

Effect of Conformal Cooling Channels on Warpage Improvement and Mold Strength of Multilayer Thin-Shell Parts

Yuan-Ping Luh*, Chien-Liang Chen** and Chen-Shan Tsai*

Keywords: Conformal Cooling Channels, Warpage, Multilayer Thin Shell Parts, Mold Strength

ABSTRACT

This study explores the application of Conformal cooling channels (CCCs) to reduce warpage in multilayer thin-shell injection-molded parts while maintaining mold strength. Using a hard disk deflector as a case study, five CCC diameters (0.6–1.4 mm) were analyzed through mold flow and structural simulations. Results show that CCCs effectively reduce warpage to within 0.025 mm, with 0.8 mm and 1.0 mm achieving the lowest warpage of 0.01 mm. Although only the 0.6 mm design meets conventional mold strength guidelines, all designs withstand cavity pressure without plastic deformation. The study demonstrates that CCCs can be effectively implemented in thin, compact molds beyond traditional design limitations.

INTRODUCTION

Injection molding is widely used in the production of plastic products with varying thicknesses. Thin-shell products are particularly susceptible to changes in ambient temperature and the cooling system, which can lead to inconsistent cooling rates and uneven shrinkage. This non-uniform shrinkage generates internal stresses that eventually result in warpage. Additionally, variations in process parameters—such as mold temperature, melt temperature, packing pressure, and injection pressure—can also induce internal stresses within the material during the molding process. When these stresses are not effectively relieved or evenly distributed, warpage and deformation of thin-shell products may occur (Lai, et al., 2022; Otieno,

Mwema, Mharakurwa, & Jen, 2024). To reduce deformation and warpage in thin-shell injection-molded products, it is necessary to optimize the cooling system design and adjust the molding parameters to achieve more uniform cooling.

The inability to effectively release or evenly distribute internal stress is the main cause of warpage and deformation in thin-shell products. This issue can usually be addressed by optimizing molding parameters and the design of cooling channels to reduce cooling variation. For example, parameter optimization was demonstrated in the study conducted by Chen et al., (2009) for 1 mm-thick products. In this study, the molding parameters were optimized through design of experiments and simulation. The optimized parameters were effective in reducing product distortion by 20%. Huang et al., (2020) studied thin shell products with a maximum thickness of only 0.19 mm, and optimized the molding parameters using the Taguchi method, which resulted in a 53.82% improvement in final warpage. Lin et al., (2022) optimized the parameters using grey theory and the Taguchi method. Finally, the warpage was reduced by 45% from 0.527 mm to 0.290 mm. Otieno et al., (2024) used fuzzy logic for parameter optimization and improved the warpage by 31.4%. Literature on parameter tuning mainly deals with the adjustment of melt temperature, mold temperature, injection speed, packing pressure, and packing time. Several experimental trials are typically required to effectively tune the parameters to minimize warpage and distortion effects.

Straight cooling channels do not allow for uniform cooling, resulting in concentrated thermal stresses that cause warpage and distortion, a common and difficult-to-control problem. Conformal cooling channels (CCCs) are a method for uniform cooling. For example, Kitayama et al. (2016) describe the ability of CCCs to fit the mold shape more closely, achieve more uniform cooling, and reduce thermal stress and warpage in the mold and product. Warpage was reduced by 46% and cooling cycle time was reduced by 53% for a 1.5 mm-thick product using CCCs compared to using straight cooling channels. This is a significant solution to warpage and distortion problems. Tan et al., (2020) produced a self-supported

Paper Received April, 2025. Revised July, 2025 Accepted August, 2025. Author For Correspondence: Chien-Liang Chen

