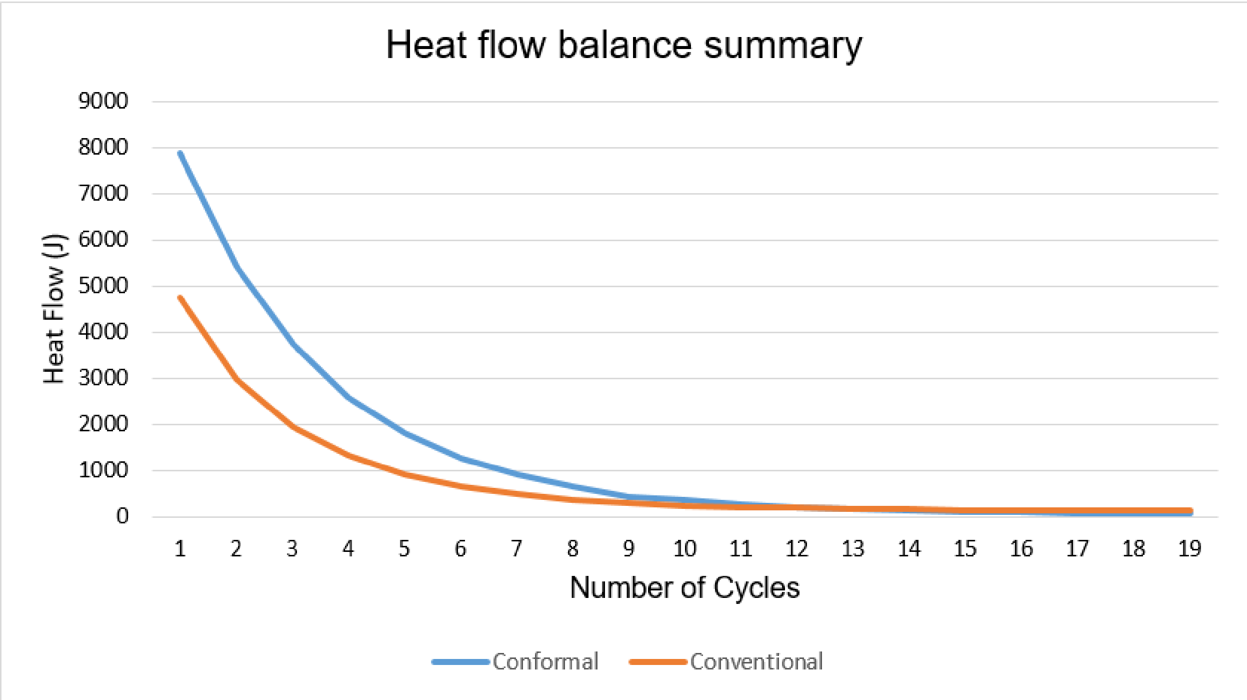



*Figure 5.14: Heat absorbed by the conventionally manufactured and AM insert from the first to the 20$^{th}$ IM cycle.*

### *Mould temperature*

A digital probe was placed inside the inserts close to the product to measure the temperature fluctuations during the first to the 20$^{th}$ IM cycles. The results of the temperature values during twenty IM cycles for both inserts are shown in Figure 5.15. The temperature fluctuations of the conformal cooling channel (shown in red) stabilised quicker and are lower than the conventional cooling channel (shown in blue). This indicates that the conformal cooling design can absorb heat from the cavity more efficiently than the conventional cooling channel design.

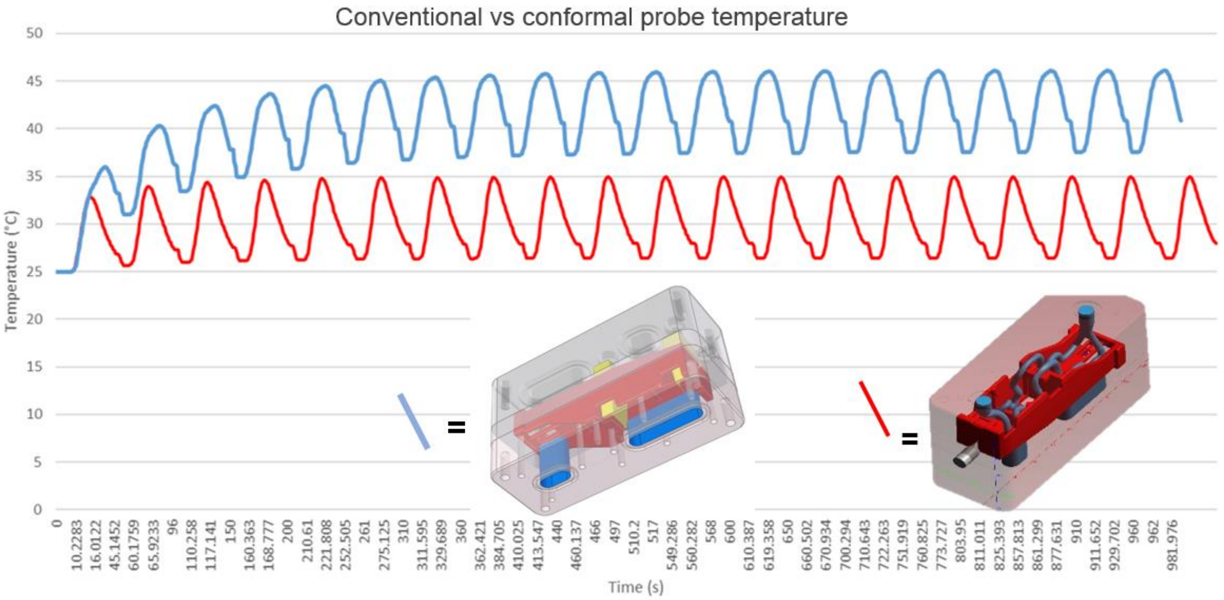



*Figure 5.15: Temperature fluctuations from the first to the 20th IM cycle for the conventional (shown in blue) and conformal (shown in red) insert.*

Figure 5.16 below shows centre-section views of the conventional cooling channel design (A) and the conformal cooling channel design (B) after the 20th IM cycle. Based upon the differences in colours seen in Figure 5.16 (A) and (B), it can be observed that the conformal cooling channels were more effective in removing heat from hard-to-reach hot spots inside the IM insert.

