Design, Optimization and Validation of Conformal Cooling Technique for Additively Manufactured Mold Insert

Ganesh G. Dongre¹, Sarang S. Chaitanya¹, Sai M. Jonnalagadda²

¹Department of Industrial & Production engineering, Vishwakarma Institute of Technology, Pune
²Renishaw Additive Manufacturing Solutions Centre, Pune

E-mail: ganesh.dongre@vit.edu, sarang.chaitanya16@vit.edu, sai.jonnalagadda@renishaw.com

Abstract. Injection molding is a cyclic process comprising of cooling phase as the largest part of this cycle. Providing efficient cooling in lesser cycle times is of significant importance in the molding industry. Conformal cooling is a proven technique for reduction in cycle times for injection molding. In this study, we have replaced a conventional cooling circuit with an optimized conformal cooling circuit in an injection molding tool (mold). The required heat transfer rate, coolant flow rate and diameter of channel was analytically calculated. Hybrid Laser powder bed fusion technique was used to manufacture this mold tool with conformal channels. The material used for manufacturing mold was maraging steel (M300). Thermal efficiency of the conformal channels was experimentally calculated using thermal imaging. Autodesk MoldFlow software was used to simulate and predict the cooling time required using conformal cooling channels. The results showed a decrease in cooling time and increase in cooling efficiency with the help of conformal cooling in additively manufactured mold insert.

Keywords: Conformal cooling, Laser powder bed fusion, Additive manufacturing, cycle time.

1. Introduction
Plastic injection molding is the most versatile and widely used technique to produce plastic parts for various applications such as automotive, electrical & electronics. The technique uses molten plastic as raw material and a specially designed tool called as mold. The molten plastic is injected using pressure in the mold cavity where it solidifies and takes the shape of the cavity to obtain the final plastic part. Cooling channels are manufactured in the mold tool through which a coolant (water/oil) is passed. This coolant carries out the heat from molten plastic and helps it solidify quickly. The speed & evenness of cooling depends on distance between cooling channels and mold wall. Improper or uneven cooling can induce defects like warping, sink marks and reduce the part quality thereby increasing scrap rate. Traditionally these channels are manufactured using straight/cross drilling and inserting plugs wherever required. The plastic part under manufacturing consists of intricate shapes, ribs, and bosses. Traditional straight channels cannot provide efficient cooling to these features. Conformal cooling is the process of manufacturing cooling channels in mold that conform to the mold wall i.e. follows the shape and profile of the mold core/cavity. Conventional machining processes cannot be used to manufacture conformal channels. Additive manufacturing or 3D printing is a manufacturing technique in which parts are manufactured layer by layer directly from the CAD data. Since theoretically any geometry can be
manufactured with these 3D printing technologies, the internal cooling channels can be made of optimum design and placed near the mold wall thus, conforming to the wall. Laser powder bed fusion is a metal 3D printing technology used in this research to manufacture the confirmly cooled mold tool. This technique uses fine metal powder and a high intensity laser beam to manufacture a part layer by layer. The CAD design is sliced into layers and this sliced data is sent to the 3d printing machine. A 50-60 µm thickness layer of metal powder is spread over a build platform. This powder is fused and locally welded using a laser beam which moves according to the sliced CAD data. Once a layer is completed, the build platform moves downward by amount equal to layer thickness and next layer is spread. In this way, an entire part is manufactured layer by layer.

2. Literature Review
Previously various researchers have contributed to the field of Conformal Cooling by conducting different experiments and using various techniques. Au and Yu, in 2007, conducted experiments by using scaffolding architecture for the conformal cooling channels design. Simulations techniques were used to compare the mold cavity with and without scaffolding structure. The mold analysis was conducted using MoldFlow plastics insight 3.1. the results showed that better cooling was provided by the scaffolding structure due to higher surface area. Hearunyakij et al used Fin concept to improve the efficiency of the Conformal Cooling Channels. In another study, the authors used square section conformal cooling channel (SSCCC) against the conventional straight cooling channels (CSCC). Polypropylene and ABS were used as the plastic materials and water at 25 °C used as coolant. The results obtained using MoldFlow Plastic Insight software showed reduction in cooling time by 35% with SSCC over CSCC.

