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Optimizing the Design of Cooling Channels in Plastic Molds Using Metal 3D Printing Technology

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I. INTRODUCTION

In today's world, many types of plastic products are used in daily life. Injection molding is a major part of the plastics industry, consuming a large amount of total plastic [1]. Plastic injection molding is a versatile process for obtaining various complex sizes and shapes of high-quality products from thermoplastics and thermosetting materials with the application of heat and pressure [2]. The design of the injection molding tool, particularly the design of the mold core and cavity, is crucial to producing plastic goods of higher quality. It has a significant impact on the business's financial elements as well. The injection molding tool cooling system plays a very important role in the total production cycle time of the injection molding process. It is important in the entire casting process, as it accounts for about half of the overall production cycle.

Figure 1.1 shows the general distribution of time in the total injection molding process.

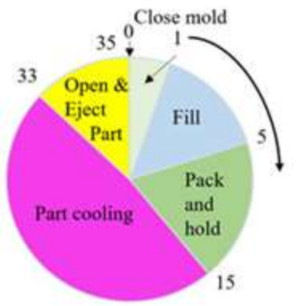

Figure 1.1. Typical cycle time in injection molding. [3]

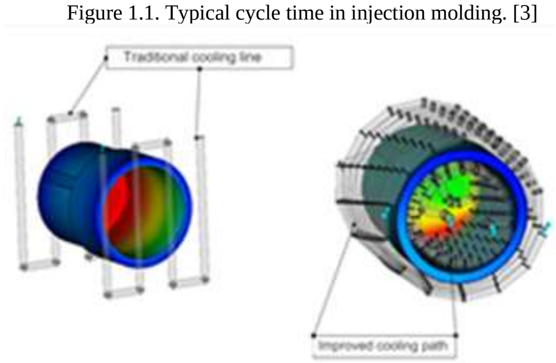

Figure 1.2. Simplified view of a traditional mold (left) and a 3D printed conformal cooling mold (right).

The manufacturing process by injection molding is a widespread and included method of production to create products from plastic. To cool the molten plastic inside the mold core, straight holes are typically drilled into solid molds. Low productivity is the result of this cooling process taking up a significant portion of the production cycle. In the context of increasingly fierce competition in the plastic products business worldwide, reducing production costs has become extremely important, and one of the ways to do this is to shorten lead times. production cycle time. With existing traditional mold manufacturing methods, the cooling channel cannot reach closer to the cavity wall; precisely, is to rounded corners or sharp edges of a complex geometry. Therefore, applying advanced technology is indispensable to solve problems and cope with the ongoing business competition. The use of highly efficient cooling channels is considered a good option to achieve this goal. Suitable cooling channels are those that have a profile that closely hugs the product, thus being able to reach closer to the molten plastic material, compared to the cases of traditional molds (figure 1.2). With the application of advanced cooling channel mold manufacturing techniques, the shape and size of the channels are no longer limited.

In Figure 1.3, temperature comparison analysis can be done directly in the tool to determine the cooling efficiency and uniformity between the conventional spiral cooling channel and the matched spiral cooling channel. Due to limitations in conventional cooling designs, heat is not removed from the insert and the plastic product as efficiently and uniformly as with proper cooling design.

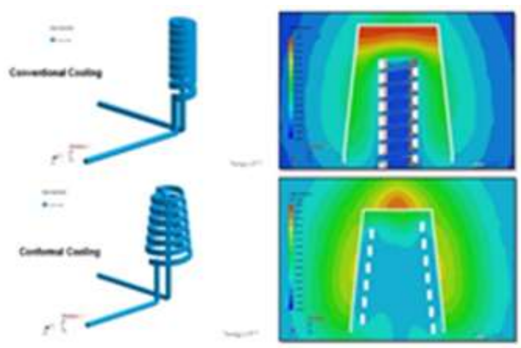

Figure 1.3. Simulation results of temperature characteristics of conventional cooling design and flood cooling design

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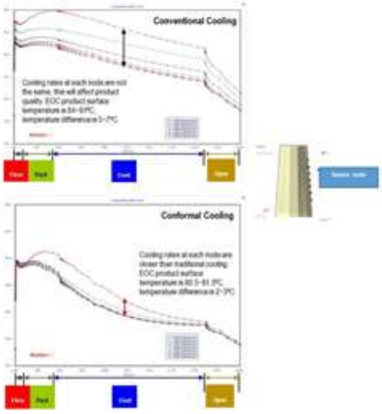

Figure 1.4. Simulation results of the temperature profile at the sensor nodes of a plastic product with a conventional and consistent cooling design of a plastic insert.

