DIRECT METAL LASER SINTERING, USING CONFORMAL COOLING, FOR HIGH VOLUME PRODUCTION TOOLING[#]

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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) with Maraging tool steel (MS1). MS1 is an additive manufacturing (AM) material made available by Electro Optical Systems (EOS) GmbH. Contrary to material removal processes, DMLS can produce MS1 tool steel inserts directly from Computer-Aided Design (CAD) files suitable for high volume plastic injection moulding. Through DMLS it is possible to create conformal cooling channels inside the MS1 inserts that have advantages in reducing heat rapidly and evenly. This can 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.

This paper will present a comparison between Finite Element Analysis (FEA) simulations of the injection mould inserts with actual mould trails of AM and conventional manufactured inserts. It also includes the design and manufacturing of conventional and DMLS inserts and compares the manufacturing costs and lead times. Using FEA simulations, the design of conformal cooling channels is optimised by comparing the mould temperature of different cooling channel layouts.

Bestaande tegnieke vir die vervaardiging van matryse vir die plastiek-inspuit giet tegniek is duur en tyd rowend. Verder is dit nie altyd moontlik om konvensionele metodes vir die vervaardiging van matryse vir geomteries komplekse gietstukke te gebruik nie. Vir sodanige gietsukke kan invoegsels relatief vinnig vervaardig word, deur van direkte laser metal sinterings metodes (DLMS) met Maraging-staal (MS1) gebruik te maak. MS1 is 'n laag vervaardings materiaal wat onlangs deur Electro Optical Systems (EOS) GmbH beskikbaar gestel is. Dit is 'n pre-allooi, ultra hoë sterkte metaal met goeie meganiese eienskappe. In teenstelling met materiaal verwyderings prosesse (masjienerings prosesse), kan DMLS MS1 staal matryse of insetsels wat vir hoë volume produksie van plastiek gietsukke bruikbaar is, direk vanaf rekenaar-gesteunde ontwerp prosesse vervaardig word. Die gebruik van DMLS kan ook vir die ontwerp en vervaardiging van vorm getroue verkoelings kanale in matryse voorsiening maak, wat tot laer hitte asook die vinnige en eweredige verspreiding daarvan sal lei. Voorgenoemde behoort tot 'n aansienlike verlaging in produksie siklus tye te lei met 'n dien ooreenkomstige verlaging in die produksie koste asook 'n verbetering in die kwaliteit van die vervaardigde produkte a.g.v. die voorkoming van defekte soos kromtrekking en hitte-putte wat normaalweg deur oneweredige hitte verspreiding veroorsaak word.

1 INTRODUCTION

From the different plastic manufacturing processes that are in use today, the plastic injection moulding process is the one most used in the plastic product manufacturing industry [1]. Plastic injection moulded products are used in a wide variety of industries due to the ability of the process to manufacture products rapidly in a cyclic process.

The cost-effectiveness of the plastic injection moulding process depends on the length of time of the cycle process during the moulding cycle. The injection moulding cycle, as illustrated in Figure 1, consists of four important stages [2]:

1. Filling of the mould cavity
2. Packing of the polymer melt
3. Solidification of the plastic product
4. Ejection of the product from the mould

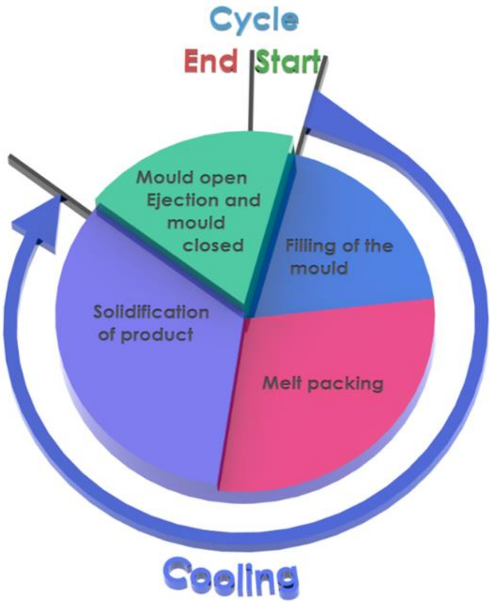

Figure 1: Injection moulding cycle

It is evident from Figure 1 that the cooling time required for the process is the most significant phase of the complete injection moulding cycle. The time spent cooling the plastic product can be significantly reduced by optimising the rate of heat transfer between the product and the cooling channels of the injection mould insert [3].