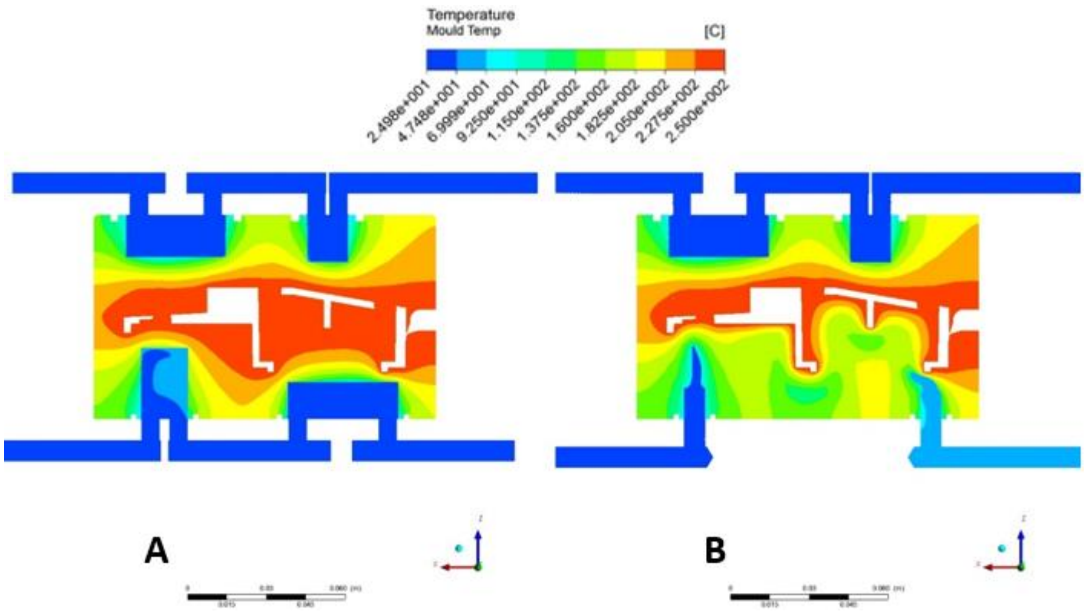



*Figure 5.16: Sectional view of the simulated temperature distribution after the 20th IM cycle for the conventional cooling channel design (A) and the conformal cooling channel design (B) according to ANSYS® CFD simulation software.*

### *Cooling channel turbulence*

Figure 5.17 shows a centre-section view of the conventional cooling channel design with flow vectors inside the cooling channels indicating the flow direction and velocity of the cooling water through the channel. Areas where there is not any flow are shown in dark blue, while areas with higher flow are shown in yellow and red.

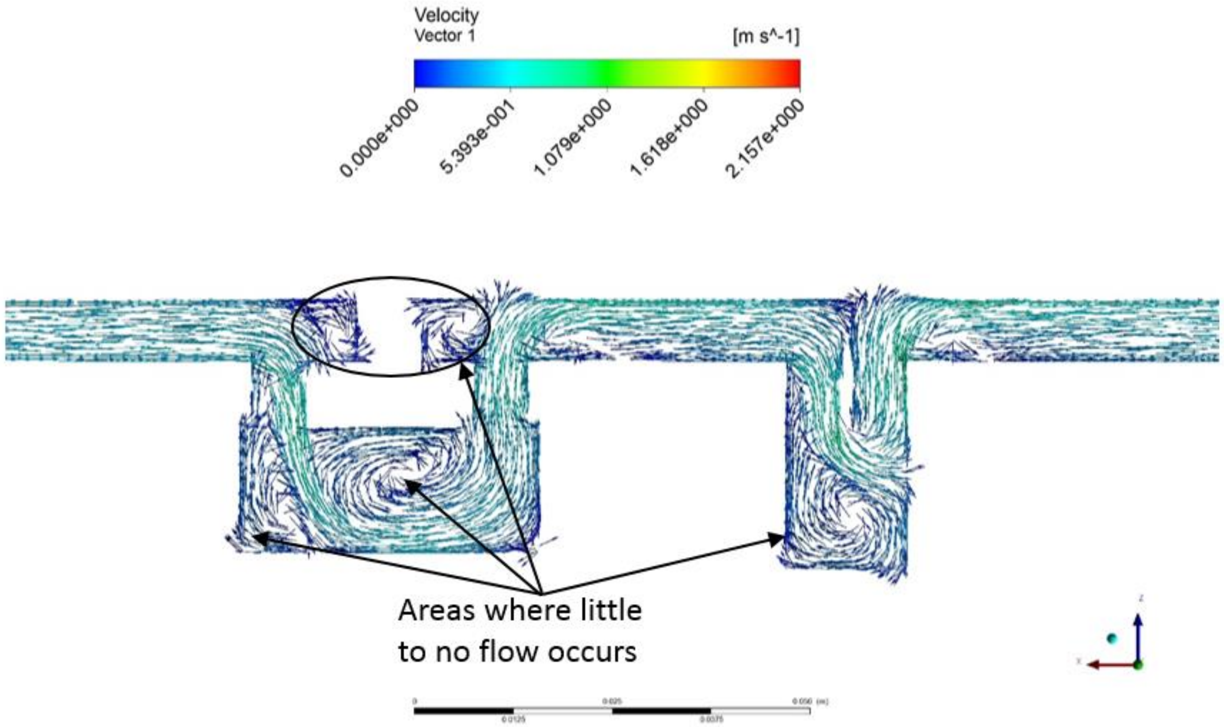



*Figure 5.17: Simulated ANSYS® CFD vector flow for the conventional cooling channel design.*

Figure 5.18 shows a centre-section view of the conformal cooling channel design. The flow vectors have higher velocities and improved directed flow through the channels, as shown by the green and yellow vectors.

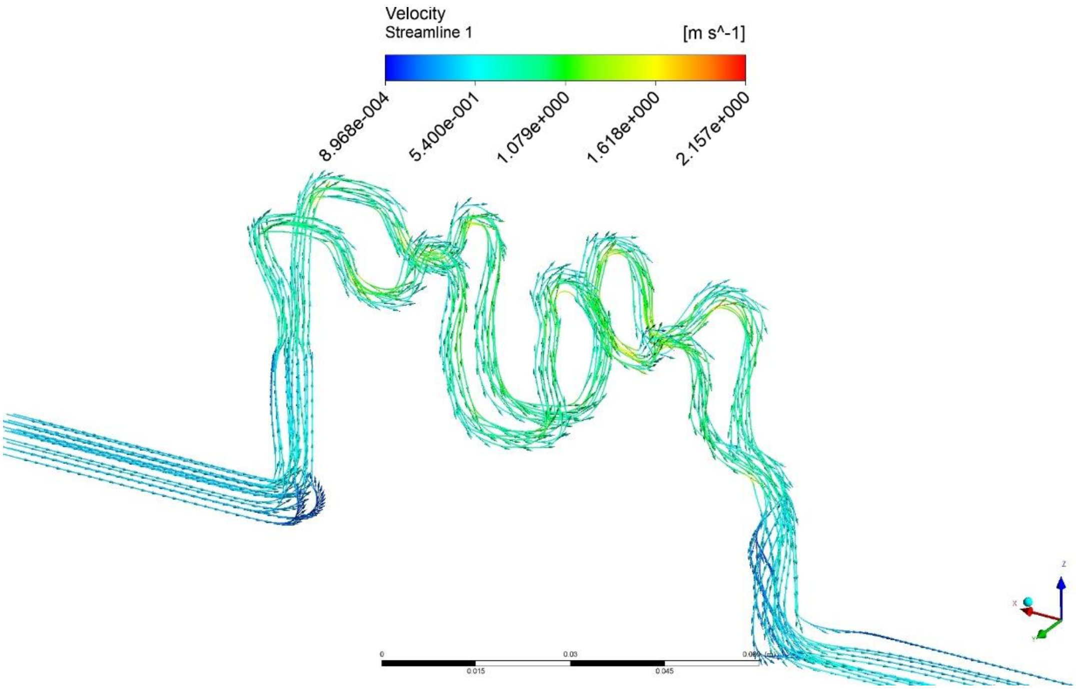



*Figure 5.18: Simulated ANSYS® CFD vector flow for the conformal cooling channel design.*

Figure 5.19 shows the turbulence kinetic energy in the conventional cooling channel (A) and conformal cooling channel (B) design.