**Graduate institute of manufacturing technology, National Taipei University of Technology*

***College of mechanical & Electrical Engineering, National Taipei University of Technology*

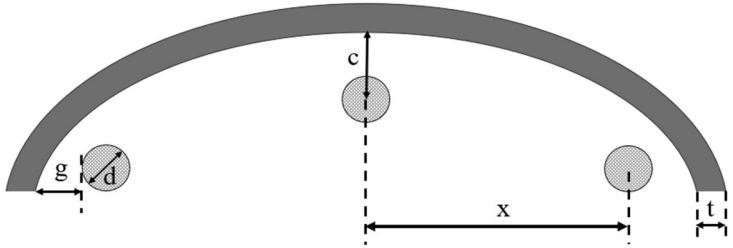
large-diameter cooling channel. A comparison involving 3 mm products showed that the CCCs can reduce the cooling time by about 20% and the cooling is more uniform, thus reducing the warpage by about 25%. Wang and Lee (2023) studied products with a thickness of less than 2 mm. The product warpage was improved by 32.29% and the cooling time was shortened by 30% with the use of CCCs. CCCs effectively reduce warping and deformation in products of all thicknesses and significantly shorten cooling times. Therefore, CCCs are a reliable solution to improve product quality and production efficiency.

The use of CCC can quickly and effectively minimize warpage and deformation of thin-shelled products during the injection process. However, many studies have pointed out that CCC should be used cautiously to avoid weakening the mold. As pointed out by Xu, Sachs and Allen (2001), CCC creates stress concentrations in the mold, which can affect the structural strength of the mold. The maximum surface deformation and tensile stresses in a mold under injection pressure are closely related to the geometry and design of the cooling channels. In terms of stress and strain, cooling channels with circular cross sections are more efficient than those with square cross sections, reducing stress concentrations by more than 50% and improving cooling efficiency while maintaining mold strength and stability. Park and Pham (2009) recommend cooling channel diameters of 6 mm to 12 mm, distances between channels of 2 to 5 times the channel diameter, and distances between channels and mold cavity surfaces of 1 to 5 times the cooling channel diameter. These design rules ensure that the mold strength is within reasonable limits to balance the cooling efficiency and temperature distribution on the mold surface and prevent surface stress problems caused by uneven cooling of the mold. According to Kuo et al., (2021) the diameter, location and roughness

of the cooling channel have a direct influence on the structural strength of the mold. The distance between the CCC and the cavity wall should be 2 to 3 times the diameter of the cooling channel, while the distance between the cooling channels should be 1.5 to 2 times the diameter of the channel. Improper placement of the cooling channels can lead to stress concentrations, especially in the corners or areas near the edge of the cavity. Stress concentrations in these areas weaken the structural strength of the mold and increase the risk of mold rupture or distortion. Table 1 summarizes the design specifications related to CCC. From the literature, it can be seen that although warpage and deformation can be easily improved by using CCC, improper design can easily lead to a reduction in the strength of the mold and affect its suitability.

In this study, an example of a hard disk deflector (Figure 1(a)) was used, where the length of the product was only 20 mm and there were four fins on it, the thinnest of which was 0.8 mm and the thickest of which was 1 mm. In order to mold the deflector and the fins on it, the slider structure mold design shown in Figure 1(b)(c) was used, which consists of 3 inserts (Figure 1(d)) with a thickness of about 2 mm. As can be seen from Table 1, in previous studies, the minimum distance from the cooling channel boundary to the mold cavity should be greater than 2 mm. In addition, few studies have addressed how to improve the warpage of thin shells with a thickness of less than 1 mm. Therefore, the thin multilayer structures discussed in this study face several significant challenges, including a thickness of less than 1 mm, mold space that does not allow for CCC, and limitations in mold strength. Therefore, this study will focus on the problem of multilayer thin shells in order to identify design criteria for placing CCCs in a limited space and maintaining the strength of the mold while ensuring minimal warpage.

Table 1. Design parameters of conformal cooling channels



Unit: mm	Part Thickness (t)	Channels diameter (d)	Distance between the center of the channel and the cavity wall (c)	Distance between the channel centers (x)	Distance for edge of channel to cavity (g)
Park and Pham (2009)	--	6-12	1d-5d	2d-5d	--
Wang et al., (2011)	--	--	1d-2d	--	c-0.5d
Dang and Park (2011)	--	8-14	1d-5d	2d-5d	--

He et al., (2016)	--	8-12	--	--	13-17
Kuo, Jiang, and Lee (2019)		8	6-16	--	2
Kanbur, Shen, and Fei (2020)	0-2	4-8	1.5d-2d	2d-3d	2-3
	2-4	8-12	1.5d-2d	2d-3d	2-3
	4-6	12-14	1.5d-2d	2d-3d	2-3
Kuo et al., (2021)	--	--	2d-3d	1.5d-2d	--
Kuo and Chen (2021)	--	4	--	17	7.5
Kuo and You (2022)	--	8,9,10	--	--	9,9,11

