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Effect of Cooling Channel Diameters on Warpage in Plastic Injection Molds: A Comparative Analysis

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Abstract:- Warpage, or dimensional distortion, is a significant issue in the plastic injection molding process, negatively affecting both product quality and manufacturing efficiency. The aim of this study is to investigate the effect of different cooling channel diameters on warpage behavior in plastic parts. In this study, ABS (Acrylonitrile Butadiene Styrene) material was used, and simulations were conducted with four different cooling channel diameters (6 mm, 8 mm, 10 mm, and 12 mm). The simulations were performed using Moldex 3D software, with 32 cooling channels used for each diameter. Mold, environmental, and material parameters were optimized for the simulations. The simulation results showed that cooling channels with a diameter of 6 mm increased the warpage rate, while 8 mm and 10 mm channels demonstrated lower warpage values. The lowest warpage was observed with the 8 mm diameter. Moreover, the effect of 12 mm diameter channels was minimal. While the effect of cooling channel diameter on warpage is limited, proper optimization of channel size and placement can lead to improved thermal distribution and dimensional accuracy in the plastic injection molding process.

Keywords:- *Plastic Injection Molding; Warpage Control; Cooling Channel Design; Thermal Homogeneity;Simulation Analysis.*

I. INTRODUCTION

Warpage in plastic injection molding is a critical defect influenced by several factors throughout the molding process. Temperature differences within the mold significantly contribute to warpage, as uneven cooling leads to differential shrinkage across the part, creating internal stresses and deformation [1]. This phenomenon is closely linked to non-uniform shrinkage, where inconsistent cooling or variations in material properties exacerbate the issue [2]. Another critical factor is material orientation, where the alignment of polymer chains during the molding process impacts shrinkage patterns and consequently, the dimensional stability of the part [1]. The role of mold design is equally pivotal; improper placement of gates and inadequate cooling systems often result in uneven cooling, further contributing to warpage [3]. Additionally, processing conditions such as melt temperature, packing pressure, and cooling time significantly influence the extent of warpage, as suboptimal settings may intensify these defects [4].

The design and implementation of cooling channels play a vital role in mitigating warpage issues. Properly engineered cooling channels improve the cooling performance, reducing the cycle time while ensuring a uniform thermal distribution across the part [5]. The use of advanced designs like conformal cooling channels, which closely follow the geometry of the molded part, has proven effective in achieving uniform cooling, minimizing internal stresses and differential shrinkage [5]. Furthermore, optimization of cooling channel designs, including the determination of optimal shape, size, and placement, can significantly enhance temperature regulation, thereby reducing the likelihood of warpage [6].

Addressing warpage in plastic injection molding requires a comprehensive approach that considers temperature control, material behavior, mold design, and process parameters. By leveraging advanced cooling technologies and optimizing the cooling system design, manufacturers can achieve higher dimensional stability and superior part quality.

Reducing warpage in plastic injection molded parts is a critical objective that directly impacts product quality and manufacturing efficiency. From a product quality perspective, warpage compromises dimensional stability, leading to parts that fail to meet design specifications, potentially impairing their functionality and assembly [7]. Furthermore, warped parts often suffer from aesthetic and functional deficiencies, which can manifest as poor surface finishes or improper fitting in applications, particularly in sectors such as automotive manufacturing [8]. These deficiencies adversely affect customer satisfaction, as high-quality products free from defects are essential for meeting industry standards and consumer expectations [8].

From a manufacturing efficiency standpoint, reducing warpage has substantial benefits. Minimizing this defect leads to less rework and scrap, significantly lowering material waste and associated costs [9]. It also facilitates the optimization of process parameters, such as melt temperature, packing pressure, and cooling time, resulting in more consistent production cycles and improved throughput [10]. Additionally, by optimizing the injection molding process, manufacturers can achieve shorter cycle times, enhancing overall productivity and operational efficiency [4].

Several key factors influence warpage. These include process parameters like packing pressure, cooling time, and melt temperature, all of which can be adjusted to reduce warpage effectively [11]. Similarly, material selection plays a pivotal role, with fiber-reinforced polymers or composite materials such as PP-Mica10+GF5 showing marked improvements in reducing warpage [8].

Reducing warpage is not only essential for producing high-quality, dimensionally stable products but also plays a vital role in achieving cost-effective and efficient manufacturing processes. By optimizing materials, process parameters, and tooling design, manufacturers can meet stringent quality standards while improving productivity and customer satisfaction [8], [9].

Warping in plastic parts produced through injection molding is a critical issue, primarily caused by variations in shrinkage during the cooling phase of the process. These variations arise due to material properties, part geometry, mold design, and processing conditions [12]. Factors such as inconsistent wall thickness, improper cooling system layouts, and suboptimal molding conditions exacerbate warpage [2].

Convection cooling systems play a vital role in regulating temperature distribution during injection molding [13]. By employing rapid heat cycle molding (RHCM) technology, which integrates convection heating and cooling, the formation of frozen layers can be prevented. This leads to improved part quality and reduced hydraulic injection pressures [14]. Moreover, convection cooling enhances cooling efficiency and decreases cooling time, contributing to uniform temperature distribution and better dimensional stability of the molded parts [15].

Convection cooling, especially through technologies like RHCM, offers significant benefits such as improved part quality, reduced molding defects, and increased productivity [15], [16]. Conformal cooling channels, a variation of convection cooling, substantially reduce cooling time while maintaining efficiency. However, challenges such as increased mold surface temperatures can arise, requiring strict adherence to structural requirements for molds [14].

The diameter of cooling channels significantly affects the warping behavior of plastic parts. Studies show that reducing the diameter of cooling channels by 75% can lead to a 24.2% reduction in cooling time [17]. Furthermore, conformal cooling channel designs have demonstrated the ability to minimize total warpage displacement, ensuring higher dimensional accuracy and reduced defects [6].

The effectiveness of convection cooling systems in reducing warpage depends significantly on the cooling channel design and diameter. By optimizing these factors, manufacturers can achieve better thermal distribution, reduced cooling times, and improved product quality. Convection cooling, particularly through advanced methods like RHCM and conformal cooling, provides a reliable solution for mitigating warpage, enhancing manufacturing efficiency, and meeting stringent quality standards.

The primary objective of this research is to investigate the effect of different cooling channel diameters on the warpage behavior of plastic parts during the injection molding process. To achieve this objective, the number and placement of cooling channels in the mold design were kept constant, while the channel diameters were systematically varied. Under these controlled conditions, simulations were conducted to analyze the impact of different cooling channel diameters on the warpage of ABS parts.