1.1 Cooling channels design criteria

For optimal cooling in a mould, the following design criteria need to be considered during the design phase of an injection mould or insert:

- Calculation of the shot weight of the moulded product.
- Calculation of the heat content for each cycle.
- Calculation of the flow rate of the cooling medium through the mould.
- Selection of the diameter of the cooling channel to be used.
- Calculation of the number of cooling channels required to accommodate the flow rate and cooling medium.

Three important parameters for successful cooling channel design are summarised in Table 1, and the different parameters are illustrated in Figure 2 [4].

Table 1: Design guideline derived from Fourier's law

Wall thickness of product (in mm)	Hole diameter (in mm) **(b)**	Centreline distance between holes **(a)**	Distance between centre of holes and cavity **(c)**
0 -2	4 -8	2 -3 x b	1.5 -2 x b
2 -4	8 -12	2 -3 x b	1.5 -2 x b
4 -6	12 -14	2 -3 x b	1.5 -2 x b

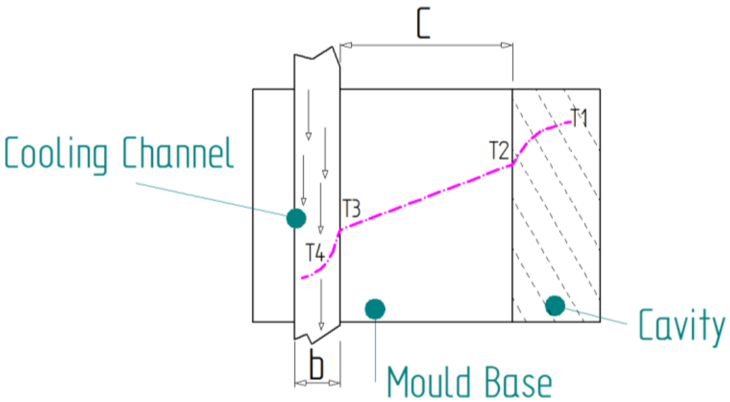

Figure 2: Cooling channel design parameters

For optimal heat transfer to the cooling channel, *c* should be as small as possible, and the distance between the cooling channels, value *a* is dependent on the value of *b*.

2 MOULD MANUFACTURING PROCESSES

Mould design and manufacturing represent important links in the entire plastic product injection moulding production chain and process [5].

The largest expense associated with new product development is usually the manufacturing of an injection mould. A global drive exists to reduce the cost and lead times of injection moulds and inserts, and to improve the quality of products produced [6].

Injection moulds and inserts can be manufactured either using conventional methods (subtractive manufacturing), or through AM technologies.

2.1 Subtractive manufacturing

Injection moulds are mostly manufactured using conventional processes such as electric discharge machining (EDM), computer numerical controlled (CNC) milling, and wire cutting, or through a combination of these processes. Manufacturing of injection moulds and inserts can be time-consuming and expensive due to the intensive labour required when using subtractive manufacturing methods [5]. Producing steel cavities is more expensive than other materials that could be used in injection mould manufacturing, such as aluminium. Steel cavities, however, are normally the preferred option, due to the longer service life obtained from the steel moulds [7]. Figure 3 illustrates the subtractive manufacturing processes where the material stock is systematically removed by machining to produce a product.

Conventional manufacturing techniques can only create cooling channels using a drill, or by machining cooling channels into one of the surfaces of an insert. Figure 4 illustrates typical cooling channels that can be manufactured using conventional methods.

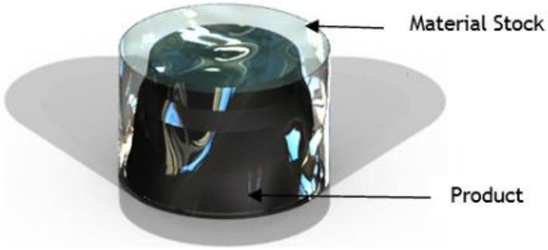

Figure 3: Subtractive manufacturing where the material stock is removed to manufacture a product.