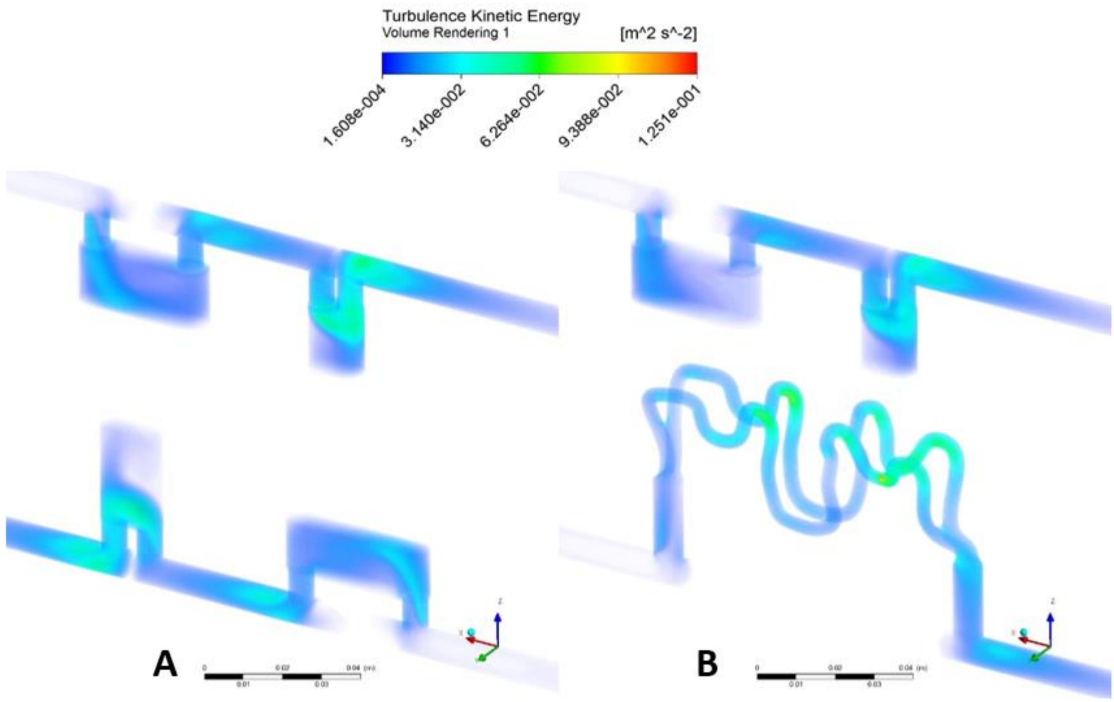



*Figure 5.19: ANSYS® CFD simulated turbulence kinetic energy inside the conventional cooling channel design (A) and conformal cooling channel design (B).*

The simulated results in Figure 5.20 B show more lighter colours (green and yellow) compared to Figure 5.20 A due to a higher turbulence kinetic energy in parts of the conformal cooling channels. Because the cooling channel geometries were unlike the cooling channel design used in Section 4.2, the five-particle approach was not considered. This approach is more suitable when similar geometrical cooling channel layouts are compared. Figure 5.20 shows the simulated water temperature distribution through the cooling channels of the conventional and conformal cooling channel inserts.

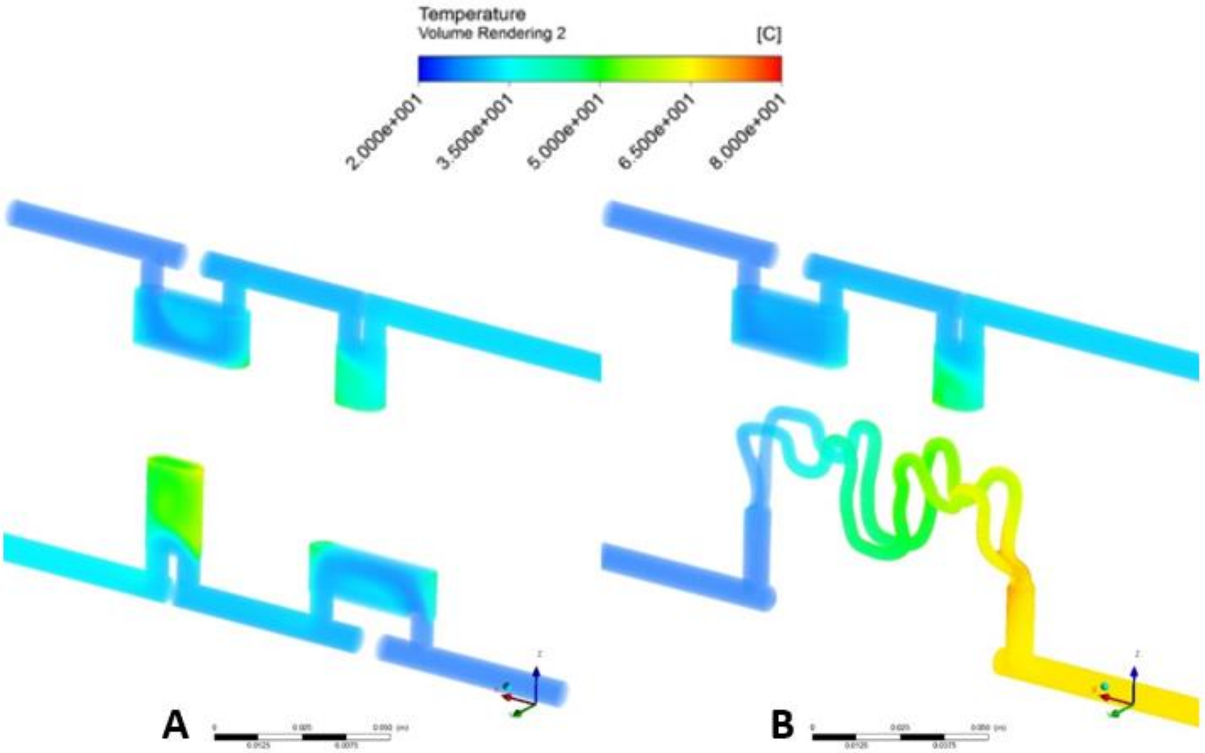



*Figure 5.20: Simulated ANSYS® CFD water temperature distribution through the conventional cooling channel (A) and the conformal cooling channel design (B).*

It is evident that the conformal cooling channel shown in Figure 5.20 (B) had a larger water temperature difference from inlet to the outlet, compared to the conventional cooling channel design (A). Thus, the rate of heat transferred from the plastic melt through the insert to the cooling medium was greater in the conformal cooling channel design compared to the conventional cooling channel design, resulting in a faster production rate.

### 5.1.3 Discussion

The simulated results shown in Table 5.2: compare the 20th IM cycle of the conformal and the conventional cooling channel designs after the mould inserts had reached a quasi-equilibrium thermal state. Five intervals (13, 22, 30, 40 and 50 seconds) throughout the 20th IM cycle were used to record the data below.