II. MATERIAL AND METHODS

This study was developed based on the flowchart shown in below. (Fig. 1)

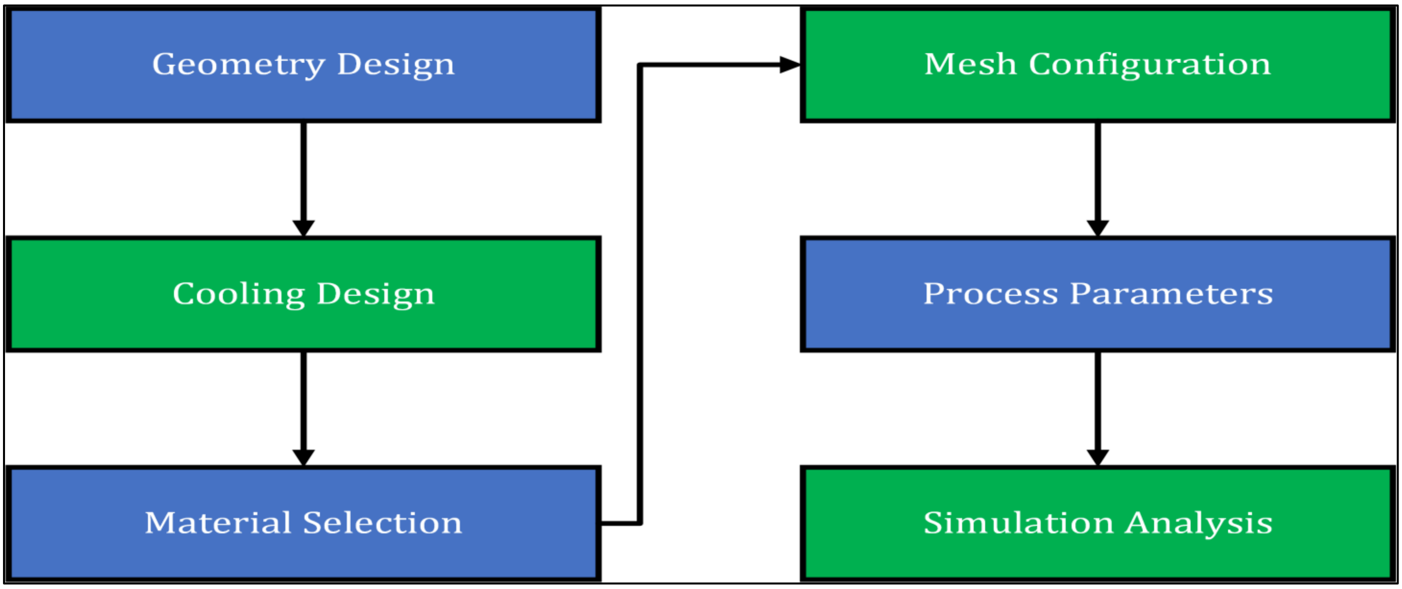

Fig 1 Flowchart

➢ *Geometric Design*

Various critical considerations must be addressed during the 3D design process of plastic parts.

Considering these requirements, a 600x200 mm part was designed to facilitate a more detailed warpage analysis. During the design process, weight reduction features were incorporated to ensure proper filling of the plastic material within the mold. Additionally, specific spacings and diameters were maintained to avoid complications during mold machining, optimizing the design for both manufacturability and functionality (Fig).

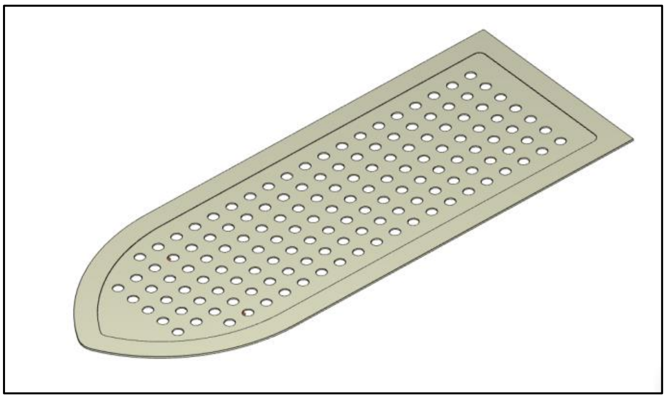

Fig 2 Part Design to be Analyzed

➢ *Cooling Design*

The cooling system was designed based on conventional cooling system principles. Conventional cooling systems are essential mechanisms in plastic injection molding processes, designed to accelerate the solidification of molten plastic. In these systems, water or a specialized coolant circulates through linear cooling channels within the mold to achieve heat transfer. Heat is transferred from the mold surface to the coolant, recirculated using a pump, and cooled via a chiller. Conventional cooling systems are widely used due to their low cost and ease of implementation. However, geometric constraints often prevent uniform cooling across all areas of the mold, resulting in warpage and residual stresses that impact part quality. Therefore, careful engineering is required during the design phase to enhance the effectiveness of conventional methods.

Specific measures were taken during the design of the cooling channels. For instance, the possibility of coolant-induced steel erosion leading to enlarged channel diameters was considered. To mitigate this and minimize surface deformation risks, a 6 mm gap was maintained between the cooling channels and the part (Fig). This design aims to extend the mold's lifespan and preserve the cooling system's efficiency [18].

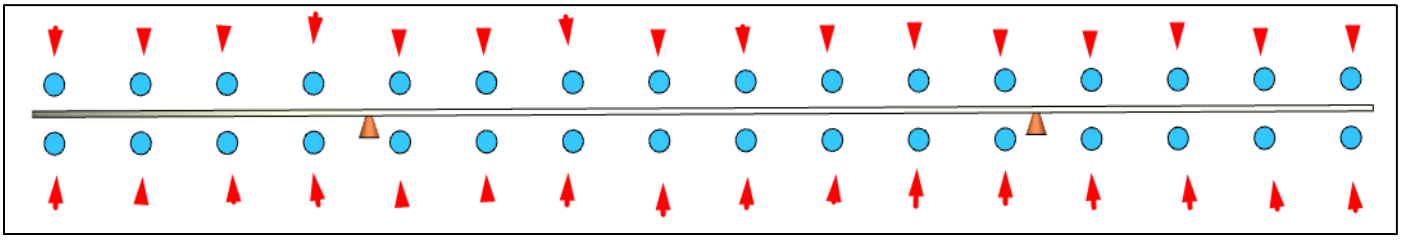

Fig 3 Layout of Cooling Channels

Four different cooling channel diameters (6, 8, 10, and 12 mm) were used to conduct simulations and evaluate their effects on plastic part behavior. The analysis aimed to observe how varying diameters influence thermal homogeneity and geometric accuracy.

➢ *Material Selection*

The selected material for the study was ABS (Acrylonitrile Butadiene Styrene), commonly used in plastic injection molding due to its durability, machinability, and broad application range. The selected material's shrinkage ratio was incorporated into the design geometry to prevent dimensional inaccuracies caused by shrinkage during production. This ensures that the manufactured part remains within the desired tolerances [19].

