"Development and Simulation Analysis of an Efficient Cooling System for Injection-Molded Plastic Components"

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ABSTRACT

The Injection Moulding (IM) process holds a pivotal role in plastic manufacturing, and the cooling phase, taking up nearly half of the entire cycle time, is of particular significance. The effectiveness of cooling channels plays a crucial role, exerting a substantial impact on both the quantity of production and the standard of the component. In Given the increasing prevalence of additive manufacturing (3D Printing), a viable solution to address this issue involves creating moulds with conformal cooling. This method enables accurate regulation of temperature distribution uniformity throughout the plastic solidification process in molding operations.

This study is cantered around the design and simulation of various conformal cooling channel types, including hybrid, zig-zag, spiral and porous configurations. These are compared with traditional straight cooling methods for a plastic part. The comparative analysis encompasses parameters such as mould ejection temperature, shrinkage, Warpage, temperature profiles to determine which configuration is better suited for achieving uniform cooling with minimal cycle time. The investigation utilizes SolidWorks Simulation Moldflow Analysis software to scrutinize the performance outputs of the cooling channels.

1. INTRODUCTION

Plastic injection molding stands out as the most versatile and extensively employed method for manufacturing plastic components across diverse applications, including automotive and electrical/electronics. This technique involves the utilization of molten plastic as the raw material and employs a specialized tool known as a mould. By applying pressure, the molten plastic is injected into the mould cavity, where it undergoes solidification, adopting the precise shape of the cavity and resulting in the production of the final plastic part. [1]. The injection moulding process stands out as the predominant method for economically mass-producing high-quality plastic parts [2]. This procedure includes melting the plastic material, injecting it into the mould cavity, and then cooling the molten material before ejection. As a result, the essential stages in the injection molding process comprise injection, packing, cooling, and ejection [3,4].

Despite its widespread use, injection moulding encounters challenges that can impact the final product's quality and production volume. Issues such as cycle time, warpage, part cooling time and shrinkage are critical factors affecting the desired products. The time taken to reach the ejection temperature part, also known as the time to freeze, encompasses the duration from injection to demoulding temperature. This period plays a crucial role in the filling, packing, and cooling phases. Warpage, a common defect in injection-moulded plastic parts, manifests as distortion leading to bending or twisting. It is primarily caused by uneven cooling, resulting in non-uniform shrinkage, and is influenced by factors such as part and mould design, gate location, type of runner, gate, and the cooling system [1].

The shrinkage observed in plastic parts is ascribed to factors such as residual stress during filling, packing, and cooling, along with packing pressure, which demonstrates a reciprocal connection with shrinkage [1]. To tackle these issues, two primary solutions are under consideration: modifying the mould design and optimizing process parameters such as mould temperature, melt point, cooling system, and packing pressure [4].

This paper aims to pinpoint the most effective configuration for a cooling system, referred to as conformal cooling, that guarantees even cooling, minimizes cycle time, and mitigates warpage and shrinkage. The research centres on designing and simulating different types of conformal cooling channels—baffle, hybrid, zig-zag, and spiral configurations—while comparing them with traditional cooling approaches for an industrial plastic component [5,6].

2. APPROACH AND PROCEDURE

2.1. Modelling the Part Using Computer-Aided Design (CAD)

The plastic container sealing cap was modelled using Parametric Technology Corporation (PTC) Creo Parametric 9.0 software. The CAD model, depicting the sealing cap without a handle and with dimensions of 96 mm in height and 200 mm in diameter (refer to Fig. 1), was subsequently exported as an Standard for the Exchange of Product Data (STEP) surface model for importation into SolidWorks Plastic simulation software (see Fig. 1).[7]

2.2. SOLIDWORKS PLASTICS [7,8,9]

SolidWorks Plastic simulation software serves as a comprehensive plastic flow simulation tool, aiding researchers and plastic engineers in optimizing the amalgamation of plastic part geometry, materials, mould design, and diverse process parameters is essential for simulating top-notch products [5]. In this study, the STEP model data of the plastic CAD model was imported as a dual-domain mesh model, considering the 1 mm thickness of the plastic sealing cap, eliminating the necessity for 3D meshing.