*Table 5.2: Comparison between the simulated results for the conventional and conformal cooling channel designs after the 20th IM cycle.*

| Variable | Conformal | Conventional | Variation |
|---|---|---|---|
| Maximum cooling rate (Cycle 20, t = 13 s) | 83.5 [°C/s] | 76.56 [°C/s] | 6.94 [°C/s] |
| Maximum cooling rate (Cycle 20, t = 22s) | 16.7 [°C/s] | 15.24 [ºC/s] | 1.46 [°C/s] |
| Maximum cooling rate (Cycle 20, t = 30s) | 7.092 [°C/s] | 6.863 [°C/s] | 0.229 [°C/s] |
| Maximum cooling rate (Cycle 20, t = 40s) | 4.459 [°C/s] | 4.149 [°C/s] | 0.310 [°C/s] |
| Maximum cooling rate (Cycle 20, t = 50s) | 3.514 [°C/s] | 3.378 [°C/s] | 0.136 [°C/s] |
| Maximum mould temperature (Cycle 20, t = 13s) | 78.70 [°C] | 93.64 [°C] | -14.94 [°C] |
| Maximum mould temperature (Cycle 20, t = 22s) | 72.58 [°C] | 99.12 [°C] | -26.54 [°C] |
| Maximum mould temperature (Cycle 20, t = 30s) | 57.58 [°C] | 95.09 [°C] | -37.51 [°C] |
| Maximum mould temperature (Cycle 20, t = 40s) | 52.24 [°C] | 87.53 [°C] | -35.29 [°C] |
| Maximum mould temperature (Cycle 20, t = 50s) | 49.99 [°C] | 79.46 [°C] | -29.47 [°C] |
| Maximum part surface temperature (Cycle 20, t = 13s) | 204.1 [°C] | 205.6 [°C] | -1.5 [°C] |
| Maximum part surface temperature (Cycle 20, t = 22s) | 179.4 [°C] | 183.0 [°C] | -3.6 [°C] |
| Maximum part surface temperature (Cycle 20, t = 30s) | 86.45 [°C] | 115.6 [°C] | -29.150 [°C] |
| Maximum part surface temperature (Cycle 20, t = 40s) | 66.76 [°C] | 99.13 [°C] | -32.370 [°C] |
| Maximum part surface temperature (Cycle 20, t = 50s) | 58.15 [°C] | 85.76 [°C] | -27.610 [°C] |
| Maximum solidification time (Cycle 20) | 45 [s] | 48 [s] | -3 [s] |
| Maximum sink marks (Cycle 20, t = 3650s) | 0.198 [mm] | 0.194 [mm] | 0.004 [mm] |
| Maximum warpage x-deformation (Cycle 20 t= 3650s) | 0.4207 [mm] | 0.4181[mm] | 0.003 [mm] |
| Maximum warpage y-deformation (Cycle 20 t= 3650s) | 0.1511 [mm] | 0.1515 [mm] | 0 [mm] |
| Maximum warpage z-deformation (Cycle 20 t= 3650s) | 0.2436 [mm] | 0.2408 [mm] | 0.003 [mm] |
| Average water outlet temperature | 66.6 [°C] | 32.7 [°C] | 33.9 [°C] |

From Table 5.2 it can be concluded that the conformal cooling channel design did improve the cooling rate and reduce the mould temperatures, especially in regions where conventional cooling channels could not reach, as shown by the maximum part surface temperature differences (32.37 °C during the 20$^{th}$ IM cycle after 40 seconds into the cycle) between the conformal and conventional cooling channel designs. This local area cooling reduced the hot spot time from 47 to 44 seconds, decreasing the overall cycle time by three seconds.

The conformal cooling channel design reduced the number of IM cycles required for the mould to reach a quasi-equilibrium thermal state. From Figure 5.14 it can be seen that the equilibrium between heat energy into the mould and the energy removed by cooling channels was obtained during the 19$^{th}$ IM cycle for the conventional cooling channel design compared to the 13$^{th}$ IM cycle for the conformal cooling channel design.

The mould temperature, water temperature and water turbulence kinetic energy were simulated with ANSYS® CFD using a steady-state simulation with a constant part wall temperature of 250 °C. The aim of the ANSYS® CFD flow simulation was to determine the dynamics of the flow and how they differ inside the cooling channels. From the simulation it was evident that there were regions in the conventional cooling channel design where no flow occurred, resulting in a reduction of heat transfer. The conformal cooling channel design caused a forced directional flow that did not resulted in stationary water inside the channels. Due to the forced directional flow, the heat transfer rate for the conformal cooling channels was greater than the conventional cooling channels, as shown in Figure 5.21.

Figure 5.20 shows that the turbulence kinetic energy inside the conformal cooling channel design was higher around corners compared to the flow in the conventional cooling channels. In some regions the flow inside the conformal cooling channel was less turbulent compared to certain regions in the conventional cooling channels. This was due to the discontinued curve inside the conventional cooling channel design from the sudden changes in the flow direction. The discontinued curve of the conventional cooling channel also resulted in areas of the cooling channel where little to no flow occurred. This was less effective in removing heat from the mould compared to the continuous curve of the conformal cooling channel. While the continuous curve of the conformal cooling channel also induces turbulent flow, it did not have any regions were low velocities in the flow occurred. It is also evident that the turbulence in the conformal cooling channel was achieved throughout most of the channel and not only in local regions as simulated in the conventional cooling channel. Because of the dissimilar cooling geometries, a comparison of the turbulence kinetic energy could not be made to determine which cooling channel design was the most effective in intermixing. This method will be more relevant to compare similar geometrical cooling channel designs.

There was a significant difference between the simulated water outlet temperature of the conventional and conformal cooling channel designs. The average outlet temperature for the conventional cooling channel was 32.7 °C compared to 66.7 °C for the conformal cooling channel, using a constant heat source during the ANSYS® CFD flow simulation. In practice, these temperature differences would be smaller because the molten polymer cools down due to the heat absorbed by the mould and cooling channels. But the simulation still illustrates the difference between the heat absorption of the conventional and conformal cooling channel designs. Figure 5.21 shows the simulated results obtained for the heat absorbed by the two cooling channel designs during the 20th IM cycle.

