

CONFORMAL COOLING CHANNELS IN INJECTION MOLDING TOOLS – DESIGN CONSIDERATIONS

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Abstract: This scientific paper presents the research conducted for defining the characteristics of the conformal cooling systems used in molds for injection molding processes (IMP). By utilizing laser-sintering additive manufacturing (AM) technologies, this type of cooling systems could be used to minimize the cooling and cycle times in the IMP's and provide a homogeneous cooling necessary to maintain a consistent quality of the part. The paper also presents an overview of the AM technologies used in manufacturing conformal cooling molds and the main guidelines for designing these cooling systems.

The research shows that the efficiency of these channels is based on the channel system's design; and for plastic parts with a lower complexity the improved temperature distribution compared to conventional cooling systems could be negligent.

The research is conducted by using Finite Element Analysis (FEA) and CAD modeling to compare different conformal shapes, as well as their cooling efficiency on a plastic part. The simulation studies are done to determine the temperature distribution in each case study. These trials are done to assess the productivity benefits that arise from the use of conformal cooling channels compared to conventional channels that utilize baffles and bubblers.

KEYWORDS: INJECTION MOLDING, CONFORMAL COOLING, 3D PRINTING, RAPID TOOLING, LASER SINTERING

1. Introduction

In thermoplastic injection molding, the mold performs three basic functions: forming molten material into the product shape, removing heat for solidification, and ejecting the solid part. Of the three, heat removal usually takes the longest time and has the greatest direct effect on cycle time. Despite this, mold cooling-channel design is often done after the feed system, mold mechanism, and ejection system designs are already finished. Consequently, many cooling designs must accommodate to the available space and machining convenience rather than the thermodynamic needs of the product and mold.

Cooling in cavity geometries is typically accomplished by drilling cooling channels around the part cavity. The need to drill these cooling lines and avoid the part ejector system limits the size and number of cooling circuits and their proximity to the molded part. Short and independent circuits yield the best temperature control performance. Parallel cooling circuits as opposed to series cooling circuits are considered a better cooling method. Short parallel circuits do not allow the coolant to heat up in the mold and offer more consistent and uniform temperature control.

Cooling of the core insert is the greatest problem in most injection molding applications. Often, no cooling is employed in the core itself. Cooling only occurs in the mold base through the core mount. With no core cooling, eventual heating of the core is unavoidable. Cooling of slender cores is often accomplished by using **inserts** made of materials with high thermal conductivity, such as copper, beryllium-copper or high-strength sintered copper-tungsten materials. When these inserts are press-fitted into steel tools, an additional heat transfer interface is created. When used in contact with the polymer melt, reductions in tool lifetime may be noted.

A **baffle** is a common cooling method in those cases in which the coolant is directly channeled through the core. A baffle uses a flat or spiral divider in a hole running through the center of the core. The inlet and return flow are separated. This method provides maximum cross sections for the coolant to flow through. The divider must be mounted exactly in the center of the hole to ensure that the coolant does not bypass the hole.

The most effective cooling of slender cores is achieved with **bubblers**. An inlet tube directs the coolant into a blind hole in the core. The diameters of both have to be adjusted in such a way that

the resistance to flow in both cross sections is equal. Bubblers are commercially available and are usually screwed into the core. One problem with baffles and bubbler cooling systems is that the necessary hollow center can result in a structurally weak core insert [7].

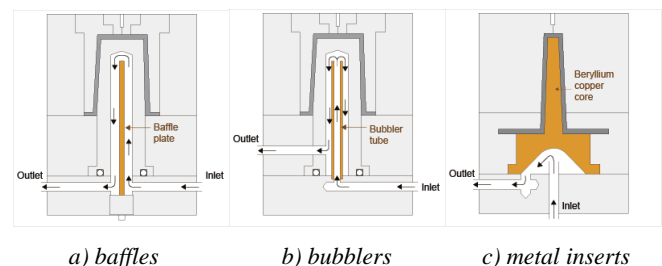


Fig.1.1 Conventional cooling strategies for injection mold cores
(Source: polyplastics.com)

2. Rapid tooling technologies

Rapid Tooling involves all additive manufacturing procedures that lead to final parts used as cores, cavities, or inserts for tools, dies and molds. Two sub-levels must be distinguished: direct tooling and prototype tooling

The primary advantage of RP and RT is its ability to create almost any shape or geometric features, even those complex shapes that would be virtually impossible to machine. With additive fabrication, the machine reads in data from a CAD model and lays down successive layers of different materials, and builds up the physical model from a series of layers. Those layers are joined together or fused automatically to create the final shape matching the CAD model.