Another research group investigated the CCC using array of baffles in plastic injection molds. Raw material used was ABS 750 and simulations were carried out with the help of MoldFlow. The temperature variation in cooling channel with an array of baffles shown an improvement of 49.41% which is uniform compared to straight channels. In another study, researcher compared the results of Profiled cross-sectional CCC (PCCC)

Ahn et al. studied the difference between conventional cooling channels and conformal cooling channels with ABS as raw material. The mold tool was manufactured using AM technology. Simulation results obtained from MoldFlow V6.1 showed a drastic reduction in cycle time by 25.7%. D. E. Dimla, M Camilotto and F Miani conducted research for the optimization of Conformal Channels. They studied the temperature, pressure and time variation in Injection Molding and provided the optimal location for Gate and cooling channels in Core and Cavity part of mold. Suchana Akter Jahan and Hazim El-Mounayri investigated the thermomechanical analysis of conformal cooling channels in 3D printed plastic injection molds. They conducted a DOE based research by considering two shapes (Conical & Cylindrical) and three wall thicknesses (1mm, 3.5mm & 6mm). The results showed optimal CCC dimensions and shapes in accordance with the considered parameters.

Tong Wu et al. designed a framework for optimizing the design of injection molds with conformal cooling for Additive Manufacturing. They performed cooling simulations and Thermo-Mechanical Topology Optimization on a generic die with conformal cooling. The results shown that the material content should be more around the cavity for better heat dissipation/cooling rate as well as structural stiffness.

3. Material and Methodology
The ultimate objective of this research was to replace the existing traditional cooling channels in the mold by optimized conformal cooling channels. Methodology followed during this research was study of existing channels and its drawbacks. Then optimized designing of conformal cooling channels using the design formulas and manufacturing of optimized mold. Finally, validation of conformal channels compared to traditional channels is carried out. The plastic material used to manufacture the component was PA6 (30% glass filled). Liquid used as coolant in this research was Mobiltherm 605 oil. Since the mold insert was additively manufactured using LPBF process, material used for manufacturing was Maraging steel (grade M300).
4. Design
An automotive component’s injection molding tool was taken under study for this research. The core section of mold tool [fig.1] was selected for optimizing the cooling channels. Before optimizing, the traditional cooling circuit designed for the mold tool was studied and findings were listed. The design consisted of a simple rectangular shaped cooling circuit with channel diameter 10 mm [fig.2]. Traditionally this cooling circuit was manufactured by drilling 8 straight holes in the mold block and inserting 4 plugs to change the coolant’s direction.

After studying the traditional cooling circuit following points were concluded and used as a reference for designing an optimized conformal cooling circuit.

1. The channels were placed farther from mold wall which affects rate of cooling and increases cooling time.
2. Internal bosses & ribs are under-exposed hence mold is unevenly cooled which may result in warping & sink marks.
3. Design consists of sharp corners which can lead to pressure drop & loss in turbulence of coolant.

Based on these conclusions, the cooling channels were optimized to provide even and efficient cooling in less time. Parameters optimized while designing conformal channels were heat flow rate from the mold tool, flow rate of the coolant through the channels and diameter of the channel. Once these values were calculated, the path of the cooling channel was decided so that it covers maximum contact area with the mold without conflicting with other mold elements. Freeform design manufacturing is a prominent advantage of additive manufacturing which helped us to design the path of channel in such a way that it covers remote areas of the mold (bosses & ribs) which could not be reached using traditional cooling channels. The data required for design calculations is summarized in below table.

| Table 1. Required data for design calculations |
|-----------------------------------------------|
| Plastic material       | PA6 (30% glass filled) |
| Wall thickness of molded part | 2.8 mm |
| Mass of molded part    | 24.5 grams |
| Melting temperature    | 270 °C |
| Ejection temperature   | 90-100 °C |
| Coolant               | Mobiltherm 605 |
4.1 Evaluation of heat transfer rate

The total amount of heat to be removed from the mold by the cooling system is

\[ Q_{\text{molding}} = M_{\text{molding}} \times C_p \times (T_{\text{melt}} - T_{\text{eject}}) \]

where:
- \( M_{\text{molding}} \) = Mass of the molding along with runner = 29.5 gm
- \( C_p \) = Specific heat capacity of Plastic (PA6) = 1.5 J/g °C
- \( T_{\text{melt}} \) = Melting temperature of the plastic = 270 °C
- \( T_{\text{eject}} \) = Ejection temperature of the part = 100 °C

Therefore,

\[ Q_{\text{molding}} = 29.5 \text{gm} \times 1.5 \text{ J/g °C} \times (270-100) \text{ °C} = 7522.5 \text{ Joules} \]

The cooling power is defined as amount of energy removed per unit time. Therefore,

\[ Q_{\text{cooling}} = \frac{Q_{\text{molding}}}{\text{Timecooling}} \]

\[ Q_{\text{cooling}} = \frac{7522.5 \text{ J}}{30 \text{ s}} = 250.75 \text{ watts} \]