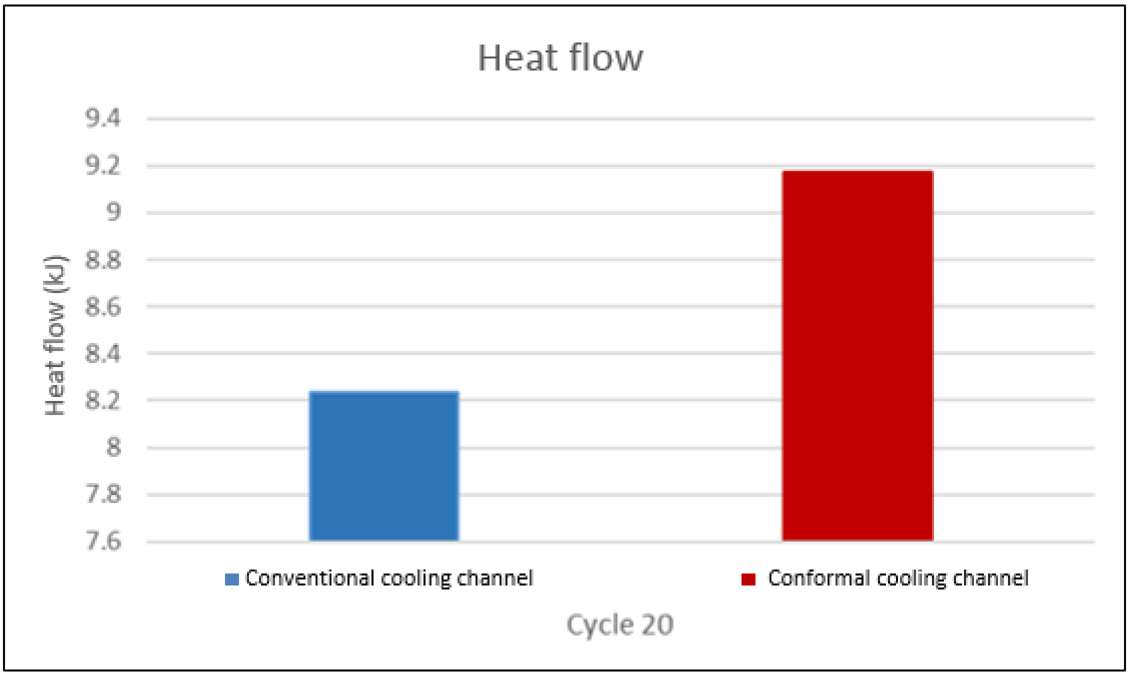



*Figure 5.21: Heat absorbed by the conventional and conformal cooling channel designs during the 20th IM cycle.*

The cycle time recorded during actual IM trials was 40 seconds compared to the 44 seconds simulated by SIGMASOFT®. The difference in the cycle times could be because the IM machine setter was able to optimise the IM process, whereas the results of the simulation was dependent on assumptions and theory that could not account for all 'real world' scenarios.

### 5.1.4 Feedback from production

The actual parameters that were used during the production of the component:

- Shot weight: 100 grams
- Material: Durethan BKV30
- Pigment: Dark grey (MP1866J)
- Injection moulding machine capacity: 100 ton
- Cycle time: 40 seconds
- Hold down pressure: 35 Bar
- Injection pressure: 80 Bar
- Injection speed: 75 mm/s
- Nozzle temperature: 280 ºC

During the time the information was requested from the client, 5 000 IM cycles had already been completed. This resulted in 10 000 parts being manufactured without any problems, with excellent part quality according to Technimark, the manufacturer of the products. Figure 5.22 shows the actual products manufactured from the AM inserts.

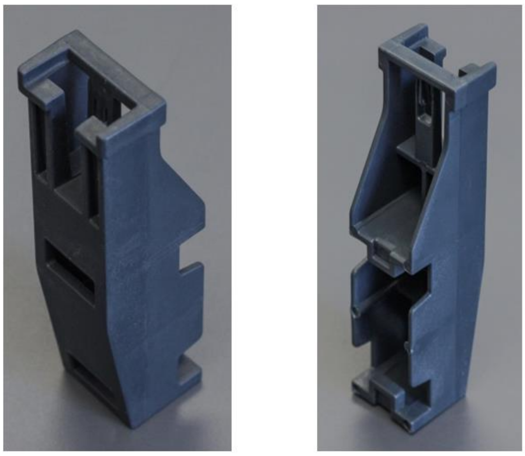


*Figure 5.22: Actual products manufactured from the AM inserts for the Triga project.*

## 5.2 Manufacturing cost and lead-time comparison

A manufacturing cost and lead-time comparison was conducted between the AM and conventional manufactured inserts.

### 5.2.1 Floor tile manufacturing costs and lead-times

Table 5.3 shows the cost comparison between the AM and conventionally manufactured inserts for the interlocking floor tile used in Chapter 4.

*Table 5.3: Manufacturing cost comparison between the AM and conventionally manufactured inserts for the floor tile.*

| | AM insert | Conventional insert |
|---|---|---|
| **DMLS process** | R 31 350.00 | N/A |
| **Material** | R 8 560.56 | R 253.80 (Tool steel 1.2316) |
| **CNC machining** | R 7 425.82 (Post processing) | R 10 501.83 |
| **Fitting** | R 400.00 | R 400.00 |
| **Additional** | R 4 500.00 (Wire EDM) | R 3 100.00 (Cutters) |
| | | |
| **Total** | **R 52 236.38** | **R 14 055.63** |

The total manufacturing time for the conventionally manufactured insert, from design to the completed insert, ready for production, was five days. This included CNC programming, CNC machine setup, CNC machining and fitting of the insert into the IM. The total manufacturing time for the AM insert was eight days which included machine setup, DMLS time, post-processing time (EDM and CNC machining) and fitting into the IM. Although the manufacturing time of the AM insert took longer than the conventional insert, the AM process could occur concurrently with conventional mould manufacturing processes. During this case study there was a considerable amount of CNC machining (post-processing) required on the DMLS insert to obtain the required geometry and surface finish, increasing the manufacturing time of the AM insert.

### 5.2.2 Floor tile inserts production costs and break-even analysis

Figure 5.23 shows the production rates and break-even points for the AM and the conventionally manufactured inserts of the floor tile product. The conventionally manufactured insert's cost of R 14 055.63 could be recovered after 88 hours of production after which it could start to generate a profit compared to 303 hours required for the AM insert to recover the manufacturing costs of R 52 236.38. The AM insert could generate a profit at a faster rate compared to the conventional manufactured insert due to the reduction in cycle time, but has a larger non-recurring cost compared to the conventionally manufactured insert.