The possibility of direct-metal rapid tooling (RT) from high quality steel is not commonly used in the injection molding industry today. However, the RT industry is in an expansive phase and new applications are evolving continuously. RT technologies can be divided into different types and [10] Menges, G et al [10] suggest the following classification:

- conventional removal and coating processes;
- material additive processes;
- master mold processes; and
- hybrid processes

L-E. Rannar, lists some of the competitive methods in the RT market today [9]:

- 3D Keltool, by 3D systems.
- EBM, electron beam melting, by Arcam.
- DLF, direct laser forming by Trumpf.
- DMD, direct metal deposition, by the POM Group.
- DMLS, direct metal laser sintering, by EOS.
- LAM, laser additive manufacturing, by Aeromet.
- LaserCusing, by concept laser.
- Laser consolidation, by Accufusion.
- LENS, laser engineered net shaping, by Optomec.
- ProMetal, by ProMetal RCT.
- RSP, rapid solidification process, by RSP tooling.
- SLM, selective laser melting, by MCP Group.
- SLS, selective laser sintering, by 3D Systems.
- Solid phase laser sintering, by Phenix systems.
- Stratoconception by CIRTES.

3. Conformal cooling

Over the last decade, conformal cooling has been proposed as a solution for controlling injection molding temperatures. Mold inserts can be built with internal cooling channels that follow the contour of the cavity beneath the surface (Fig. 3.1, b). Because the form of the channels follows the contour of the mold, the method is called conformal cooling. Due to the increased heat extraction, the productivity of a plastic injection mold can be increased significantly. In addition, cooling and heating channels can be designed to obtain an integrated heat management system and thus much more effective tools. Improperly designed cooling systems often result in two undesirable outcomes. Firstly, cooling and cycle times are much longer than what could have been achieved. Secondly, significant temperature gradients arise across the mold, causing differential shrinkage and warpage of the moldings. To operate effectively, cooling systems must be carefully designed to manage the heat flow throughout the mold without incurring undue cost or complexity.

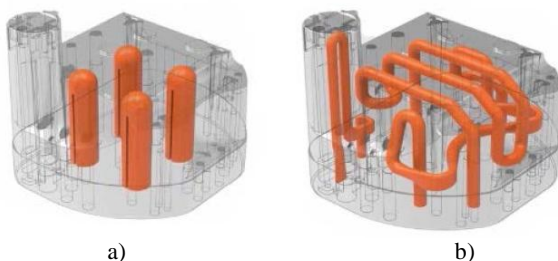


Fig. 3.1 Conventional cooling channel core with buffers (a) vs. conformal cooling channel design (b) (Source: 3dsystems.com)

In recent years, a lot of case studies have been done proving the effectiveness of cooling channels for parts with complex geometry. One of those studies featured by 3DSystems with is for a core with a tapered helix that is positioned on the inside of a spacing cone used for industrial assemblies (Fig 3.2).



Fig. 3.2 A Bastech mold core insert with conformal cooling channels prototyped using 3D Systems' Stereolithography (SLA) technology and printed in maraging steel on the ProX® DMP 200. (Source: 3dsystems.com)

The conformal cooling mold maintained a lower temperature throughout the run and reduced cycle time by 14%. This design can also be applied to molds made by materials other than metals, but as it stands now, metal based AM technologies are still the standard when it comes to designing conformal channels for larger production series molds.

3.1. Design for conformal cooling

In order to remove a molded part from the mold, the material must be sufficiently cooled to provide ejection without distortion. Adequate mold cooling can be considered to have occurred if the part surface is hard enough to prevent ejector pins from penetrating. Cooling-channel placement determines cooling efficiency and uniformity. Positioning the channels too close to the cavity surface can cause cold spots and uneven cooling. If they are too far away, cooling becomes more uniform but less efficient.