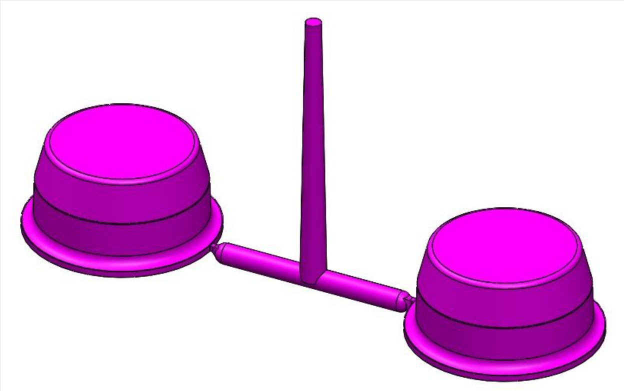

Fig.1 Product Data (STEP) With Feeding System

2.2.1 MESHING

The original global edge length of the mesh sizes underwent refinement, reducing from 12.43 mm to 7 mm. Mesh statistics revealed numerous Alerts regarding mesh element intersections were issued, leading to a modification in the global edge length of length of 5mm was selected for mesh generation, with a merge tolerance of 0.3mm. The resulting mesh comprised solid mesh 1,44,643 triangular elements, exhibiting zero element intersection, free edges & unmatched elements. Based on gate location analysis, the optimal injection point was identified on the sealing cap bottom. Subsequently, a cold tapered sprue with dimensions L50, D6, d3 mm was created at this optimal location (see Figure 2 B). Furthermore, mesh verification was carried out to guarantee the connectivity between the component and the cold sprue, utilizing the mesh repair wizard.

2.2.2 MATERIAL SELECTION

Sealing cap is made with low density polyethylene (LDPE) material, trade name is 16MA400 with 30MFI (High melt flow index) and the manufacturer name is Reliance LDPE Injection Moulding. Limited Company, India. Properties of the plastic component are shown in below Table 1.

Family Name	**Low-density polyethylene**	**Melt Temp**	**190°C/2.16 kg**
Trade Name	White Reline	**Melt Temp. Range**	180-240
Manufacturer Name	Reliance Limited Company	**Injection Temp.**	155
Family Abbreviation	LDPE	**Material Id.**	19725692912
Melt Flow Index (190 o C / 2.16 Kg)	30	**Material Structure**	Crystalline
Tensile Strength at Yield	10	**Elongation at Yield**	40

Table 1. Properties of the plastic component

2.2.3 SURFACE AREA OF COOLING CHANNELS

The surface area of cooling channels plays a crucial role in influencing the cooling rate [6]. It is essential to ensure that the surface areas of all types of cooling channels are either equal or differ by no more than 5%. This requirement ensures that a meaningful comparative analysis can be conducted to determine the optimal cooling channel systems. The cooling channels in this study have a diameter of 5 mm, use pure water with a temperature of 30°C as the coolant, and have a Reynolds number of 11476.7. Traditional cooling channels are being compared with four types of conformal cooling channels: Hybrid (HCCC) with a length of 572.76 mm, Spiral Helix (SHCCC) with a length of 396.72 mm, zigzag (ZCCC) with a length of 912.28 mm, Porous (PCCC) with a length of 1876.74 mm and Traditional straight cooling channels (TSCC) with a length of 681.2 mm. [8,9,10]

- Surface area of HCCC = $(2.\pi.r.h) + (2\pi.\ r^2) = (2\pi*2.5*572.76) + (2\pi*6.25) = 9{,}036.16\ mm^2$
- Surface area of SHCCC = $(2.\pi.r.h) + (2\pi.\ r^2) = (2\pi*2.5*396.72) + (2\pi*6.25) = 6{,}270.93 mm^2$
- Surface area of ZCCC = $(2.\pi.r.h) + (2\pi.\ r^2) = (2\pi*2.5*912.28) + (2\pi*6.25) = 14{,}369.33 mm^2$
- Surface area of PCCC = $(2.\pi.r.h) + (2\pi.\ r^2) = (2\pi*2.5*1876.74) +(2\pi*6.25) = 29{,}519.03 mm^2$
- Surface area of TSCC = $(2.\pi.r.h) + (2\pi.\ r^2) = (2\pi*2.5*681.2) + (2\pi*6.25) = 10{,}739.53\ mm^2$