➢ *Mesh Configuration*

A detailed mesh configuration was applied to the geometric model to ensure accurate simulations. The analysis software assigned meshes to the part, mold, runner, and cooling channels. The automatic mesh size of 3.5 mm was reduced to 1.5 mm to achieve greater precision in analyzing parameters such as temperature and warpage. The mesh assignments for the mold were intentionally kept coarse to expedite the analysis, thereby optimizing computational efficiency.

➢ *Process Parameters*

The warpage analysis was conducted using Moldex 3D software. In the simulation process, the machine mode was selected as the initial step within the software-defined process stages. A 700-ton BOLE injection molding machine was selected from the software's library to simulate real-world production conditions (Fig).

In the next step, the injection pressure was selected. At this stage, the "Use 100% of machine capacity" option was chosen to ensure that the simulation parameters were defined realistically and accurately (Fig). This setting optimized the injection process to align with the maximum machine capacity and ensured that the analysis results reflected the production process as accurately as possible.

In the cooling settings, specific parameters were defined to model the mold and environmental conditions in alignment with the actual production process. In this context, the mold temperature was set to **60°C**, the ambient temperature to **25°C**, and the cooling fluid flow rate to **120 cm³/s**. These values were optimized to ensure effective thermal management and accurate results in the warpage analysis (Fig). The melting temperature of the selected ABS material was defined as **240°C**.