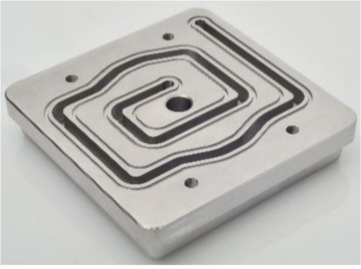

Figure 4: Cooling channels manufactured using conventional machining methods

2.2 Additive manufacturing

Additive manufacturing (AM) is a process where products are manufactured using a layered technique. Since the introduction of AM in the early 1980s, the technology has become an important part of the product development process chain in many industries. AM's benefits are well-established. Prototype parts can be produced quickly for validation, measurement, and, in some cases, actual trials. AM can be a major cost-saver because it allows the designer and manufacturer to see what a part will look like in its early development stages. It also allows for design changes or product cancellations when such decisions are least expensive, particularly with highly complex designs [6].

DMLS is a process that is suitable to produce high-quality metal tool inserts, prototypes, and end-products in metal. The build platform is a tool steel base on to which the metal powder is sintered layer-upon-layer, as illustrated in Figure 5. The tool steel base can also be incorporated into the mould insert design, saving additional manufacturing time and costs to remove the manufactured insert from the base.

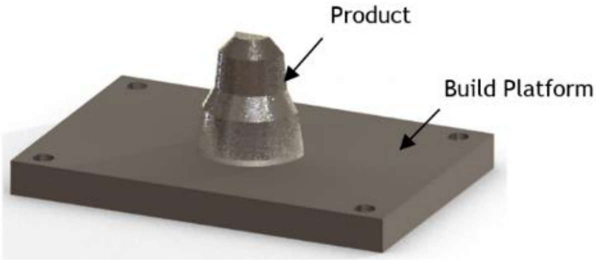

Figure 5: A DMLS product built on a tool steel build platform

2.2.1 Advantages of additive manufacturing in tooling

Mould inserts consisting of complex geometries that will be time-consuming and difficult to manufacture using conventional processes can easily be produced using AM technologies. Using DMLS MS1 inserts, injection mould inserts can be manufactured that include complex cooling channels that conform or fit to the shape of the core or cavity. These are known as 'conformal cooling channels' [13]. The properties of the MS1 material are summarised in Table 2 [9]. The MS1 material compares favourably with standard tool steel grade 'werkstoffnummer' 1.2312 that is used commercially.

Table 2: MS1 material data sheet

Technical data	Physical, mechanical, and thermal properties
Minimum recommended layer thickness	40-60 µm
Minimum wall thickness	0.3-0.4 mm
Relative density with standard parameters	Approximately 100%
Density with standard parameters	8.0 -8.1 g/cm^3
Ultimate tensile strength – as build	1100 MPa ± 100 MPa
Ultimate tensile strength – after age hardening	1950 MPa ± 100 MPa
Yield strength – as build	1100 MPa ± 100 MPa
Yield strength – after age hardening	1900 MPa ± 100 MPa
Young's modulus	180 GPa ± 20 GPa
Hardness – as build	33 -37 HRC
Hardness - after age hardening	50 -54 HRC
Thermal conductivity - as build	15 ± 0.8 W/m°C
Thermal conductivity - after age hardening	20 ± 1 W/m°C
Specific heat capacity	450 ± 20 J/Kg°C

Traditional methods of creating cooling channels in moulds involve straight-line drilling and slotting, which are limited to the manufacturing of channels that are able to reach critical hot spots. DMLS enables built-in conformal cooling channels that can be optimised to extract heat more rapidly and more evenly. This also reduces the cycle times and increases part quality by eliminating warpage and other defects [2]. Figure 6 illustrates conformal cooling channels implemented in an injection mould insert. Conformal cooling channels can reduce the cost of plastic injection moulded parts by reducing the cooling time required, which can account for up to 70 per cent of the cycle time.

Figure 6: Example of conformal cooling channels designed by Pole Europeen de la Plastyrgie (PEP) [2]

3 CASE STUDY: INTERLOCKING POLYPROPYLENE FLOOR TILE

A flat product (150mm x 150mm x 4mm), illustrated in Figure 7, was designed using solid works by considering the following criteria during the design phase of the product:

- Ease of mould manufacturing.
- Cost of mould manufacturing.
- Practicality of product.
- Polymer to be used during the manufacturing of the product.
- Dimensional restraints due to the built envelope of AM equipment and cost of an AM insert.