2.2.4 HYBRID CONFORMAL COOLING CHANNEL (HCCC) [13,16]

The Hybrid Conformal Cooling Channel (HCCC) represents a departure from the Traditional Straight Cooling Channel (TSCC), aiming to overcome limitations associated with intricate component shapes. In the design process of HCCC, intricate shapes, especially circular components, are accommodated more effectively. The creation of HCCC involves configuring nodes and lines within PTC Creo parametric, akin to TSCC. However, the key distinction lies in the enhanced adaptability of HCCC to complex geometries. Following the design phase, the model is exported as a STEP file extension, encompassing surface models, Datum curves and points in SolidWorks plastic software are converted into channels through the designation of nodes and lines. specified characteristics, such as a 5 mm diameter, Distance to extend beyond part 10mm with 0.05 mm roughness, and a coolant temperature of 30°C (refer to Figure 2A for details). The HCCC approach thus offers a more versatile and tailored solution to conformal cooling needs without comparing directly to TSCC. [16]

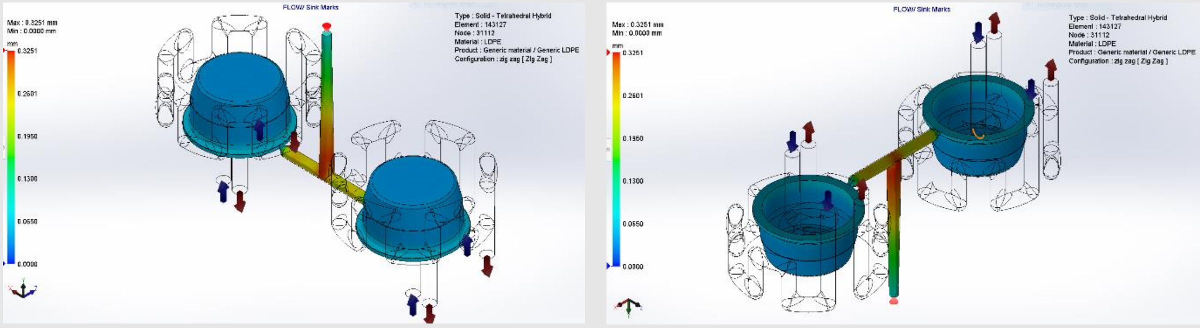

Fig.2A Hybrid conformal Cooling system.

2.2.5 SPIRAL HELIX CONFORMAL COOLING CHANNEL (SHCCC)

The Spiral Helix Conformal Cooling Channel (SHCCC) represents a departure from the traditional straight cooling approach, aiming to address the limitations posed by intricate component shapes, particularly circular parts, which can impede cooling efficiency. The design process for SHCCC involves the utilization of PTC Creo Parametric, where nodes and lines are configured to create a helical, spiral pattern. The resulting design is then exported in STEP file format, encompassing surface models, In SolidWorks plastic software, designated nodes and lines represent datum curves and points. are transformed into conformal cooling channels characterized by a spiral helix geometry.[8] These channels maintain a 5 mm diameter, distance between two channel line about 6 mm, Distance to extend beyond part 10mm and 0.05 mm channel surface roughness (Ra), and are subjected to a coolant temperature of 30°C, as depicted in Figure 2B for reference. This innovative approach aims to overcome the challenges associated with intricate shapes, offering a potentially more effective cooling solution for components with complex geometries.

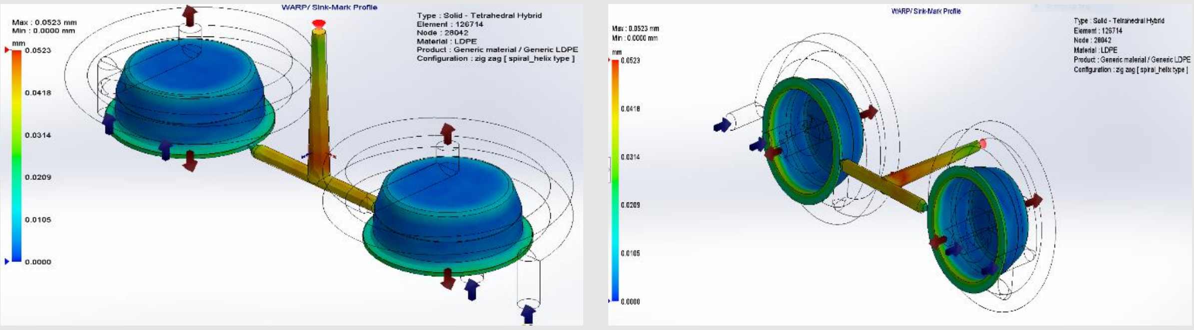

Fig.2B Spiral helix conformal Cooling system.