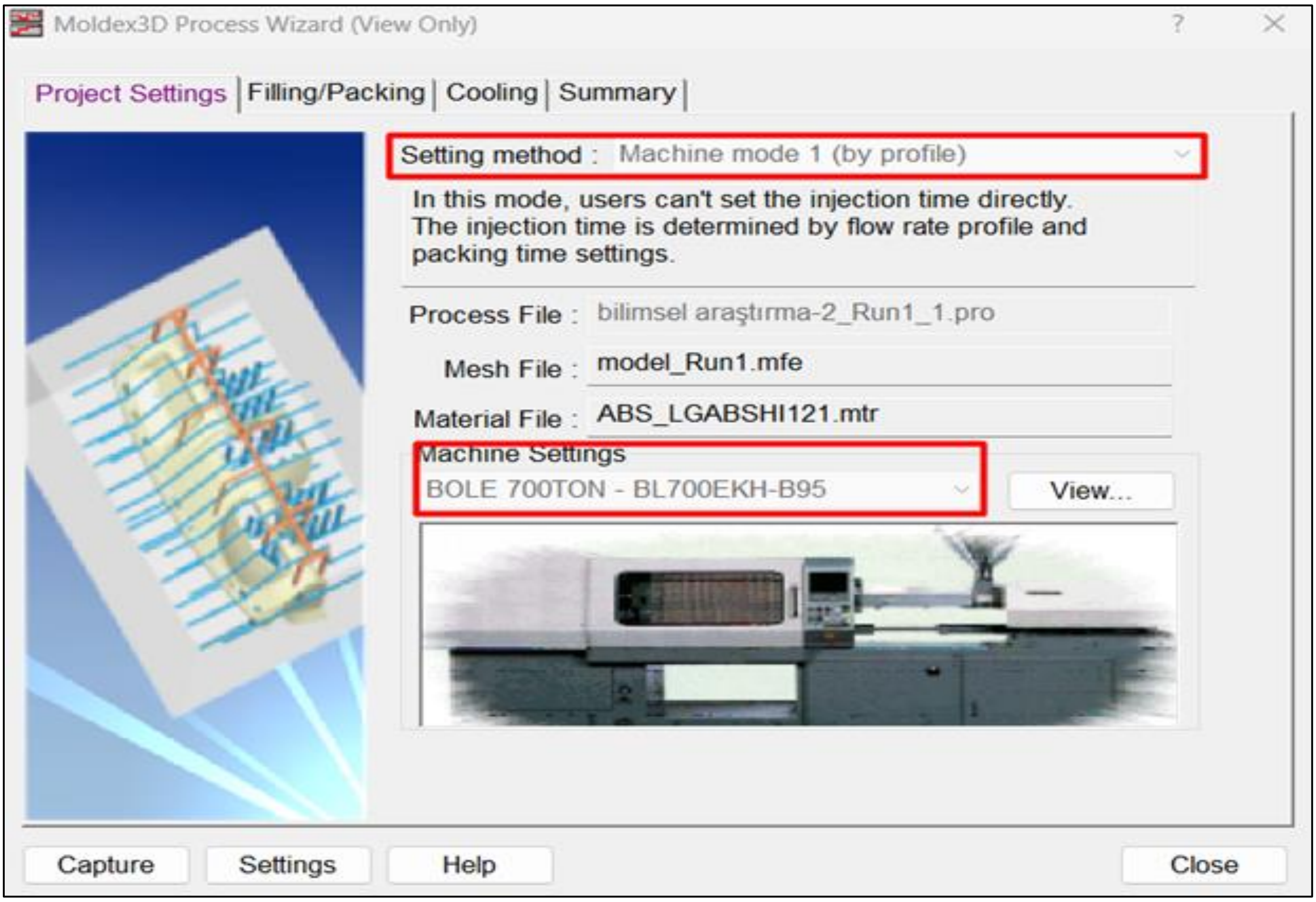

Fig 4 Determination of Process Parameters; Machine Selection

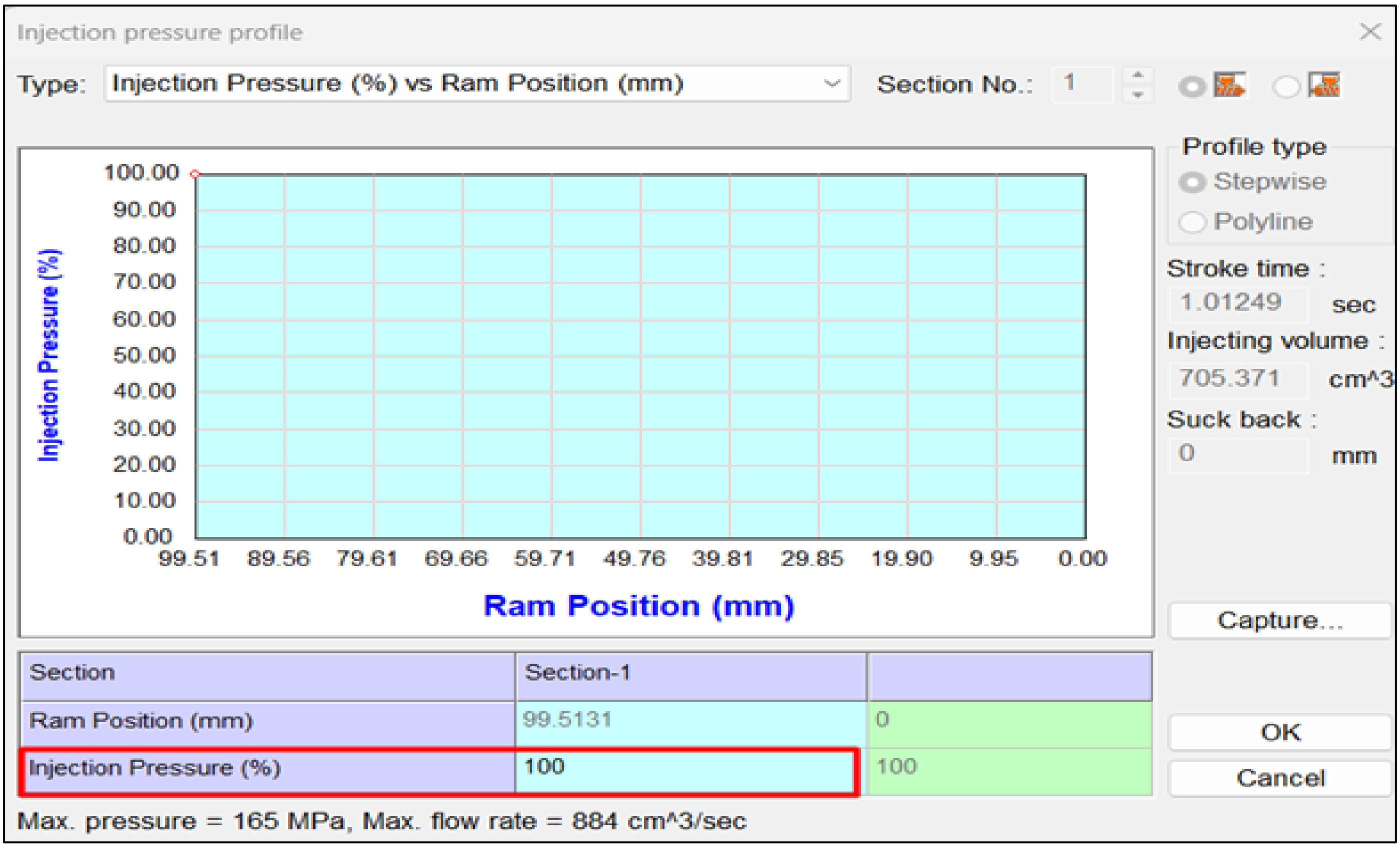

Fig 5 Determination of Process Parameters; Injection Pressure

➤ *Simulation Analysis Warpage Control*

Simulations were conducted using four different cooling channel diameters to assess their effects on warpage and thermal uniformity. Each simulation included 32 cooling channels (16 in the stationary steel and 16 in the moving steel). The channels were spaced 50 mm apart, with a 6 mm gap between the channels and the part surface. This setup was designed to maximize cooling performance while minimizing warpage.

III. RESULTS

This study aims to investigate the effect of varying the diameters of cooling channels in plastic injection molds on part warpage, while maintaining a constant distance between the channels and the part.

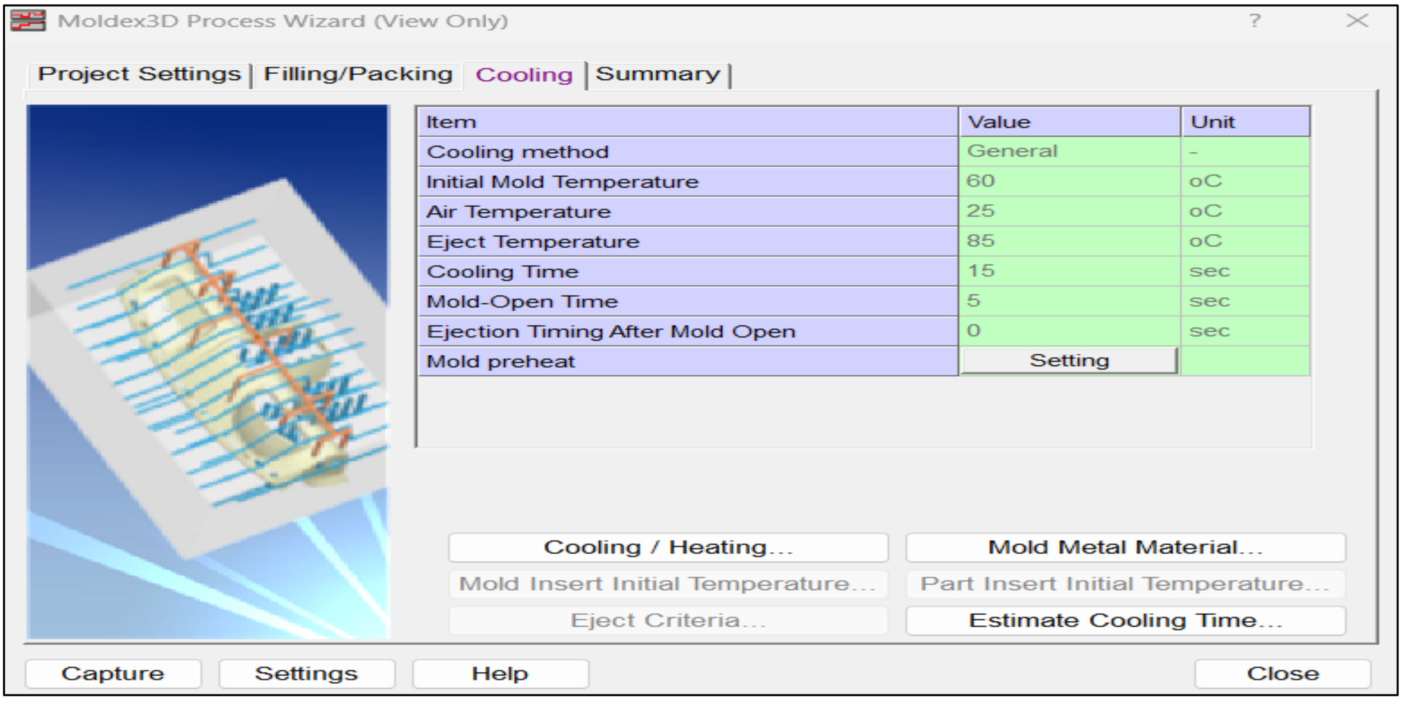

Fig 6 Determination of Process Parameters; Cooling

For this purpose, comprehensive analyses were conducted using the Moldex 3D simulation software as the primary method.