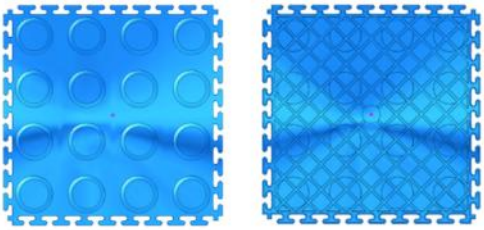

Figure 7: CAD model of product

A prototype, shown in Figure 8, was manufactured in Polyamide 2200 using an EOS Formiga P100 laser sintering system to test the fit and function of the product prior to the mould design and manufacturing stage, as part of the product optimisation process.

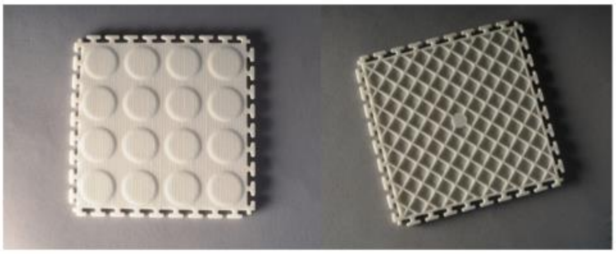

Figure 8: PA2200 prototype of product to test the fit and function of the design

3.1 Mould design

The design of the mould was done so that either the conventional manufactured or the AM manufactured mould insert could be used to shape the bottom of the product. This was done to compare the cooling performance of the two different mould inserts. Efficient cooling of the mould insert is important because it will affect not only the cycle time during production, but also the functionality of the mould. A reduced temperature in the mould insert, compared with the fixed half of the mould, will cause the product to 'stick' to the fixed half of the mould (where the ejecting mechanisms are situated to eject the product from the mould) during production, as illustrated in Figure 9.

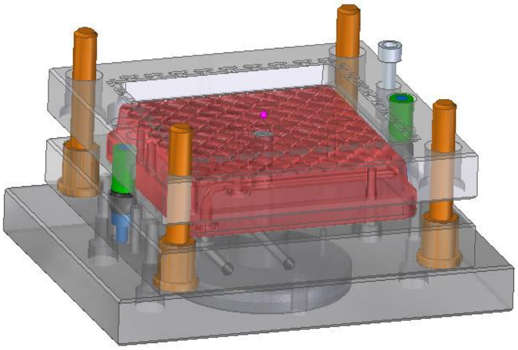

Figure 9: Fixed half of the injection mould, illustrating the ejection mechanism

3.2 Manufacturing of conventional insert

Numerical controlled (NC) codes for the machining tool paths were programmed using EdgeCam 2014 R1 computer-aided manufacturing (CAM) software (see Figure 10 below). The insert was machined using a Jyoti VMC850 vertical CNC machine, as illustrated in Figures 11 and 12.

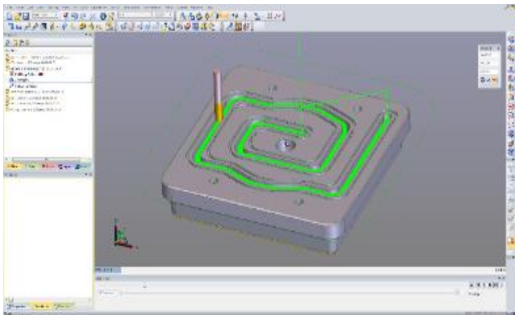

Figure 10: NC toolpaths programmed using EdgeCam 2014 R1

Figure 11: Jyoti VMC850 vertical CNC machine used to manufacture the conventional insert

Figure 12: CNC machining of conventional manufactured insert

When designing cooling channels for the conventional process, slots and straight holes are used while avoiding existing holes and features of the insert.

3.3 Manufacturing the AM insert

The DMLS MS1 mould insert was manufactured through the EOS M270 IM Xtended machine using a layer thickness of 50 microns. A material thickness of 0.5 mm was added to all the external faces of the insert to provide for possible distortions during the growing process that could influence the accuracy of the insert. Before the MS1 insert could be used in an injection moulding machine, a finishing cut using a CNC machine was necessary.

3.3.1 Cooling channel design of the AM insert

Finite element analysis simulation was done using ANSYS® simulation software to identify the most effective conformal cooling channel design before the AM insert was manufactured. Two different conformal cooling designs (shown in Figure 13) were used during the analysis: a spiral and a meander cooling channel design.