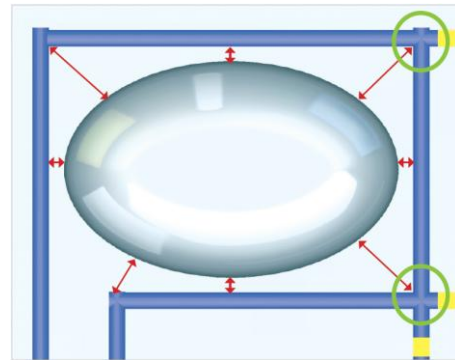


Fig. 3.3 Conventional tooling mold temperature control. Uneven distances to the cavity surface throughout the length of the channels (Source: [5])

As shown in Fig 3.3, uneven distances to the cavity surface leads to an uneven heat conductance. The areas with the threaded heat conductance limit the coolant flow (marked with green). These locations are susceptible to accumulation of dirt deposits which lead to pressure losses that result in a steady decline of the general flow in the cooling circuit.

The use of conformal cooling channels optimizes the molding process by providing a constant temperature gradient throughout the mold all the while increasing the total surface area of the cooling circuit. This also results in savings in manufacturing the inserts.

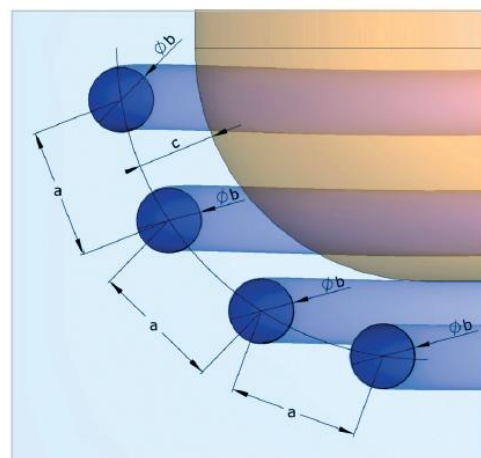


Fig. 3.4 Optimal design of a conformal cooling channel system (Source: [6])

The ultimate objective is the creation of a mold temperature control system, which enables a constant and adapted temperature level for the material, during the running injection molding process on each point of the molding surface. In order to achieve this result, the channel diameter should be chosen depending on the distance between the heating/cooling channel and the cavity. Provided that the design for the mold part is correct, the product can recrystallize

uniformly and efficiently in the mold after the injection phase, which improves the quality and reduces the cycle time.

Table 3.1: Conformal cooling channel diameter based on the wall thickness (Source: [6])

Wall thickness [mm]	Hole diameter [mm] (b)	Centerline distance between holes [mm] (a)	Distance between the center of the holes and the cavity [mm] (c)
0 ÷ 2	4 ÷ 8	$(2 \div 3) \cdot b$	$(1,5 \div 2) \cdot b$
2 ÷ 4	8 ÷ 12	$(2 \div 3) \cdot b$	$(1,5 \div 2) \cdot b$
4 ÷ 6	12 ÷ 14	$(2 \div 3) \cdot b$	$(1,5 \div 2) \cdot b$

The design guidelines used for conventional cooling circuits can also be applied to conformal cooling channels. Some of the recommended dimensions are given in the schematic in Fig 3.4 and the recommended hole diameters based on the average wall thickness of the plastic part are shown in table 3.1. Selective laser sintering techniques can build cooling channels down to a diameter of 1 mm, but such small channels can only be put into service using specific coolant fluids in order to avoid clogging.

According to Park and Pham [7], there are three basic techniques that can be used when designing conformal cooling channels: zigzag, parallel, and spiral. (Fig. 3.5).

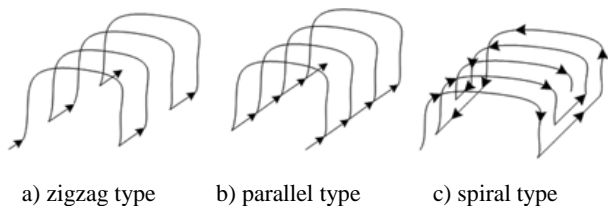


Fig. 3.5 Basic shapes used in designing conformal cooling channel systems (Source: [7])

Depending on the geometry of the part, these methods may be used in combination or on their own. The zigzag pattern, also known as a series cooling path, cools regions of the part one after the other rather than at the same time. Cooling in series is generally not preferred unless parts are small enough that the delay is negligible. The parallel channel design allows for different areas of the mold to be cooled at the same time, but requires a lot more coolant. The spiral conformal cooling channel design is often used with parts that have curvature or spherical elements.