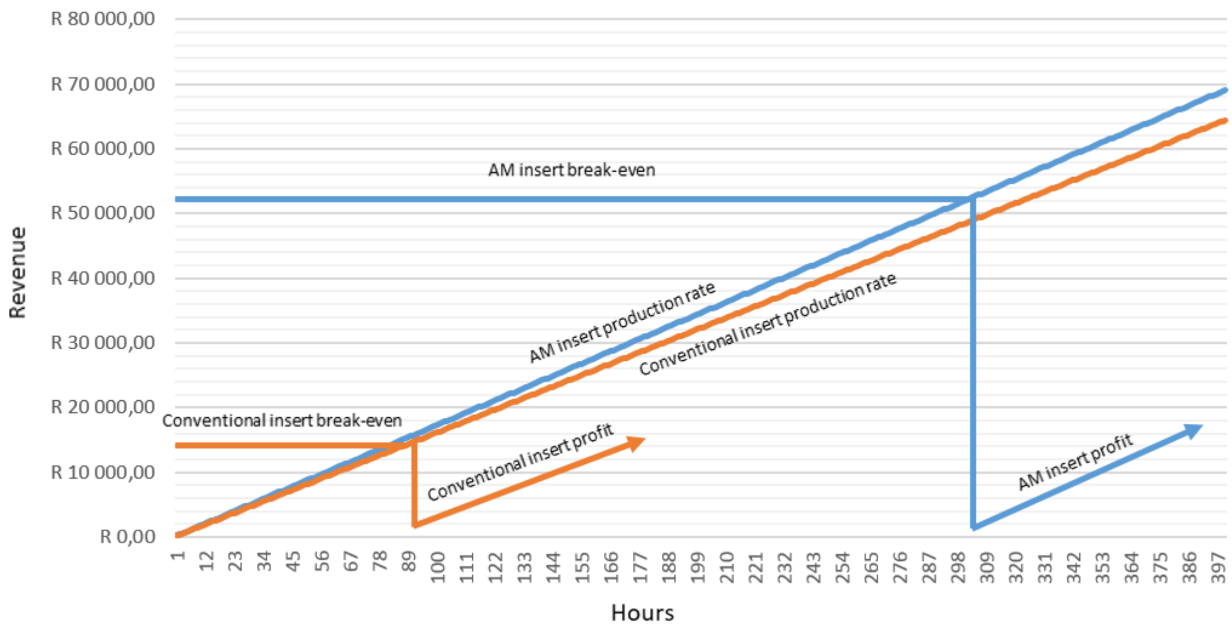



*Figure 5.23: Break-even analysis of the AM and conventionally manufactured inserts for the floor tile product.*

After 103 hours of production, the conventional manufactured insert had already generated a profit after its manufacturing costs were recovered. The AM insert only recovered its manufacturing costs after 303 hours into production. After 3 287 hours of production (400 970 products) the AM insert became more profitable than the conventionally manufactured insert, as shown in Figure 5.24 below.

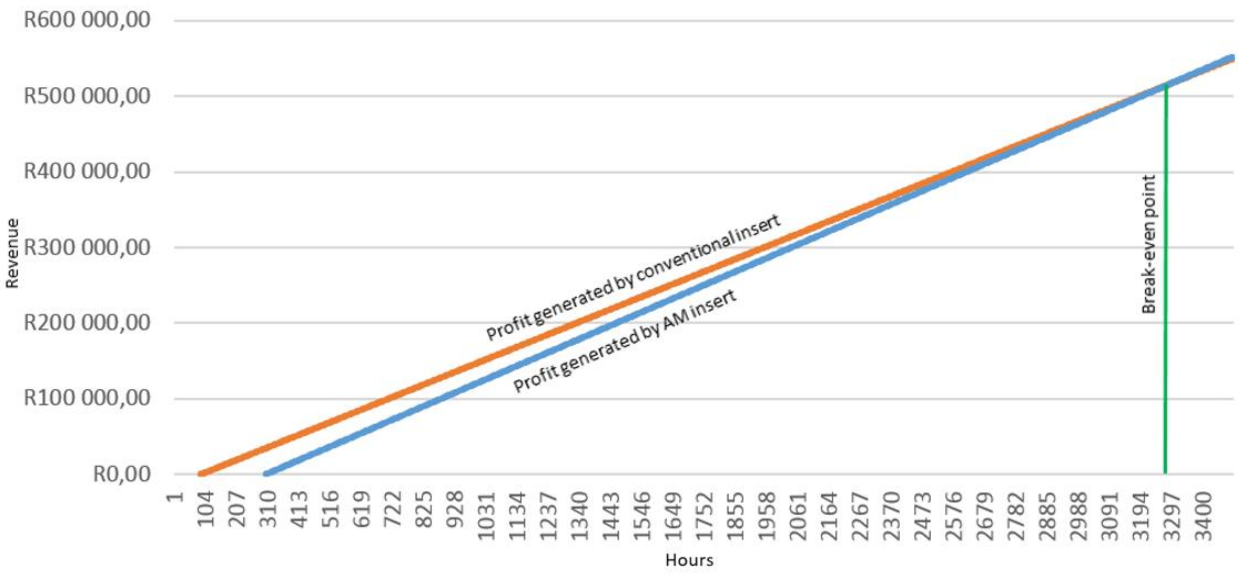



*Figure 5.24: Break-even point for the AM and conventionally manufactured floor tile inserts.*

For the interlocking floor tile, it would be worth investing in an AM insert with a higher non-recurring cost, if the demand for the product is more than 473 328 products (9 466 $m^2$ of floor tiling). According to the SPI mould classification system shown in Table 3.2, this production quantity falls within the 103 SPI class and is considered a medium production application for an IM machine smaller than 400 tons.

### 5.2.3 Triga manufacturing costs and lead-times

Table 5.4 shows the comparison between the manufacturing costs of the AM and conventionally manufactured inserts for the Triga case study described in Section 5.1.

*Table 5.4: Manufacturing cost comparison between the AM and conventionally manufactured inserts of the Triga case study.*

| | AM insert | Conventional insert |
|---|---|---|
| **DMLS process** | R 22 250.03 | N/A |
| **Material** | R 8 364.67 | R 180.50 |
| **CNC & EDM** | R 6 500.00 (CNC and EDM cost) | R 12 804.83 (CNC cost) |
| **Fitting** | R 400.00 (fitting) | R 400.00 (fitting) |
| **Additional** | N/A | R 4 100.00 (cutters) |
| | | |
| **Total** | **R 37 514.70** | **R 17 485.33** |

The manufacturing time for the conventional insert, from design to the finished insert, ready for production, was five days. This included CNC programming, CNC machine setup, EDM spark erosion, CNC machining as well as fitting of the insert into the IM. The total manufacturing time for the AM insert was eight days. This included machine setup, DMLS time, post-processing time (EDM and CNC machining) and fitting into the IM. Although the AM process has a longer manufacturing lead-time, it could be manufactured concurrently with the conventional mould manufacturing processes.

### 5.2.4 Triga IM inserts production costs and break-even analysis

A difference of three seconds in cycle time was measured between the AM and conventional inserts by the simulation software. The effect of the reduction in cycle time during production was analysed and shown in Figure 5.25 below.

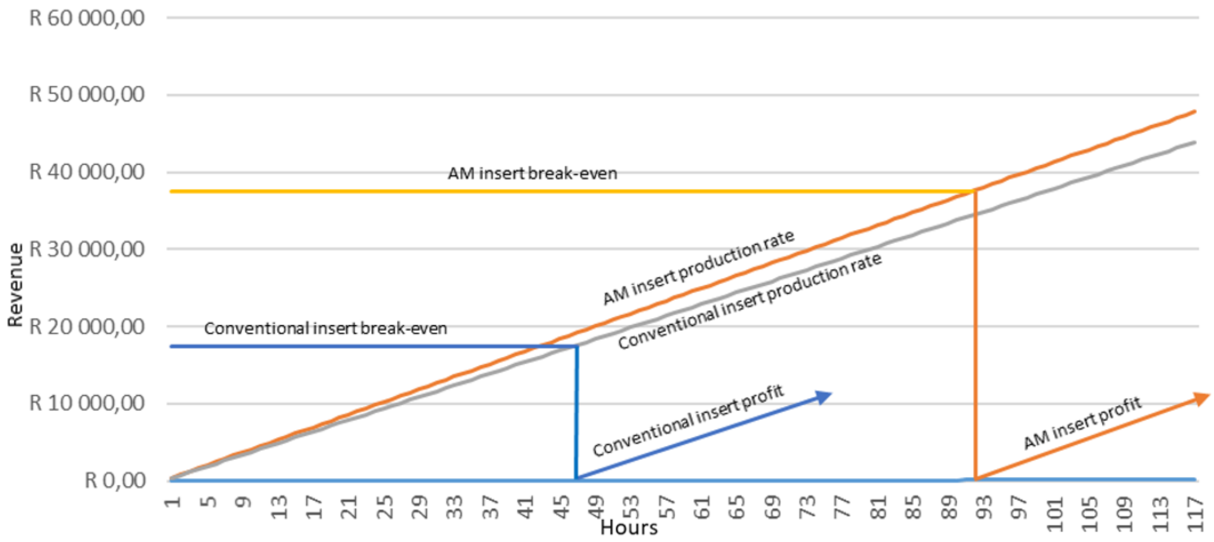



*Figure 5.25: Break-even analysis of the AM and conventionally manufactured inserts for the Triga product.*