One factor in minimizing warping is minimizing differential shrinkage. With better mold temperature uniformity, differential shrinkage can be reduced, which again helps minimize warping. Figure 1.4 compares the simulation results at sensor nodes placed on the surface of the plastic product to determine the temperature profile through the injection molding cycle comparing the t_w° Cooling channels above.

The temperature profile shows a maximum ΔT of about 2~3°C for the case with a suitable cooling design compared to a maximum ΔT of about 5~7°C for a conventional cooling design. Because the temperature difference of the plastic product is reduced, the rate at which the material of the plastic product freezes and shrinks both increases, and thus warping is reduced. [4]

So how does proper cooling reduce injection molding cycle time? Tailored cooling provides precise thermal regulation, optimizing cooling rates and significantly reducing cycle times. Traditionally designed linear cooling mechanisms only provide partial coverage of the shape of the plastic product in the mold. However, suitable cooling channels are 3D printed to achieve all the geometric contours of a plastic product in molds or tooling inserts.

Temperature control is critical in the injection molding process, as The mold heats up as molten plastic is injected into it. With conventional cooling techniques, the temperature of the mold often increases beyond the threshold for successful extrusion of the plastic part – wasting time and money while the mold cools to a temperature at which the plastic part can be ejected. Proper cooling maintains nominal temperature, allowing for faster temperature reduction to reduce overall cycle time each time the mold opens and closes. [5]

With continuous research and development in additive manufacturing technology, printing methods are becoming more advanced and efficient every day. Suitable cooling channels are capable of improving the performance of the mold in terms of uniform and fast cooling, less warping and defects, etc., as any channel design can be produced using additive manufacturing to create an optimal solution to this problem. Therefore, the research focused on achieving a suitable design method for suitable cooling channels and conducting thermal mechanical analysis for optimization..

II. Literature Review

Using cooling channels aligned with the molding cavity improves control of mold temperature and part dimensions. This was reported by a group at MIT in the 1990's. They realized that with a properly designed cooling channel for the product, they would be able to produce a product with significantly improved quality. Mold surface temperature, pressure drop, mold material strength, etc. are considered as design parameters in their study [6]. 3D printing was applied to directly fabricate a new cooling channel using metal powder. In the process of applying 3D printing technology, they have improved the areas of heat management, size control, and surface finishing. They used stainless steel powder with a resultant tooling hardness of 25-30HRC [7].

Ferreira and Mateus presented a study on rapid soft tooling for plastic injection molding. The main aim of their research is to propose some initial applications for integrating advanced processing technologies, with composite materials cooled by suitable cooling channels for the production of injection molding tools [8]. The efficiency of consistent cooling channels to reduce cooling time and increase part quality, compared to traditional straight cooling channels was also presented by Meckley and Edwards.

Hopkins and Dickens demonstrated the use of suitable cooling channels to heat and cool a single injection molding tool. This provides the potential of 3D printing technology to achieve successful production of complex geometries [9]. One of the advantages of 3D printing is the construction of suitable heating or cooling channels for enhanced thermal control.

Altaf et al. presented a technique for fabricating conformal cooling channels in an aluminum-filled epoxy mold using rapid prototyping techniques. This paper provides insight into a suitable channel fabrication method, which cannot use traditional drilling or machining processes [10].

Although there has been a series of research in the field of designing and improving suitable cooling channels in the injection molding process, the concept of simulating designs has originated for more than 10 years. Since then, many different simulation projects have been used to analyze cooling channel design.

In 2009, Saifullah, A., S. Masood, and I. Sbarski used MPI simulation software to analyze the results and compare the results for conventional and square-section conformal cooling channels; concluded that conformal channels make the cooling time 35% less than conventional channels [11]. They included research comparing conformal molds to conventional molds and integrated a square cross-section conformal cooling channel system for injection molds [12].