2.2.6 ZIGZAG CONFORMAL COOLING CHANNEL (ZCCC)

The Zigzag Conformal Cooling Channel (ZCCC) represents an innovative departure from the Traditional Straight Cooling Channel (TSCC), aiming to overcome the limitations associated with intricate component shapes. Developed to enhance cooling efficiency, ZCCC utilizes a distinct zigzag pattern in its design, enabling better adaptation to circular parts and other complex geometries. The creation of ZCCC involves configuring nodes and intricate zigzag paths within PTC Creo Parametric. Subsequently, the design is exported as a STEP file extension encompassing surface models, In SolidWorks plastic software, specified nodes and zigzag channels represent datum curves and points. are maintained with specific parameters, such as a 5 mm diameter, a distance of about 6 mm between two channel lines, and a 0.05 mm channel surface roughness (Ra), as illustrated in Figure 2C for reference. The ZCCC system aims to provide an effective cooling solution while addressing the challenges posed by intricate component shapes in manufacturing processes.

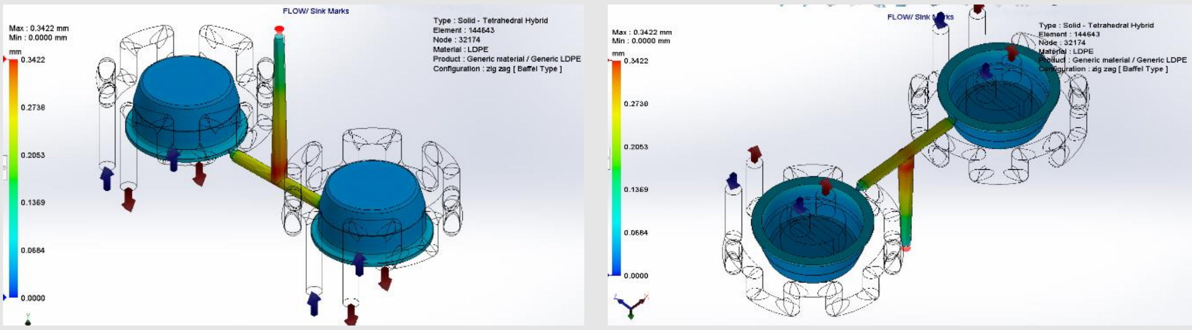

Fig.2C Zigzag conformal Cooling system.

2.2.7 POROUS CONFORMAL COOLING CHANNEL (PCCC)

The Porous Conformal Cooling Channel (PCCC) represents a departure from the Traditional Straight Cooling Channel (TSCC) due to its unique design approach. While TSCC relies on straight drilling methods, PCCC is characterized by a more intricate structure that allows it to conform to the complex shapes of components, especially circular parts, thereby enhancing overall cooling efficiency. In the creation of PCCC, nodes and lines are configured within software like PTC Creo parametric, and the design is exported in STEP file format, encompassing surface models, In SolidWorks plastic software, specified nodes and channels are preserved along with datum curves and points. a 5 mm diameter, a distance of about 6 mm between two channel lines, and a 0.05 mm channel surface roughness (Ra), as illustrated in Figure 2D for reference. The PCCC design represents a more versatile cooling solution, addressing the limitations of TSCC in accommodating intricate component shapes. [8,9]

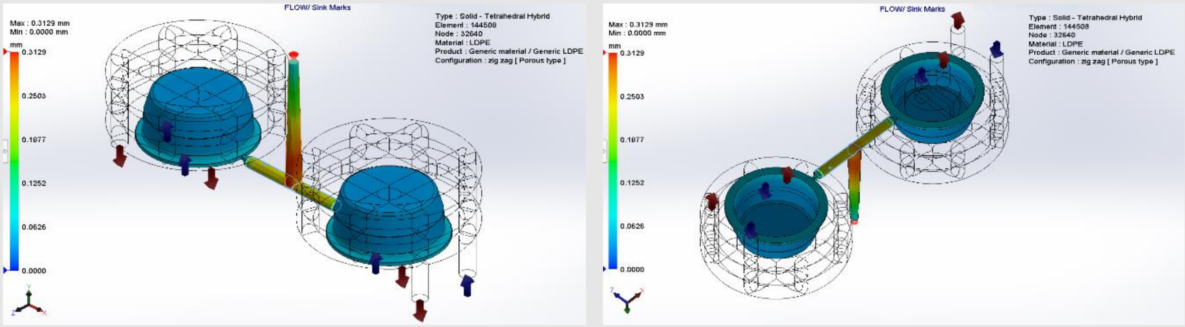

Fig.2D Porous conformal Cooling system.