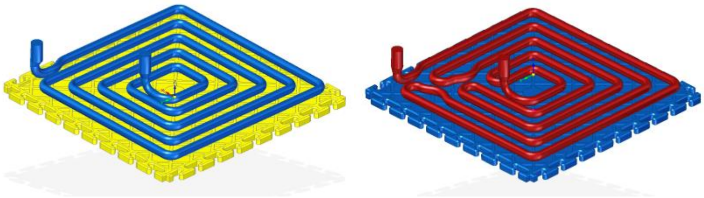

Figure 13: Spiral and meander conformal cooling design

The outlet temperature from the cooling channels was simulated, and the heat absorbed by each channel design was compared using the following formula:

$$Q=\dot{m}C_p\,\Delta T \tag{1}$$

The most efficient design can be chosen based on the amount of heat removed between the inlet and the outlet of each cooling channel. The results of the two different cooling designs are summarised in Table 3.

Table 3: Heat transferred to the water inside a cooling channel

Heat absorbed by water, calculated for the spiral conformal cooling channel	Heat absorbed by water, calculated for the meander conformal cooling channel
$Q=\dot{m}\,C_p\,\Delta T$ $Q = 0.133(4.187)(341.281 - 293.15)$ $Q = 26.803$ kJ	$Q=\dot{m}\,C_p\,\Delta T$ $Q = 0.133(4.187)(4.187)(340.928 - 293.15)$ $Q = 26.606$ kJ

This procedure does not accurately compare the heat absorbed by each channel design because the path of a particle flowing through the two different channels is not the same.

A second method, using five equally-spaced particles moving through each channel design (see Figures 14 and 15), was considered. A temperature–time graph was plotted for each particle. The area underneath the curve of the graph was calculated using the trapezium theorem (see Figures 16 and 17).The area divided by the total time resulted in an average temperature for each particle. From these results, the overall average temperature for each channel was obtained. The results of the temperature difference between the two cooling channel designs are summarised in Table 4.

Table 4: Comparison of temperature difference between the spiral and meander conformal cooling channel designs

Variable	Spiral channel	Meander channel
Outlet temperature [K]	341.28	340.93
Maximum turbulence kinetic energy [m^2.s^2]	2.91	3.13
Heat transfer [kJ]	26.80	26.61
Average water temperature [K]	316.22	316.43

From Table 4 it can be concluded that the meander cooling channel produced better results, comparing temperature and maximum turbulence kinetic energy measured in root mean square (RMS) velocity fluctuations. Thus the meander conformal cooling design was chosen for the AM insert based on the results obtained.