A study was conducted using Moldflow Plastic Insight 3.1 to investigate the thermal impact of cooling channel design on injection molding in 2007 by Au and Yu [13]. They propose a new standard for uniformly consistent cooling design. In their 2013 study, Hsu et al. determined that for irregularly shaped cavities, the distance between the cooling channels and the span varies throughout the plastic product and causes heat

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buildup and product defects such as sink marks, warping, etc. They applied a true three-dimensional simulation technique to predict the cooling time and compared the results with traditional molds [14]. Dang and Park applied an algorithm to calculate the temperature distribution through the thickening casting process and presented a suitable channel with a series of baffles to obtain uniform cooling over the entire form surface. freedom of molded parts [15]. They also provide insight into using suitable cooling channels to provide uniform cooling and reduce cycle times for the injection molding process. They presented U-shaped milling groove matching channels and proposed an optimization procedure to obtain the optimal matching channel configuration [16]. The comparative effects of conventional, series, parallel, and additive cooling channels have been reported by Khan et al. study conducted in 2014 using AMI software that examined temperature differential, cooling time, overall cycle duration, and volumetric shrinkage [17].

Wang et al. in 2011 presented an automatic method to design suitable cooling channels by establishing the relationship between suitable cooling and the shape of the plastic body [18]. Choi et al. recognize a higher degree of freedom in designing suitable cooling channels using 3D printing applications and focus on the branching law principle to improve cooling efficiency in injection molding. They used the Voronoi diagram algorithm and the binary branching algorithm t° Create a suitable design for cooling channels [19].

Although there has been a lot of research on the analysis of suitable cooling channels, the amount of research dedicated to the design parameters of suitable channels for different types of plastic product designs is very limited. To date, most of the designs have been made based on the designers' experience. Additionally, any kind of mixture and combination between design parameters, cross-sectional dimensions, and corresponding experimental analyses is quite rare to the author's knowledge. However, some preliminary information can be gathered from the documents as a basis for further research in this project.

III. METHODOLOGY

In this paper, a hybrid thermal optimization technique is applied to obtain the best performing injection mold with suitable cooling channels.

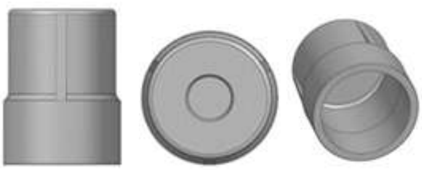
Figure 3.1. Test product

The chosen design is a simple cylindrical cap with a wall thickness of 7.5mm, a height of 150mm and an outer diameter of 150mm (figure 3.1). The core and cavity have a height of 160 mm and a length and width of approximately 160 mm. The diameter of the cooling channel is 10mm.

The experimental design is based on the fact that for manufactured printing injection molds, the channel design depends on the size and shape design of the plastic part being molded. The important design parameters are channel diameter (for circular channels), pitch distance, cooling channel profile, etc. The parameters are illustrated in the diagram in Figure 3.2 [20].

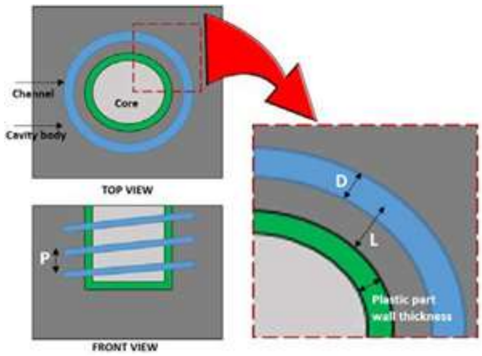

Figure 3.2. Die cavity diagram with parameter definition.

T° Create a simple cylindrical plastic cap by injection molding process, the mold cavity and core design depend on the plastic cap design itself. Designers can create the required configuration of cooling channels. In this study, several suitable channel design configurations were developed using the Design of Experiments method and each design was integrated into the same mold cavity and core and thermomechanical performance of the mold. has been fully analysed. The results were also Compared with the same mold and core cavity design with traditional straight cooling channels.

During the injection molding process, molten plastic is injected into the mold cavity through the injection unit, and cooling water is sent through the cooling channels. Water serves two purposes. First, cool the hot plastic and second, warm the cavity and core body. This heating process is necessary to ensure minimal shrinkage of the plastic part produced. Therefore, it can be understood that the temperature of the cooling water needs to be higher than the temperature of the mold cavity and core. The water temperature is several degrees higher than room temperature.

The initial temperature of the molten plastic is 238°C and the inlet water temperature is 60°C. The convection heat transfer coefficient is applied on the cooling channel surfaces. The thermal analysis model has been validated with experimental studies found in the literature and validation studies have been described in previous publications by the authors [21].