The general opinion is that when designing conformal cooling channels, it's always recommend to use an injection molding simulation software package in order to identify different temperature zones within a mold so that the conformal cooling channels can be separated and optimized within each region.

The freedom offered by additive manufacturing opens a lot more possibilities when it comes to optimizing the coolant flow in the cooling circuits. One of those possible optimizations is to change the cross section of the channels in order to improve the coolant flow. In a study done by Manat et. al. [5], the efficiency of a conformal cooling system is studied by using different cross sections. The cooling channels had a different number of fins as shown in Fig. 3.6.

In that study, the novel cooling channel design showed a decrease in total cooling time by up to 6.5 sec for channels with seven fins compared to the cooling channels with circular cross sections and the cooling efficiency in term of the heat flux increased by 22.6 %.

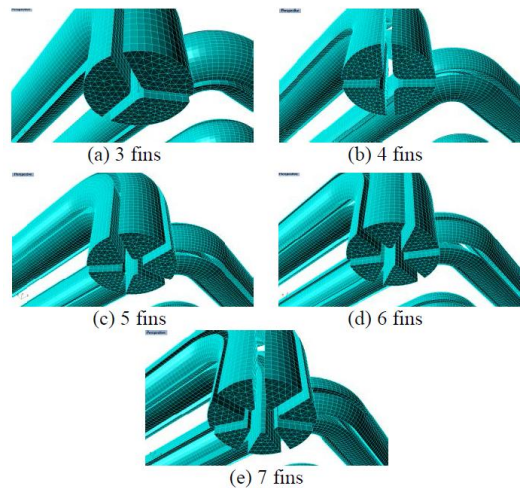


Fig. 3.6 Conformal mold cooling by using fin concept (Source: [5])

3.2. Case study of the viability using FE analysis

This study investigates the impact of the conformal cooling circuits on a plastic injection mold for parts with a simple shape. The analysis of the cooling efficiency is done by comparing 3 different circuit geometries, one conventional and 2 conformal channels that correspond to the spiral and linear type mentioned in [7] (Fig.3.5). All of the shapes are shown in table 3.3. Every channel has a circular cross-section with a diameter of 8 mm that corresponds to the recommendation found in table 3.1 for a wall thickness of 4 mm. The injection molding software used for the simulation was Solidworks Plastics. The simulation was done using a virtual mold to account for a more accurate heat transfer. All of the relevant information concerning the part and mold properties, as well as the process parameters are given in table 3.2.

Table 3.2 Material properties and process parameters

Part properties	
Material	PA66+30% Glass fiber
Dimensions	Ø 39 x 164 mm
Volume	84,15 cm ³
Weight	115,73 g
Thermal conductivity (polymer)	0.27 W/(m-K)
Specific heat (polymer)	2.2 · 10 ⁷ erg/(g-C)
Virtual mold properties	
Mold material	Steel – 420SS
Density	7,73 g/cm ³
Thermal conductivity	2,5 · 10 ⁶ erg/(sec-cm-K)
Specific heat	4,62 · 10 ⁶ erg/(g-C)
Process parameters	
Fill time	10 sec
Pressure holding time	12.59 sec
Mold open time	5 sec
Injection pressure limit	100 MPa
Max. injection flow rate	194 cc/s
Average Coolant Flow Rate	150 cc/s
Melt temperature	295 °C
Mold temperature	60 °C
Ejection temperature	220 °C
Glass transition temperature	235 °C
Coolant temperature	25 °C
Ambient temperature	30 °C