2.2.8 TRADITIONAL STRAIGHT COOLING CHANNEL (TSCC)

The Traditional Straight Cooling Channel (TSCC) is widely recognized as the predominant cooling system, owing to its simplicity in fabrication using traditional straight drilling methods. However, this simplicity comes with inherent limitations, particularly when it comes to accommodating the intricate shapes of components, such as circular parts, which can adversely affect overall cooling efficiency. [10] The creation of TSCC involves configuring nodes and straight lines within PTC Creo parametric, followed by exporting the design in the form of a STEP file extension that encompasses surface models, In SolidWorks plastic software, all designated nodes and lines function as channels alongside datum curves and points. a 5 mm diameter, Distance to extend beyond part 10mm 0.05 mm roughness, and a coolant temperature of 30°C.

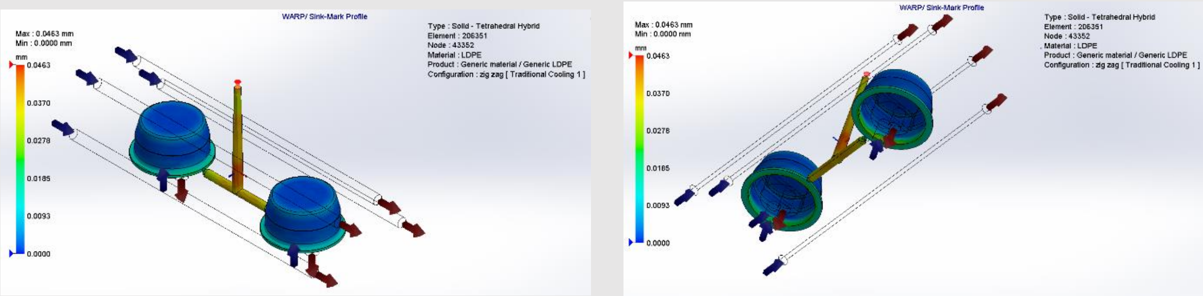

Fig. 2E Traditional Straight Cooling Channel.

3. RESULTS AND DISCUSSION

In the comprehensive evaluation of four distinct types of cooling channels in comparison to traditional cooling channels, various critical parameters have been meticulously investigated and summarized in Table 3. The Fill Time, representing the duration of material injection during the molding process, provides insights into the efficiency of each cooling channel type. Pressure at the end of Fill is indicative of the force exerted on the material at the completion of the filling phase. Volumetric Shrinkage at the end of Fill highlights the extent of material contraction during solidification. Moving to the packing phase, Pressure at the end of Pack signifies the force exerted on the material after complete packing. [12] Volumetric Shrinkage at the end of Pack reveals the degree of material contraction during the packing phase. Finally, the assessment extends to Part Cooling and Warpage Deflection, crucial factors influencing the quality and integrity of the molded part. The detailed comparison presented in Table 3 enables a comprehensive understanding of the performance variations among the different cooling channel types and aids in informed decision-making for optimizing the molding process.

3.1 FILL TIME AND PRESSURE AT THE END OF FILL [13,14]

The fill time and pressure at the end of fill has been analysed, and the results of the analysis show that, the fill time and pressure at the end of fill play crucial roles in assessing the performance of different cooling channel configurations (CCC). For the Hybrid Type CCC, the fill time is impressively low at 0.44 seconds, coupled with a relatively moderate pressure of 32.97 MPa. Spiral Type CCC exhibits a slightly longer fill time of 0.64 seconds and a higher pressure of 67.83 MPa. Meanwhile, Zig Zag Type CCC demonstrates a fill time of 0.46 seconds with a pressure of 31.72 MPa. The Porous Type CCC stands out with the shortest fill time of 0.43 seconds and a comparatively lower pressure at the end of fill, measuring 25.74 MPa. The Traditional Straight CCC stands out with the shortest fill time of 0.44 seconds and a comparatively lower pressure at the end of fill, measuring 26.12 MPa. These results underscore the importance of selecting an appropriate cooling channel design based on the specific requirements of the molding process, considering factors such as fill time and pressure for optimal performance shown in Table 2.