Break-even points and profit generated were calculated to obtain an indication of when it is viable to use DMLS inserts. With an assumed selling profit of R 5 per product, a cycle-time saving of three seconds per cycle results in a R 375 profit per hour for the conventionally manufactured insert compared to the R 409.09 profit per hour for the conformal cooling channel insert. The change in the potential profit that could be generated equates to R 34.09 per hour.

Figure 5.26 below shows the faster production rate of the AM insert (R 34.09 per hour) with a steeper slope compared to the conventional insert's production rate.

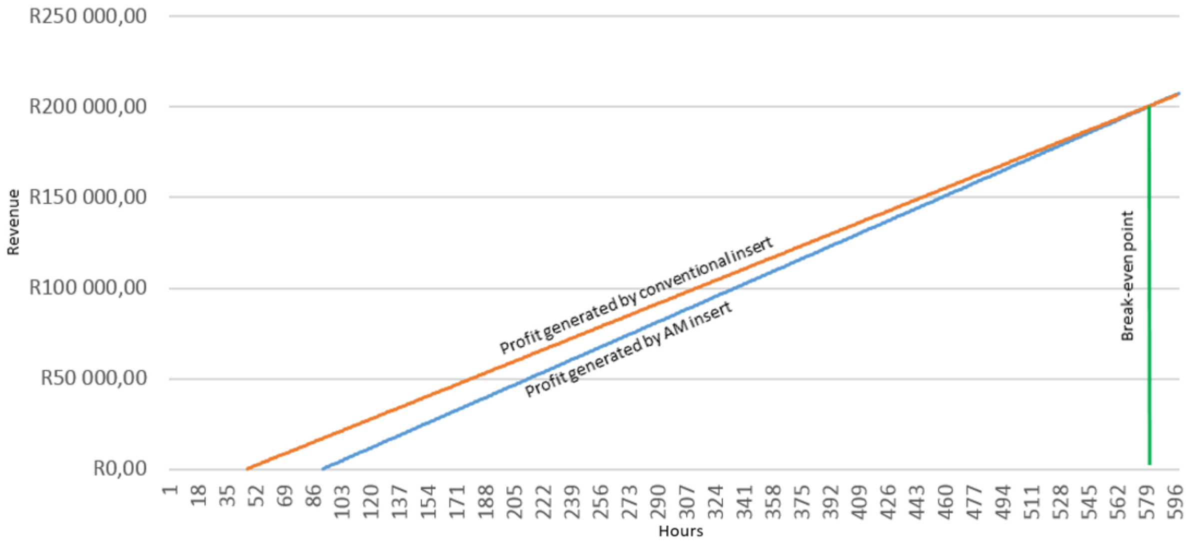



*Figure 5.26: Break-even point for the AM and conventionally manufactured Triga inserts.*

After 92 hours of production, the cost of the AM insert could be recovered and start to generate a return in profit. During this time, the conventional insert had already recovered its investment cost (after 47 hours) and generated a profit of R 17 250. After 586 hours of production (52 740 products), the increased production rate of the AM insert exceeded that of the conventional insert's production. From this time on during production one can capitalise using the AM insert. This means that for a 104 SPI mould classification (low-production application) or higher, the AM insert will become more profitable compared to the conventional insert.

### 5.2.5 Conclusion

The significant difference in the manufacturing costs between the AM and conventionally manufactured inserts can be attributed to factors such as the size of the insert (material costs being the major cost driver for this technology), manufacturing time of the AM machine while producing the insert (recovering the machine's investment costs and process overheads) as well as the exchange rate and importation costs. In addition, post-processes like EDM wire cutting and CNC machining costs should also be considered when using this technology. For the Triga case study, the use of DMLS inserts was feasible when a plastic IM with a product lifecycle of more than 47 945 products was to be made, increasing the profitability of the product due to the increased production rate of the AM insert compared to the conventional insert in this study. The AM insert with conformal cooling channel designs for the interlocking tile product only resulted in a slight difference in production rates compared to the conventional manufactured insert. Therefore, a higher number of products needed to be manufactured before the cost of the AM insert could be recovered. For the interlocking tile, it will be worth investing in an AM insert if the demand for the product is more than 473 328 products (9 466 $m^2$ of floor tiling) due to the significant difference in manufacturing costs.

The manufacturing time for the conventional insert, from design to the finished insert, ready for production, was five days. This included CNC programming, CNC machine setup, EDM spark erosion, CNC machining as well as fitting of the insert into the IM. The total manufacturing time for the AM insert was eight days. This included machine setup, laser sintering time, post-processing (EDM and CNC machining) and fitting into the IM. Although the AM process had a longer manufacturing lead-time, it could be manufactured concurrently with the conventional mould manufacturing operations.

# 6 CONCLUSION AND FUTURE WORK

## 6.1 Conclusions and recommendations

To determine the potential of using DMLS Maraging Steel MS1 inserts to improve the IM value chain by creating cost effective inserts with conformal cooling channels, the following were investigated during the study:

i. **A literature review on product development using thermoplastic materials, the IM process and RT techniques using AM.**

Through the literature review the latest trends in the field of product development and the usage of plastic materials was obtained. The value additive manufactured DMLS inserts with conformal cooling channels could have in IM applications was also establish.

ii. **The influence of different layouts of conformal cooling channels inside a DMLS insert as well as determining the most efficient conformal cooling channel layout using simulation software.**

Two different AM cooling channel design layouts (spiral and meander) were analysed and compared. Simulation software, ANSYS® CFD was used to solve complex fluid flow-related physics, and SIGMASOFT® virtual moulding was used to simulate heat transfer between the injected polymer, mould components and cooling channels. The conformal cooling channels were designed to achieve a high turbulent flow inside the cooling channel in order to increase the heat transfer of the cooling channel. This was accomplished by frequently altering the flow direction of the cooling channel, as shown in Figure 4.6 and Figure 4.11. The centre distances between the cooling channels and the distances from the cavity surface were based upon the guidelines of Table 3.5, derived from Fourier's heat transfer equations. Both inserts were simulated using the same simulation parameters determined by the polymer material used and the capabilities of the IM machine used during the actual IM trials.