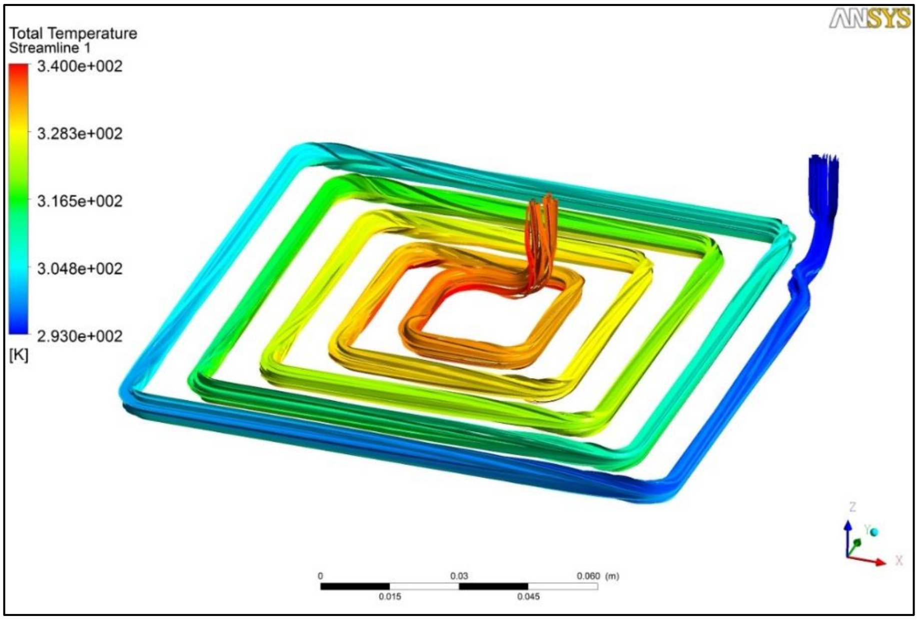

Figure 14: Spiral streamline temperature

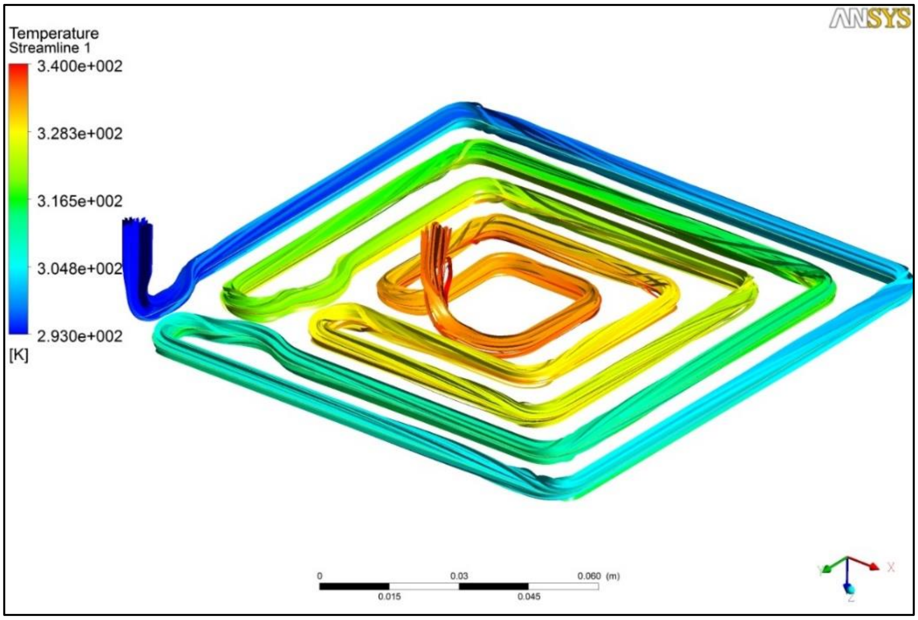

Figure 15: Meander streamline temperature

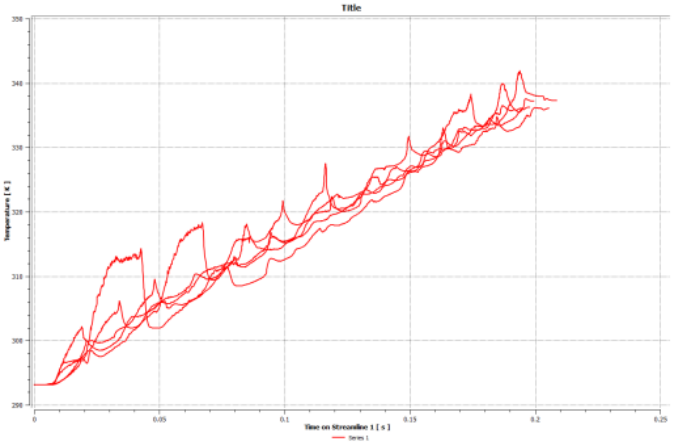

Figure 16: Spiral temperature vs time

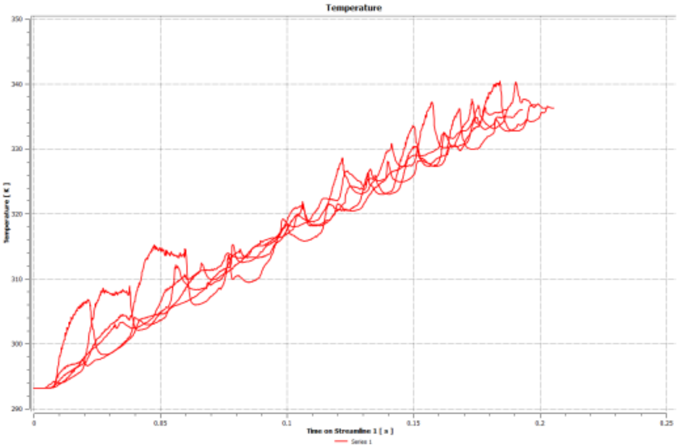

Figure 17: Meander temperature vs time

4 RESULTS

‘SIGMASOFT® virtual moulding principle’, a computer-aided engineering (CAE) software, was used to simulate and compare the DMLS insert with the meander conformal cooling channel against the conventional manufactured insert for a duration of twenty injection moulding cycles. The layouts of the two different cooling channels of the AM insert and the conventional manufactured insert are shown in Figure 18.