Processing parameters for ABS plastic pellets:

- *Raw material temperature: 200 – 280°C.*
- *Mold temperature: 40 – 85°C.*
- *Injection pressure: 600 – 1800 bar.*

The main method is to use input parameters such as plastic material, mold cavity, mold core, cooling channel diameter, initial coolant temperature, gate, mold parting surface, etc. In the test case, we only change the cooling channel profile to optimize the cooling ability of the product.

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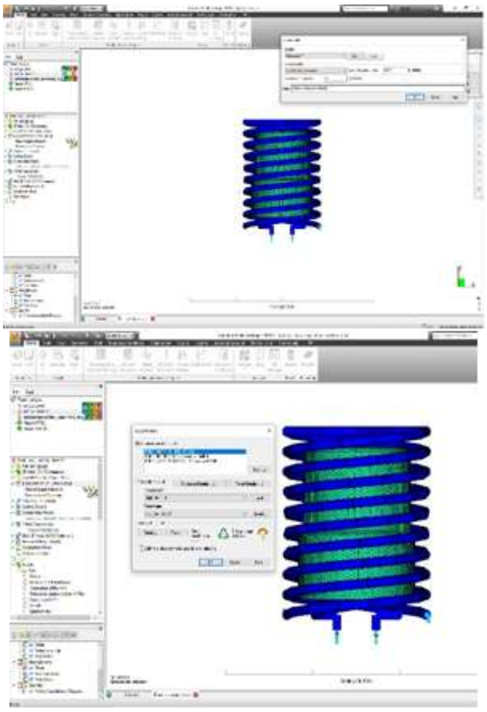


Figure 3.3. Some input parameters

IV. RESULTS AND DISCUSSION

A. Thermal and mechanical simulation results

and mechanical results of the design of experiments are listed in Table 4.1. For all cases, the value of D was kept constant at 10 mm and the inlet temperature was 60°C. From these results, it can be seen that the mold surface temperature in each case changes quite clearly. Therefore, the shape of the cooling channel has a great influence on the mold surface temperature after cooling. The configuration of suitably improved cooling channels is expected to provide better cooling performance than conventional straight cooling channels. However, they lead to higher stresses inside the mold compared to Conventional molds. This, in effect, raises the issue of creating an optimized design that serves the purpose of thermal and product accuracy after cooling.

From Table 4.1, we can see the change in mold cavity temperature after cooling with different cooling channel designs. With the change in cooling channel shape, there is a tendency to reduce the temperature as well as the temperature difference in the mold cavity, increasing stability. It should also be noted that, in some cases, the minimum temperature decreases but the temperature difference increases. Therefore, it can be assumed that there is an optimal point where the minimum temperature or maximum temperature is minimum. Changing the cooling channel shape is to improve the cooling channel shape to suit the product shape. Here, with this product, we improve the spiral cooling channel. Compared t° Conventional cooling channels with straight lines, spiral cooling channels will distribute cooling more evenly. Due to the twisted form, the cooling water flow will be more than the straight form and can be distributed to curved or circular positions. Changing and improving the cooling channel system to suit the product is very important.

The improved cooling channels in all design cases are observed to have smaller temperatures and mold cavity differences compared to those of conventional cooling channels.

TABLE 4.1. Pre-flow temperature analysis table for cooling cases

Case	D (mm)	Initial coolant temperature (°C)	Temperature before flow, mold cavity	
			T° min (°C)	T° max (°C)
Traditional cooling line	10	60	74.54	180.3
Cooling line twisted in			69.73	165.9
Traditional cooling line combined with internal twist			66.61	101.7
The inner twisted cooling line combines with the outer twisted			65,62	88.54