To determine the amount of heat energy that could be removed by each cooling channel layout, five equally spaced particles flowing through a cooling channel design were considered. This approached was followed because the path of each particle flowing through the cooling channel was not the same, thus the heat flow results between the two different cooling channel designs could not be compared and calculated accurately. The average temperature from each particle was used to calculate the total heat absorbed by each cooling channel design. Even though a comparison between the simulated results of the two cooling channel designs, shown in Table 4.4, indicated that the spiral cooling channel design had a slightly higher (0.7%) heat transfer rate than the meander cooling channel design, the meander cooling channel was selected as the more efficient cooling channel design based upon the higher maximum turbulence kinetic energy induced inside the cooling channel design (7% more than the spiral cooling channel design).

From these results it was shown that simulation software can successfully analyse different cooling channel designs to identify the most efficient conformal cooling channel layout. Simulation results can also be used to evaluate different designs to increase the efficiency of cooling channels for an insert. This could improve the cycle time required to manufacture a component, increasing the efficiency of the IM process by reducing the time and energy required to manufacture a product.

iii. **Use simulation software to compare a DMLS insert with a conventionally manufactured insert.**

Cooling channels for an insert manufactured using conventionally manufacturing techniques were designed according to the guidelines in Table 3.5. Conventional manufacturing limitations, such as straight-line drilling and slotting, were considered during the design phase. The meander cooling channel design (AM) and the conventionally manufactured insert design were simulated with SIGMASOFT® virtual moulding using the same simulation parameters.

Simulated results in Table 4.5 showed that the AM insert was able to remove more heat (about 30%) from the mould compared to the conventionally manufactured insert. This was due to conformal cooling channels placed in regions of the insert that could not be reached by conventionally manufactured cooling channels. This resulted in the product produced by the AM insert solidifying quicker, reducing the time required to eject the product from the insert. The difference in solidification time between the two inserts, shown in Figure 4.21, resulted in a 1.8 second decrease in cycle time due to the more efficient heat energy transfer of the AM insert. This increased the production rate of the insert by 6.7% compared to the conventionally manufactured insert, as shown in Table 4.6. The overall mould temperature of the mould with the AM insert was also lower than the mould with the conventionally manufactured insert (38.9 ºC compared to 49.2 ºC), as shown in Figure 4.19 after 25 simulated IM cycles. The insert temperature was also 12 ºC lower than the conventionally manufactured insert after 25 IM cycles, as shown in Figure 4.20. Actual IM trials conducted with the AM and the conventionally manufactured inserts fitted with temperature probes confirmed the simulated values. The average deviation between the simulated and actual values was 4.2% for the conventional manufactured insert and 3.4% for the AM insert.

From these results it can be concluded that CAE and CFD software can be successfully used to accurately simulate cooling channel designs to obtain the most efficient design. The results also showed that AM inserts with conformal cooling channels can remove heat more efficiently compared to conventionally manufactured inserts, resulting in a reduction in cycle times.

**iv. Comparison of the simulated results with experimental values during actual IM trials through case studies.**

To test the suitability of DMLS inserts for production tooling, experimental results obtained from the floor tile inserts were applied to an industrial application. A conventional and an AM insert were designed and compared using ANSYS® and SIGMASOFT® virtual moulding software. The geometry of the product and mould features, such as ejector pins, made it difficult to obtain effective cooling using conventional manufacturing techniques (shown in Figure 5.4 and Figure 5.17), compared to AM conformal cooling channels, which was able to reach these regions more easily (shown in Figure 5.3 and Figure 5.18). From the simulated results summarised in Table 5.2, it was evident that the AM insert was able to remove heat more effectively compared to the conventionally manufactured insert. This resulted in a reduced mould temperature of about 30 ºC in the AM insert during the 20$^{th}$ IM cycle compared to the conventionally manufactured insert after 20 IM cycles. There was more turbulence induced inside the conformal cooling channel than inside the conventional cooling channel resulting in a higher water outlet temperature, as shown in Table 5.2. These factors resulted in a three second shorter cycle time for the AM insert. From these results the benefits of using an AM insert to manufacture the Triga product was clearly shown.

v. **Manufacturing time and cost comparisons between Maraging Steel MS1 inserts and conformal cooling channels and conventionally manufactured inserts.**

Table 5.3 and Table 5.4 showed that an AM insert's manufacturing cost is about two to three times more than an insert manufactured using conventional manufacturing techniques. These higher costs could be due to the size and time required to manufacture the AM insert. An important factor that can also influence the cost of DMLS AM inserts is the Euro to Rand exchange rate and importation costs as well as post-processing operations, such as wire EDM required to remove the insert from the build platform.

Although the AM insert's manufacturing costs are higher than the conventionally manufactured insert, it can produce products at a faster rate and generate a profit quicker after the break-even point has been reached, as shown in Figure 5.23 and Figure 5.25. For the interlocking tile product, using an AM insert with conformal cooling channels would be more profitable if more than 473 328 products (3 287 production hours) were required, as shown in Figure 5.24. A similar comparison was done for the Triga product and it was found that 47 945 products (586 production hours) were required before the AM inserts with conformal cooling channels would be more profitable, as shown in Figure 5.26. From these results it can be concluded that for certain products, AM inserts with conformal cooling channels will only be beneficial or have an influence on the profitability of a product to be manufactured in high-volume production runs which are required to recover the higher manufacturing costs of an AM insert.

The selection criteria to determine when to use AM inserts for IM applications should be well-defined, where important factors such as part geometry, complexity and the life cycle of the product to be produced should be considered when making the decision regarding mould manufacturing techniques. To assist the designer, CAE and CFD simulation software can be used to evaluate and compare different insert and cooling channel designs during the IM process to gain insight on how the inserts would perform during the IM process.

From results obtained during this study, it can be concluded that it is possible to use Maraging Steel MS1 inserts to improve the IM value chain by creating cost effective and value-adding inserts with conformal cooling channels. This technique is likely to reduce mould manufacturing lead-times and costs of the plastic IM products by reducing cycle times and potentially increasing the overall product quality.

The selection criteria to determine when to use DMLS for IM application should be well-defined and considerations, such as part geometry, complexity and the life cycle of the mould, should be included when deciding upon mould manufacturing techniques. This is where CAE and CFD simulation software can be effectively used to evaluate and compare different scenarios during the IM process, providing further insight on how the different manufactured inserts would likely perform during the IM process.

The techniques applied during this study proved that using DMLS Maraging Steel MS1 inserts to produce plastic IM components is not only feasible for series production but can also be profitable by adding value to the IM process.

## 6.2 Future work

Future work that can follow from this study include:

- Development of a ‘design rule matrix’ that can assist designers to determine when to use AM or conventional manufacturing for an IM insert through inputs such as product geometry and complexity, product specifications, product life cycle and product costs.
- DMLS Maraging Steel MS1 DMLS process optimisation for IM applications. An analysis focused on optimising the current DMLS manufacturing process which includes substrate material selection, preparation, processing parameters and requirements such as surface finish.
- Investigate the age-hardening effect that thermal stress relieving has on Maraging Steel MS1 as well as the annealing requirements to attain the desired hardness for tooling applications.
- Possible means to reduce the hardness of DMLS Maraging Steel MS1 inserts through thermal post-processing techniques to improve the machinability of these inserts during post-processing.

- The influence that stress relieving through vibration (VSR) would have on Maraging Steel MS1, as an alternative post-processing process to relieve residual stress as opposed to thermal processes.

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