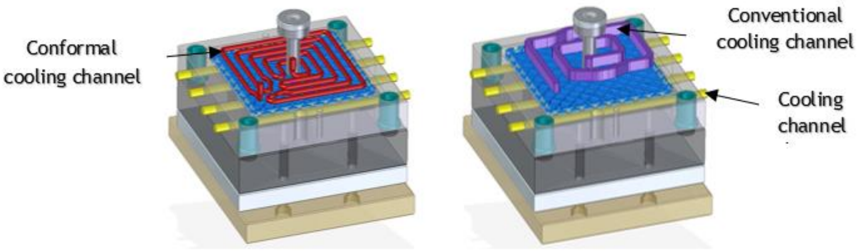

Figure 18: Conformal and conventional cooling channels

The following data was obtained from the CAE analysis:

- The wall surface temperature of the inserts.

- The effect of the different cooling channels on the cycle times.
- Cooling rate of the product.
- The degree of crystallisation on the products produced by the AM and the conventionally manufactured inserts.
- Product warpage or displacement after ejection from the mould.
- The effect of the different cooling channels on the internal mould temperature.

The results obtained from the CAE analysis are summarised in Table 5.

Table 5: Comparison of the AM meander conformal cooling channel and the conventionally manufactured cooling channel

Variable	Conformal channel	Conventional channel
Maximum cooling rate (Start of first cycle)	477.2 [° C/s]	466.6 [°C./s]
Maximum cooling rate (Start of 20th cycle)	458.6 [° C/s]	436.5 [°C./s]
Crystallisation	0.99	0.99
Maximum X-direction displacement	1.04 [mm]	1.04 [mm]
Maximum Y-direction displacement	1.04 [mm]	1.04 [mm]
Maximum Z-direction displacement	0.01567 [mm]	0.01571 [mm]
Maximum mould temperature (End of first cycle)	37.62 [° C/s]	40.38 [° C/s]
Maximum mould temperature (End of 20th cycle)	44.72 [° C/s]	56.41 [° C/s]
Maximum insert wall surface temperature (End of first cycle)	37.66 [° C/s]	40.7 [° C/s]
Maximum insert wall surface temperature (End of 20th cycle)	41.15 [° C/s]	56.7 [° C/s]
Heat dissipation (Cooling channel 2, Cycle 1)	6.323 [kJ]	1.569 [kJ]
Heat dissipation (Cooling channel 2, Cycle 20)	9.552 [kJ]	6.576 [kJ]
Wattage dissipation (Cooling channel 2, Cycle 1)	316.15 [W]	78.45 [W]
Wattage dissipation (Cooling channel 2, Cycle 20)	477.6 [W]	328.8 [W]
Cycle time	19s	20s

For the part to be ejected successfully, the interlocking regions need to be solidified. The cycle time of the product was determined by taking into account the time taken for each insert to produce a product that is 86 per cent solidified, as shown in Figure 19. This was achieved in 20 seconds with the conventional manufactured insert, and in 19 seconds using the AM insert.

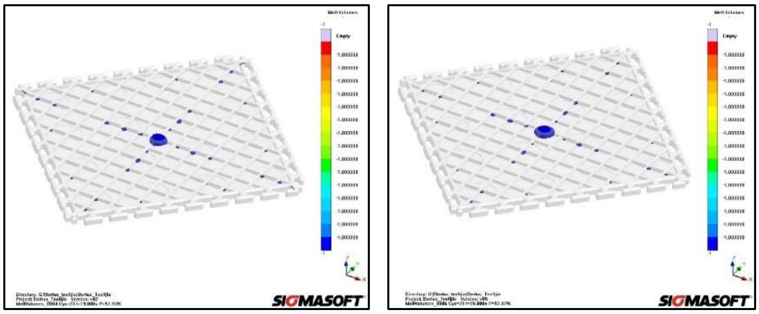

Figure 19: Solidification of product (left side conformal; right side conventional)

The internal mould temperature distribution obtained from the SigmaSoft CAE simulation during the 23rd second of the 20th cycle is shown in Figures 20 (AM insert) and 21 (conventionally manufactured insert). After the 23rd second of the 20th cycle, the maximum temperature inside the mould using the AM insert was 44.72 °C compared with the 56.41 °C of the mould using the conventional manufactured insert. This is due to the conformal cooling channel being closer to the mould surface, preventing the heat from being conducted to the rest of the mould. This results in lower temperatures around the bottom of the product. This is significant, in that it encourages the product to stick on the desired side of the mould, which is important for ejecting the product.