3.2 SHRINKAGE AT THE END OF FILL AND PRESSURE AT THE END OF PACK

The simulation results highlight significant variations in Volumetric Shrinkage at the end of Fill and Pressure at the end of Pack among different cooling channel configurations. In particular, the Hybrid Type CCC exhibits a Volumetric Shrinkage of 15.78%, while Spiral Type CCC and Zig Zag Type CCC demonstrate 8.78% and 15.39%, respectively. Porous Type CCC stands out with a Volumetric Shrinkage of 16.5%, Traditional straight CCC exhibits a Volumetric Shrinkage of 16.35%. Moving to the Pressure at the end of Pack, Hybrid Type CCC records 13.18MPa, Spiral Type CCC shows 26.83MPa, Zig Zag Type CCC registers 12.37MPa, and Porous Type CCC achieves 10.27MPa, Traditional straight CCC records 10.11MPa. These findings, illustrated in Table 2, underscore the critical influence of cooling channel design on both shrinkage and pressure dynamics during the injection molding process, providing valuable insights for optimizing manufacturing parameters.[15]

3.3 SHRINKAGE AT THE END OF PACK AND PART COOLING TIME.

The simulation outcomes reveal distinctive characteristics in Volumetric Shrinkage at the end of Pack and Total Part Cooling Time for various cooling channel configurations. Specifically, in Hybrid Type CCC, Volumetric Shrinkage at the end of Pack is recorded at 14.05%, while Spiral Type CCC and Zig Zag Type CCC exhibit 6.63% and 14.08%, respectively. Porous Type CCC stands at 14.11% in this parameter and Traditional straight CCC, Volumetric Shrinkage at the end of Pack is recorded at 14.21%. Furthermore, the Total Part Cooling Time for Hybrid Type CCC is 1.12 seconds, closely followed by Spiral Type CCC and Zig Zag Type CCC at 1.11 seconds and 1.12 seconds, respectively. Porous Type CCC excels with a Total Part Cooling Time of 1.08 seconds and Traditional straight CCC is 1.12 seconds. These findings, detailed in Table 2, underscore the nuanced performance differences in cooling channel designs, emphasizing their impact on key aspects such as shrinkage and cooling times during the molding process. [15,16]

	HCCC	SHCCC	ZCCC	PCCC	TSCCC
FILL TIME (SECONDS)	0.44 sec	0.64 sec	0.46 sec	0.43 sec	0.44 sec
PRESSURE AT END OF FILL (MPA)	32.97MPa	67.83MPa	31.72MPa	25.74MPa	26.12 MPa
SHRINKAGE AT END OF FILL (%)	15.78%	8.78%	15.39%	16.5%	16.35%
PRESSURE AT END OF PACK (%)	13.18MPa	26.83MPa	12.37MPa	10.27MPa	10.11MPa
SHRINKAGE AT END OF PACK (%)	14.05%	6.63%	14.08%	14.11%	14.21%
COOLING TIME (SECONDS)	1.12 sec	1.11 sec	1.12 sec	1.08 sec	1.12 sec

Table 2. Findings from the analysis

4. CONCLUSION

Five distinct configurations of conformal cooling channel types were assessed for their efficiency in comparison to traditional straight cooling channels using SolidWorks plastics Software. The study evaluated various parameters, including fill time, pressure at the end of fill, volumetric shrinkage at the end of fill, pressure at the end of pack, volumetric shrinkage at the end of pack and part cooling time. The results demonstrated a significant improvement with Conformal cooling channels differ from the traditional straight cooling configuration. These channels, conforming to the part profile, align themselves with the part surface in contact with the mold cavity, exhibited enhanced heat extraction during the entire molding cycle, particularly during the cooling phase through conduction heat transfer. Despite their advantages, conformal cooling channels require specialized fabrication techniques. Additive manufacturing proves instrumental in creating these channels, offering the capability to generate intricate cooling configurations that conventional straight cooling methods cannot achieve, catering to the evolving needs of current technological mold developers.

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