Therefore, improving cooling channels as well as

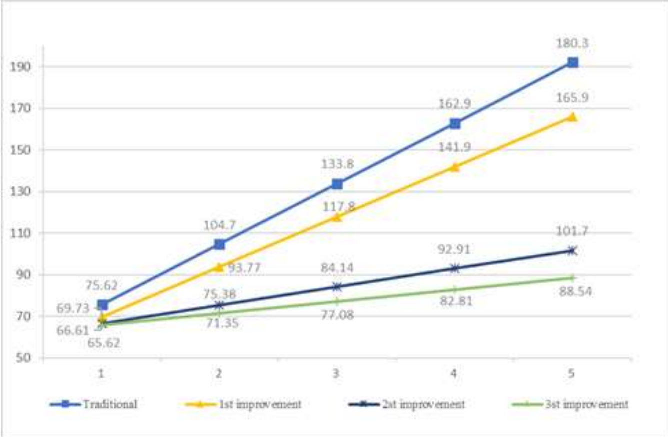
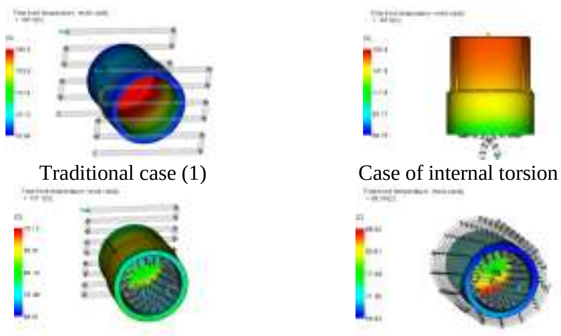


Figure 4.1. Variation of mold cavity temperature with cooling path types combining suitable cooling channels has great potential to improve cooling efficiency. Such configurations not only reduce the temperature of the mold cavity but also reduce the temperature difference to help the cooling process be stable, thereby reducing shrinkage and warping, leading to better product quality and less disability.



Traditional case (1) — Case of internal torsion (2)

Traditional case incorporating internal twist (3) — Case of internal torsion combined with external torsion (4)

Figure 4.2. Results of temperature analysis before flow and mold cavity

4.2. Optimization results

From table IV we see that in case 1 the temperature is the highest with Min = 74.54 °C, Max = 180.3 °C, and the difference is 105.76 °C. In cases 2, 3, and 4, the temperature difference is 96.17 °C, 35.09 °C, and 22.92 °C, respectively. After analyzing the above cases, we can easily see that the temperature difference in front of the flow, the cavity. The mold tends to gradually decrease and become more stable through improvements in the cooling channel.

In case 2, the temperature difference is reduced but not too optimal compared to case 1. However, in cases 3 and 4, when there is a combination of cooling channel types, the temperature difference is reduced a bit. The results are clear and quite optimal compared to the other two Cases. It can be seen that combining improved cooling channels has great potential to optimize the cooling process and improve product quality.

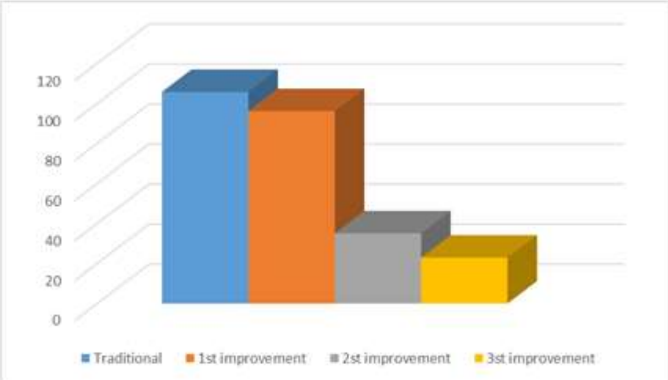


Figure 4.3. Results of temperature analysis before flow and mold cavity"

V. CONCLUSION AND FUTURE WORK

In this study, a design method to introduce suitable cooling channels in conventional molds is developed and demonstrated using an experimental simulation approach. Regarding the thermal and mechanical performance of the mold with suitable cooling channels, optimal design solutions were obtained. The cooling channel configuration suitable for the cooling channel located inside and outside the product (i.e. the circular spiral cooling channel in both the cavity and core) was chosen as the optimal design. However, when implementing this method in practice, the cost is very high compared to the traditional one. The mold designer can follow the appropriate approach and design the cooling channel configuration depending on the specific geometric and design constraints of the industrial problem. Traditional molds and 3D printed molds have different thermal and structural properties, and these are also significant factors while designing injection molds. The results obtained throughout the paper are based on numerical analysis, although the models are validated against previous experimental studies in the same field. Furthermore, for more accurate results, optimization needs to be performed using 3D printing materials with appropriate properties. The optimized design can be integrated into existing injection molds with the use of additive manufacturing DMLS technology. The mold will be tested in an actual injection molding machine to verify performance in the near future. The results are expected to provide new effective guidelines for mold designers to select suitable and optimal cooling channels.

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