Table 3.3: Material properties and process parameters

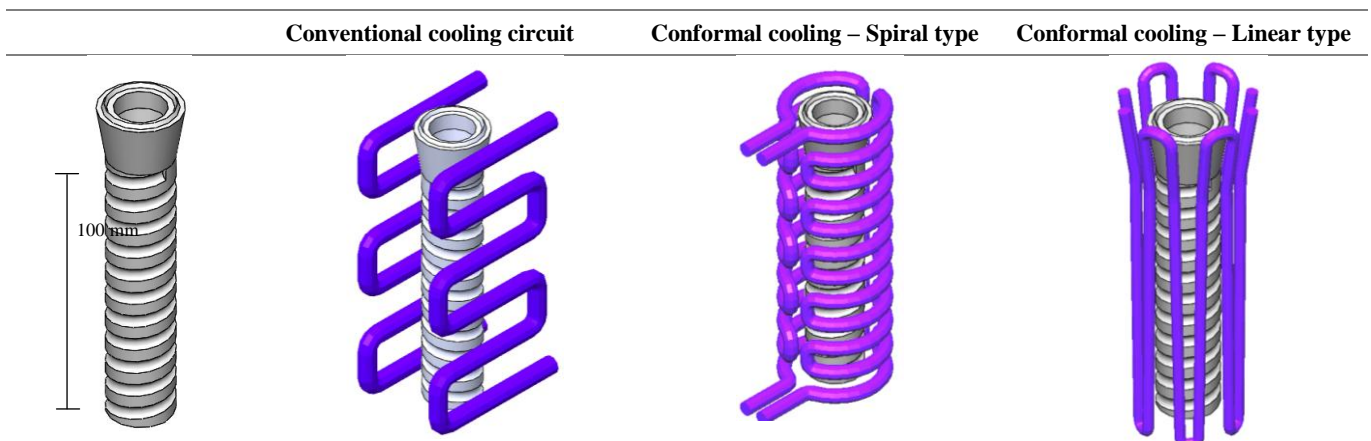


Table 3.4: Summary results

	Conventional cooling circuit	Conformal cooling Spiral type	Conformal cooling Linear type
Total cycle time	71.09 sec	70.44 sec	70.09 sec
Pure cooling time	46.95 sec	46.00 sec	45.65 sec
Averaged part temperature	161.63 °C	163.00 °C	162.50 °C
Averaged mold cavity temperature	44.42 °C	40.45 °C	40.40 °C
Averaged mold cavity heat flux	2.33 J/cm ² -sec	2.40 J/cm ² -sec	2.38 J/cm ² -sec
Averaged cool channel heat flux	1.71 J/cm ² -sec	1.16 J/cm ² -sec	1.46 J/cm ² -sec

4. Conclusion

Rapid tooling has numerous advantages and applications and few of them have been covered in this paper. The use of CAD technologies allows the use of modular dies and specially fabricated inserts. It reduces the high cost of skilled laborers and die makers and significantly improves lead times. Still there are some challenges to overcome when moving forward. The main shortcoming of rapid tooling is the potentially reduced tool life compared to conventional tools. The parts produced by RT still need to be machined, as in most cases the initial surface finish is not good enough. Currently, metal based AM processes are the only viable technologies for large series of injection moldings, mainly because of conformal cooling circuits. Conformal cooling designed for plastic injection molding is a valuable alternative in improving the plastic part quality and in reducing cycle times and energy consumption. However, due to the high manufacturing costs linked to additive manufacturing techniques, its application is still in its infancy.

This paper presented two conformal designs and compared them to conventional cooling channels. Even though the temperature distribution throughout the part improved, the reduction in the cycle time was not significant. We suspect that the reason behind this is the low degree of complexity of the tested model. Previous research showed that conformal cooling tends to be valuable when the product has deeper regions from which linear cooling channels are unable to achieve a significant heat transfer due to low accessibility. In these cases, as previous research showed, the cycle times are reduced by up to 20% when using conformal cooling channels.

Conformal cooling, however, adds new layers of design and production complexity to the mold making process, placing it beyond the means of most shops. The investment in AM machines is not always justified, especially when manufacturing simpler injection molded parts. In those cases, the use of conformal cooling is not needed and conventional channels manufactured with drilling can be used to get similar results. In some cases RT is still slower than traditional manufacturing due to its incomplete integration and the number of available materials that can be used is limited.

5. References

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