As a result of the analysis conducted using Ø12 mm cooling channels, a warpage of 8.65 mm in the Z-axis direction was observed in the plastic part (Fig 7 Warping in Z Direction)(Fig).

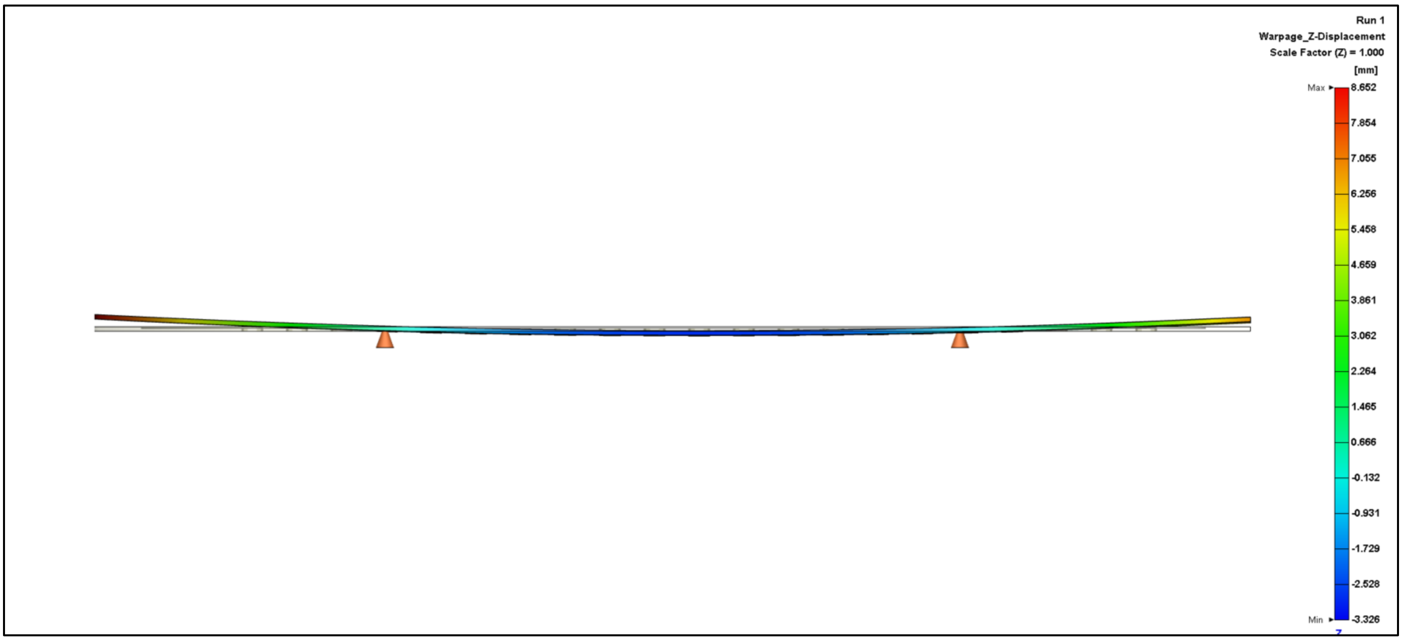

Fig 7 Warping in Z Direction

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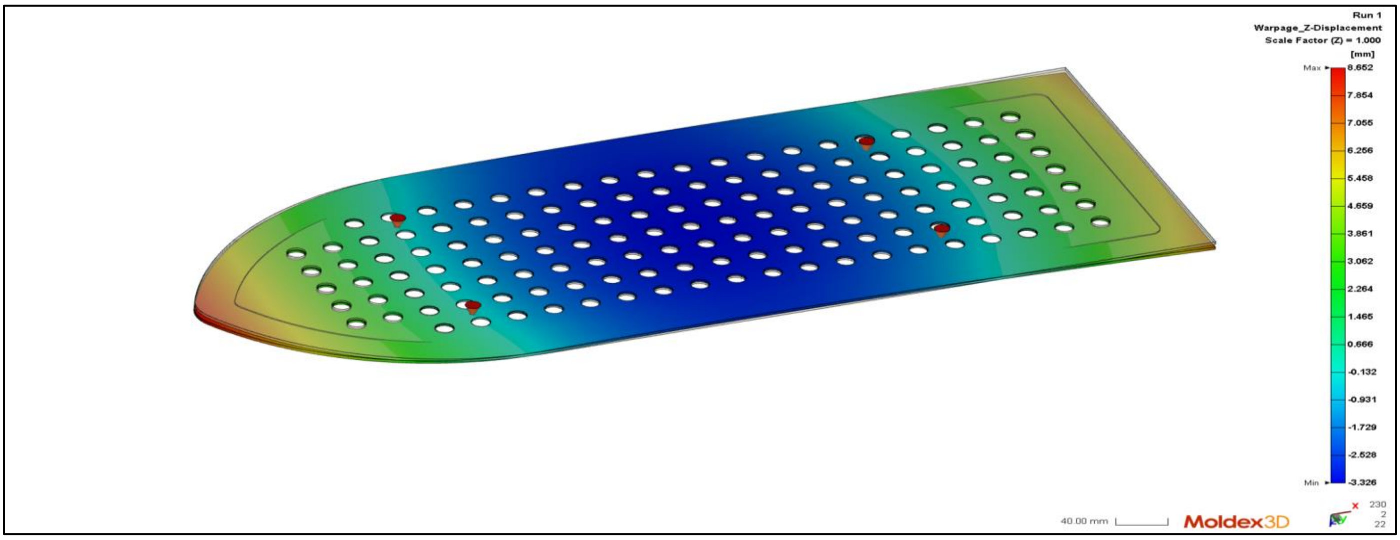

Fig 8 Warping in Z direction

As a result of the analysis conducted using Ø8 mm cooling channels, a warpage of 8.45 mm in the Z-axis direction was observed in the plastic part (Fig)(Fi).