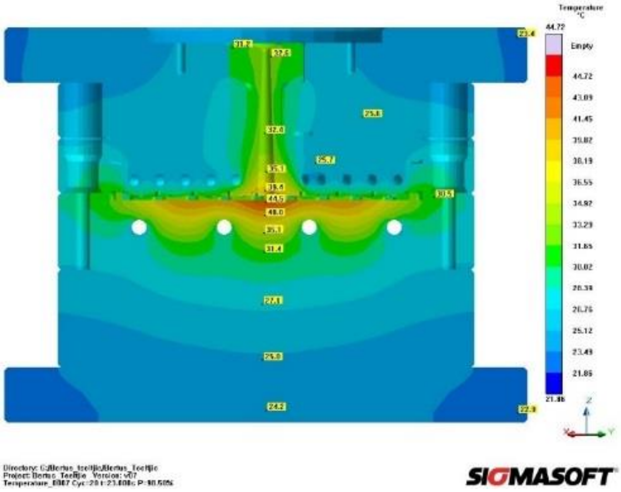

Figure 20: Internal temperature of the mould using the AM insert after the 20th cycle

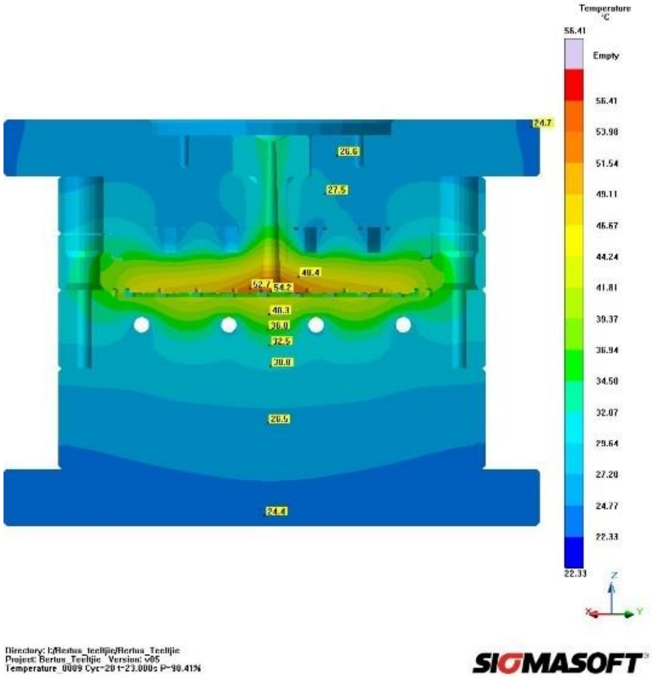

Figure 21: Internal temperature of the mould using the conventionally manufactured insert after the 20th cycle

5 CONCLUSION

Comparing Figures 20 and 21, it can be concluded that AM inserts using conformal cooling technologies are more efficient in removing heat from an IM than are conventionally manufactured inserts.

The significant difference in cost to produce mould inserts is due to the geometry of the insert; this was not perfectly suited to manufacturing with AM technology because the geometry could easily have been machined using a CNC milling machine. CNC costs could also have been saved by incorporating the build platform into the design of the AM insert. Table 6 compares the manufacturing costs of the mould inserts. The Rand/Euro exchange rate also contributed to the high manufacturing cost of the AM insert.

Table 6: Manufacturing costs comparison

AM insert manufacturing cost	Conventional insert manufacturing cost
R39 910.56 AM cost	R 253.80 Tool steel (1.2316) cost
R7 425.82 CNC cost	R10 501.83 CNC cost
R400.00 fitting	R400.00 fitting
R4 500.00 wire EDM cost	R3 100.00 cutters
Total: R52 236.38	Total: R14 055.63

Results from the FEA simulation indicate a shorter cycle time using the AM insert with conformal cooling channels. This shorter cycle time reduces the production time needed to manufacture the plastic components, increasing the efficiency of the IM process.

However, a large number of products need to be produced to recoup the additional manufacturing costs (± R38 000.00) of the AM insert compared with the manufacturing costs of a conventional manufactured insert.

FEA analysis software was successfully used to analyse different conformal cooling channel designs, making it possible to obtain the optimal cooling channel geometry for an AM insert. Further trials will be conducted to investigate the long-term effects and performance advantages of using AM inserts with conformal cooling channels in a high-volume injection moulding production environment.

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