4.2 Evaluation of coolant flow rate

While carrying out the heat from molten plastic, the coolant temperature increases. The increase in coolant temperature reduces cooling efficiency hence sections of mold where coolant reaches last are not cooled evenly. Given a volumetric flow of coolant \( V \), increase in coolant temperature is given as

\[ \Delta T_{\text{coolant}} = \frac{Q_{\text{molding}}}{(V_{\text{coolant}} \times \rho_{\text{coolant}} \times C_p)} \]

Allowable increase in coolant temperature is 1 °C for precision injection molding. So, by rearranging equation (1) volumetric flow is determined as,

\[ V_{\text{coolant}} = \frac{Q_{\text{molding}} \times \rho_{\text{coolant}} \times C_p \times \Delta T_{\text{coolant}}}{250.75 \text{ W}/(857 \text{ Kg/m}^3 \times 1°\text{C} \times 2.32 \text{ J/g °C})} \]

\[ = 0.1261 \times 10^{-3} \text{ m}^3/\text{s} \]

\[ = 7.566 \text{ Lit/min} \]

This flow rate also makes sure that turbulence in the channels is maintained without losing pressure.

4.3 Evaluation of channel diameter

Optimum value of channel diameter can now be calculated based on heat transfer in mold and fluid flow constraints. To ensure adequate heat transfer, turbulent flow of coolant is necessary. To safeguard turbulent flow, the Reynold’s number (Re) should be greater than 4000.

\[ R_e = 4\times \rho_{\text{coolant}} \times V_{\text{coolant}} / (\pi \times \mu_{\text{coolant}} \times D) \]

Since \( R_e > 4000 \)

\[ D = 4\times \rho_{\text{coolant}} \times V_{\text{coolant}} / (\pi \times \mu_{\text{coolant}} \times 4000) \]

Where \( \mu_{\text{coolant}} \) = Dynamic Viscosity of the coolant

\( \mu_{\text{coolant}} = 4.4 \text{ Centipoise} = 4.4 \times 10^{-3} \text{ Pa-s} \)

So,
After determining the optimum values for heat transfer rate, coolant flow rate and channel diameter, path of cooling channel was designed. Important criteria while designing the path of cooling channel in an injection mold tool is to place the channels as close as possible to the mold wall since the evenness of cooling depends on the distance between channels and mold wall. While positioning the channels it is necessary to ensure that there is no loss in strength of the mold. The plastic injection mold is an assembly of various components. So, the path of channel should be such that it does not conflict with other mold tool elements such as ejector pins. Considering all these constraints, a cooling channel path was determined which can carry the coolant to remote areas of mold [fig.3].

\[
D = \frac{4 \times 857 \text{ (Kg/m3)} \times 0.1261 \times 10^{-3} \text{ (m3/s)}}{\pi \times 4.4 \times 10^{-3} \text{ (Pa- s)} \times 60 \times 4000}
\]

\[
D = 0.007821 \text{ m} = 7.821 \text{ mm}
\]

5. Manufacturing

Once the cooling channel diameter and its path was determined, the mold insert was manufactured by additive manufacturing. Specifically, Laser powder bed fusion technique of metal AM was incorporated for manufacturing. After completing the CAD design of conformally cooled mold insert, it was divided in two parts [fig.4]. First part being the base and second being the top section consisting of optimized cooling channels. Then it was decided to manufacture the mold using hybrid AM technique. Hybrid AM is a process of building a 3D part layer by layer on the surface of a pre-machined part. Since the base was bulky and simple in shape, it was traditionally manufactured using milling and drilling. This machined base was mounted on the build platform of 3D printing machine and the remaining top section of mold was additively built on this pre-machined base. Important parameter while hybrid manufacturing was the alignment of the top and base. After carrying out alignment trials, the top and base were perfectly matched and 3D printing was initiated. Material used for manufacturing was maraging steel M300. This is an alloy of Iron and Nickel which exhibits high levels of strength and hardness. High machinability even after heat treatment is an important property of maraging steel which makes it suitable for mold tool applications. The mold was manufactured on Renishaw’s AM250 machine [fig.5]. Parameters used while manufacturing were, layer thickness = 40 μm and laser power = 250 Watts. Hybrid 3D printing of mold was completed in 24 hours.