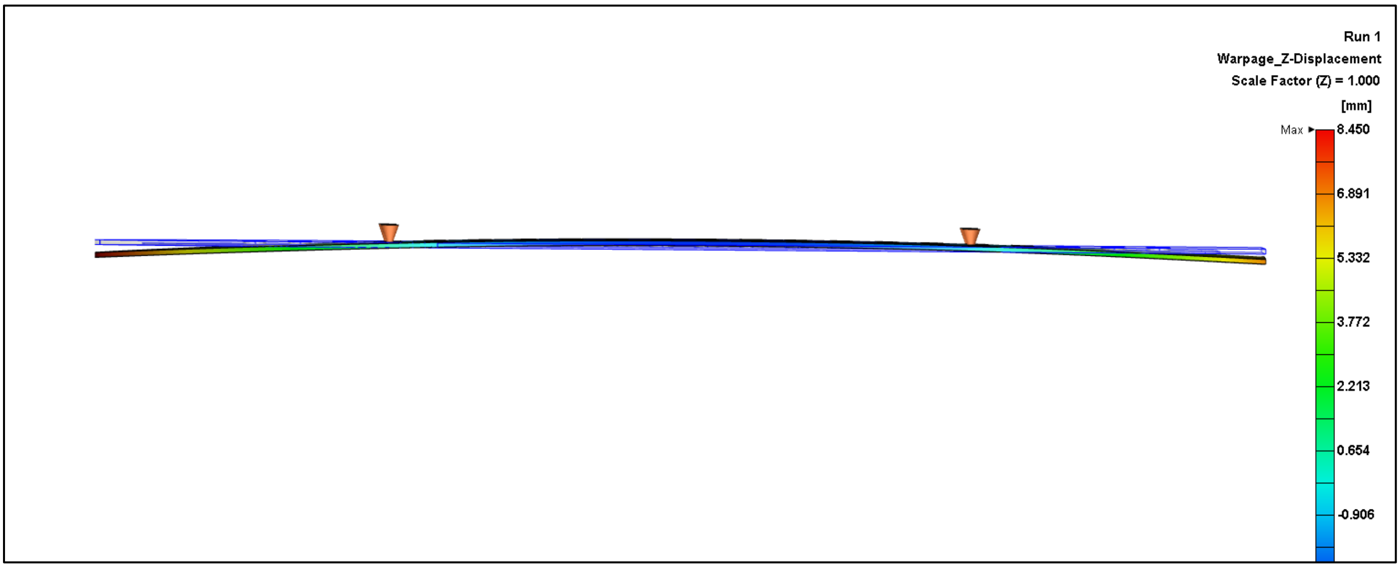

Fig 9 Warping in Z Direction

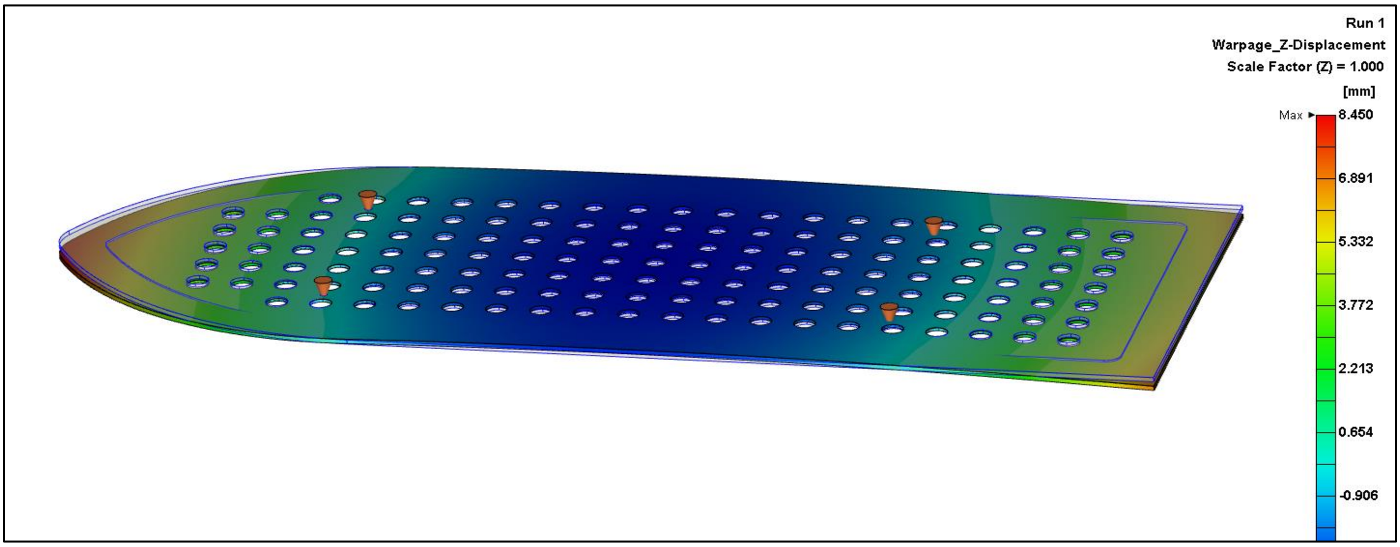

Fig 10 Warping in Z direction

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As a result of the analysis conducted using Ø8 mm cooling channels, a warpage of 22,19 mm in the Z-axis direction was observed in the plastic part (Fig)(Fig).

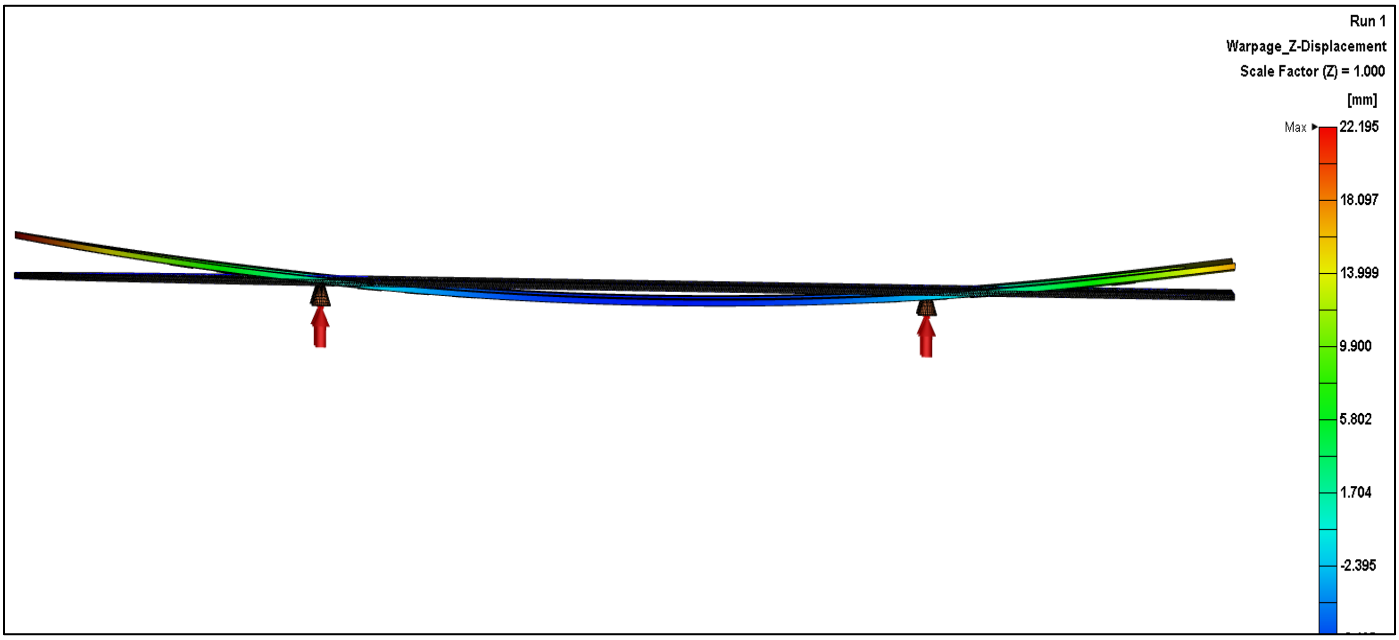

Fig 11 Warping in Z Direction

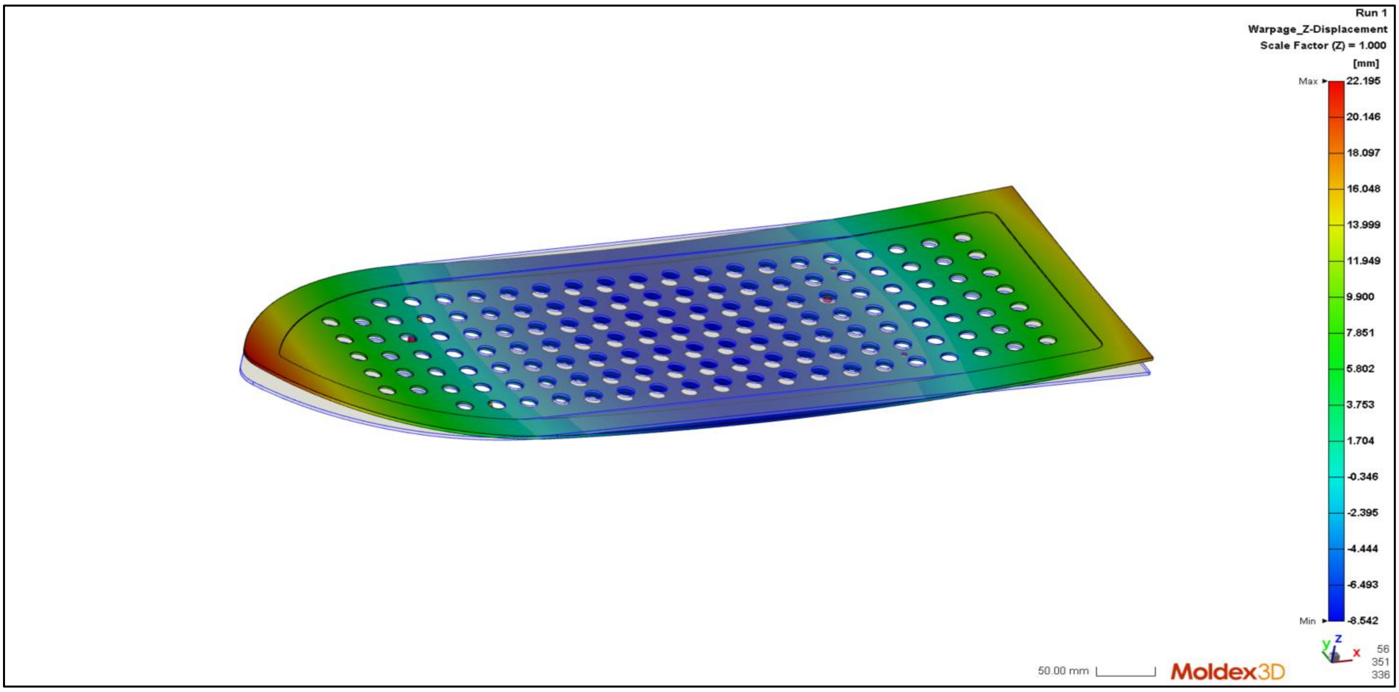

Fig 12 Warping in Z Direction

As a result of the analysis conducted using Ø10 mm cooling channels, a warpage of 8,54 mm in the Z-axis direction was observed in the plastic part (Fig)(Fig).

IV. DISCUSSION

This study investigates the effect of different cooling channel diameters on warpage in plastic injection molds. In the literature, it is emphasized that the optimization of cooling systems should systematically address channel design and process variables. Uniform temperature distribution and reduced variation lead to more effective cooling and minimal deformation [20]. The analyses conducted indicate that the effect of cooling channel diameters on the warpage of plastic parts is not significantly pronounced.