After completing, part was heat treated to relieve the stresses induced due to additive manufacturing. The cooled part was removed from furnace and bead blasting was performed to remove the burn marks and unfused powder particles from the mold surface. Burn marks and unfused powder particles can deteriorate the part properties and aesthetics. Since injection molding tools need high tolerances, the part was post-machined after 3D printing to achieve the required tolerance levels. The holes present in
part were wire cut to precision and other features like ribs and corners were spark eroded to achieve the final geometry of part.

6. Result and Discussion
Analytical results derived using formulas and calculations confirmed that channel diameter (8 mm) and path of channel will be effective to optimize heat flow, cycle time and part qualities. But these analytical results had to be checked against practical results. Our final aim was to compare the results of conventional cooling and conformal cooling for given mold. To validate the optimized heat flow in the mold, thermal imaging analysis was performed. To simulate the cooling of mold using conformal channels and compare with cooling time of conventional mold, simulations were performed using Autodesk MoldFlow software.

6.1. Thermal imaging analysis
After setting up the mold tool in the mold base, it is generally pre-heated. This step is performed to calculate the time in which mold gets heated to the plastic ejection temperature. The mold base is connected to MTC oil controller through hoses and hot oil is circulated through the channels. Time is measured using stopwatch. Once the mold gets heated to required temperature, hot spots are observed using thermal camera. Thermal images show where the heat is concentrated and temperature at various sections of mold. Testo 868 thermal imager was used for this validation.

To compare the pre-heating times and heat concentrations in conventional and conformal molds, these two molds were fitted in same mold base and oil controller was connected in loop [fig.6]. Hot oil at 100 °C was passed through loop. Temperature readings were taken at 3:30 mins, 4:00 mins and 4:30 mins. Thermal images of both molds were taken at respective times which showed us mean and maximum temperatures along with heat distribution profiles. Mold 1 represents conventional mold whereas Mold 2 represents conformal mold.

| Time (mins) | Mold 1 mean T (°C) | Mold 1 max T (°C) | Mold 2 mean T (°C) | Mold 2 max T (°C) |
|-------------|-------------------|-------------------|-------------------|-------------------|
| 3:30        | 44.9              | 66                | 54.2              | 88                |
| 4:00        | 54.9              | 66.8              | 55.3              | 87.9              |
| 4:30        | 60                | 69                | 69.7              | 88.3              |
Table 2 shows that after passing same coolant at same temperature for the same period through the two molds, the conformal channels mold tool exhibits higher rise in temperature compared to conventional channels mold. Since the ejection temperature of plastic is 100 °C, above results were linearly forecasted. Mean temperature values were forecasted because overall mold temperature should reach 100 °C at ejection. Forecasted values showed that conventional mold will require 7:30 mins to reach ejection temperature whereas conformal channels mold reaches ejection temperature in 6:30 mins. Hence approximately 15 % of mold pre-heating time is saved during each cycle.

The thermal images captured during pre-heating experiment clearly showed that in confirmally cooled mold insert [fig.7], only those areas where effect of conformal cooling (in this case heating) was expected are getting heated. On the other hand, in conventional mold [fig.8], entire mold is getting heated. Hence conformal cooling technique will provide effective cooling to the remote areas (ribs and bosses) of mold where conventional channels could not provide.
6.2. MoldFlow analysis

MoldFlow is specialized software by Autodesk which simulates the process of plastic injection molding. Cooling simulation package of this software was used to calculate the cooling time of plastic part using additively manufactured mold consisting of conformal cooling channels. Simulation is dependent on plastic and coolant material used for molding. The diameter and path of cooling channel also plays vital role in deciding the cooling time. The CAD design consisting of conformal channels was imported into the software and simulation was performed. Results deduced from simulation showed that cooling time required for plastic part to reach ejection temperature using conformal channels is 27 seconds [fig.9]. The existing cooling time of the plastic part using conventional cooling 30 seconds. Hence using conformal channels, total reduction in cooling time and eventually cycle time is 3 seconds. So conformal cooling channels helped us reduce the cycle time of each part by 10%.

![Figure 9. Simulation results using MoldFlow software](image)

7. Conclusion

An existing mold design consisting of conventional rectangular type cooling channel circuit was optimized to reduce the process cycle time and provide effective cooling to mold thus reducing manufacturing defects. This optimized mold insert was successfully 3D printed. After validation, following conclusions are drawn,

1. Reduction in cooling time of the plastic by 10% per cycle.
2. Reduction in mold pre-heating time by 15% per cycle.
3. Effective cooling to remote areas of the mold.
4. Faster production rate with better quality can be achieved using conformal cooling..

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