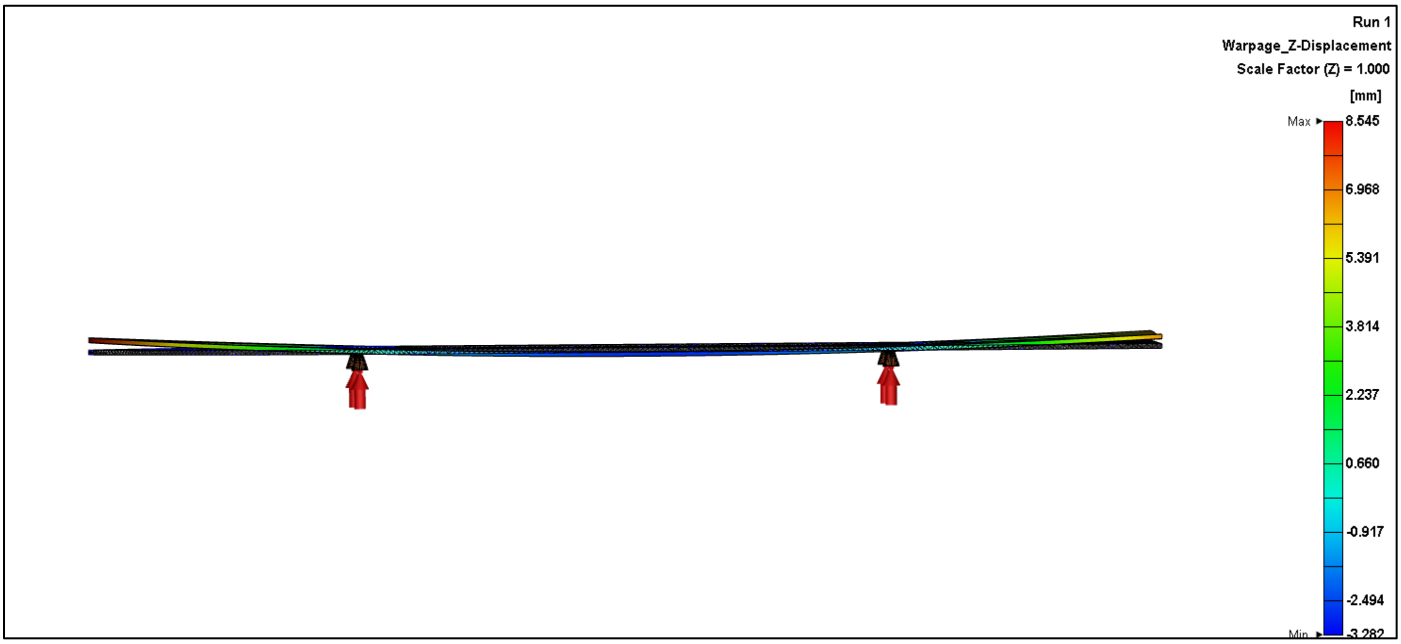

Fig 13 Warping in Z Direction

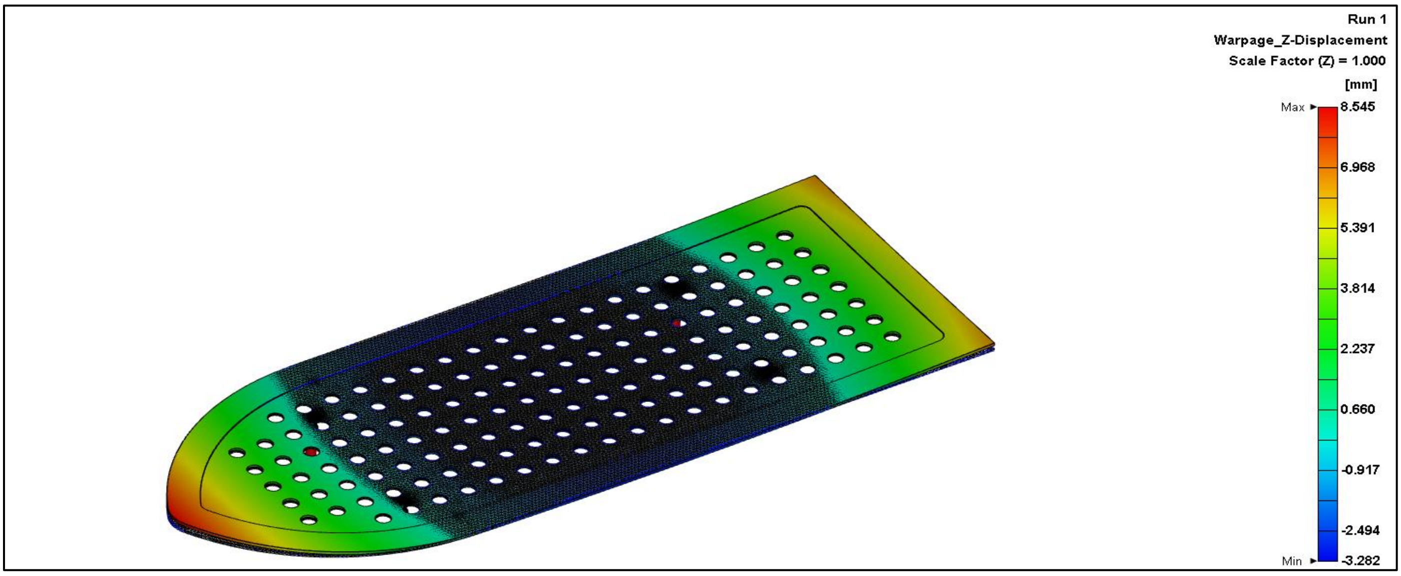

Fig 14 Warping in Z Direction

The results of the analysis have been compared (Result).

Table 1 Result

Cooling Channel Diameter (Ø mm)	Z-Axis Displacement (mm)	Material Melting Temperature (°C)	Mold Temperature (°C)	Ambient Temperature (°C)
Ø6	22,19	240	60	25
Ø8	8,45	240	60	25
Ø10	8,54	240	60	25
Ø12	8,65	240	60	25
Note: Z-axis displacement values represent simulation and estimated analysis results.				

In the literature, the geometry and placement of cooling channels are frequently emphasized for their impact on warpage. Saifullah and Masood (2011) reported that conformal cooling channels provide 35% shorter cooling times compared to conventional straight cooling channels, significantly reducing warpage [3]. This study demonstrates that cooling channel diameter plays a critical role in minimizing warpage by influencing heat distribution. Specifically, the 8 mm diameter channel has been found to promote uniform heat distribution and reduce warpage effectively.

Yu and Wang (2008) highlighted that the design parameters of cooling systems (such as channel diameter, placement, and flow rate) impact temperature distribution and product quality [20]. While larger diameter channels enable faster cooling, they may compromise thermal uniformity. Similarly, Prasetiyo and Fauzun (2018) found that 8 mm channels optimize temperature distribution and enhance cooling efficiency [21]. The findings of this study confirm that 8 mm channels deliver optimal performance in reducing warpage.

Shanthakumar et al. (2018) emphasized that cooling time is one of the most critical parameters for minimizing warpage in thin-walled parts during injection molding optimization [11]. This study aligns with their findings, showing that 8 mm and 10 mm diameter channels yield lower warpage values, attributed to uniform cooling and balanced thermal distribution.

Kitayama et al. (2018) achieved up to a 43% reduction in warpage using conformal cooling channels, underscoring the superiority of this technology over conventional methods [4]. While this study focuses on simpler geometries associated with traditional cooling channels, the literature supports the potential benefits of adopting conformal cooling technologies in future designs.

Özçelik and Erzurumlu (2005) identified critical roles for mold temperature, injection time, and pressure in reducing warpage [7]. Similarly, this study found that smaller diameter channels enhance thermal uniformity, thereby reducing warpage, in line with the conclusions of Özçelik and Erzurumlu.

In conclusion, this study evaluates the effect of cooling channel diameter on warpage in plastic injection molding processes in a manner consistent with the findings in the literature. The results highlight the 8 mm diameter as the optimal choice. Future studies are recommended to explore the effects of advanced technologies such as conformal cooling channels in greater depth.

V. CONCLUSION

This study aims to analyze the effect of cooling channel diameters, one of the factors influencing warpage behavior in plastic injection molding processes. Simulation results indicate that the effect of cooling channel diameters on the warpage should be evaluated alongside other factors such as channel design and process parameters. The analysis conducted on ABS material evaluated the influence of cooling channel diameters on thermal homogeneity and geometric accuracy.

The results show that changes in cooling channel diameters have a limited impact on warpage behavior; however, the optimal design and placement of cooling channels play a critical role in reducing warpage. Specifically, channels with diameters of 8 mm and 10 mm were found to minimize warpage by ensuring thermal homogeneity. In contrast, very small channel diameters (e.g., 6 mm) were observed to significantly increase warpage instead of improving thermal efficiency. Based on the findings, it is recommended to analyze various channel sizes and use diameters that result in minimal warpage to mitigate warpage issues in plastic injection molding processes.

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