1. METHOD

1.1 Analysis of the causes of warpage

In order to understand the cause of warpage, we analyzed the warpage using Autodesk moldflow analysis software, and the parameters used in the analysis were the same as those used in actual molding. The results showed that the warpage in the Z-direction at the end of the deflector was very obvious after cooling (Figure 2). Compared with the actual injection molding sample in Figure 1(a), both the upper and lower deflector ends exhibited obvious inward warpage, which is consistent with the warpage deformation trend of the actual sample.

From the temperature distribution on the deflector surfaces, the temperature of the inner layer is significantly higher than that of the wall, which is due to the absence of cooling channels in the inner region of the deflector. As shown in Figure 3, surface A is 65-68°C, surface B is 73-106°C, surface D is 66-69°C, and surface C is 69-104°C. The temperature difference between the upper and lower fins is about 10-40°C. After the deflector is ejected, severe warpage can result due to the temperature difference between the inner and outer plastics during shrinkage and the residual heat difference. In addition, the slider has no cooling channel design, so the heat brought by the melt filling into the mold cavity during the molding process cannot be taken away, resulting in the temperature of the insert reaching as high as 100-106°C. Since the cooling channels can carry away the heat, the temperature on both sides of the core and cavity is 66-68°C. This leads to a temperature difference between the side of the core and cavity and the slider, resulting in warpage. The temperatures of the mold and slider insert are shown in Figure 4.

1.2 Conformal cooling channels design

According to the analysis of the causes in 2.1, this study will increase the cooling channels in the slider inserts to reduce the temperature difference and improve the warpage. However, as shown in Figure 1(d), the thickness of the slider insert is $T = 2$ mm, so it is necessary to ensure that the cooling efficiency can meet the structural strength requirements of the injection

mold. As shown in Figure 3(c), the highest temperature region is inside the deflector near the edge, so the cooling channel should be designed as close as possible to the deflector. In order to ensure the strength of the mold, referring to Table 1, the distance g between the cooling channel wall and the edge of the mold cavity is set to 3 mm; considering the thickness of the inserts, according to the limitation of T , the cooling channel diameter d is taken as 0.6, 0.8, 1.0, 1.2, and 1.4 mm; the distance x between the cooling channels is set to $2d$, and the design of the channel is shown in Figure 5.

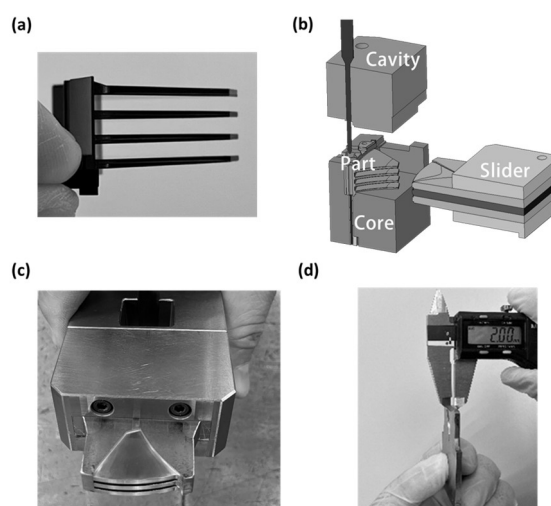


Figure 1. Deflector (a) deflector actual appearance; (b) mold Schematic; (c) slider; (d) insert thickness 2mm.

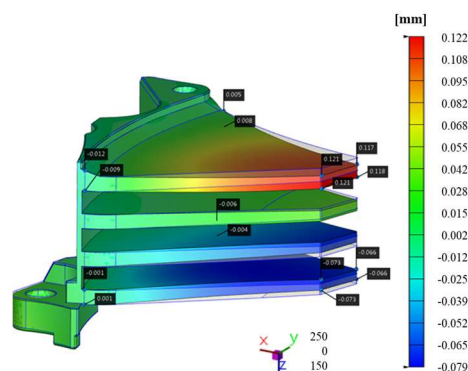


Figure 2. Simulated deflector molding warpage result.

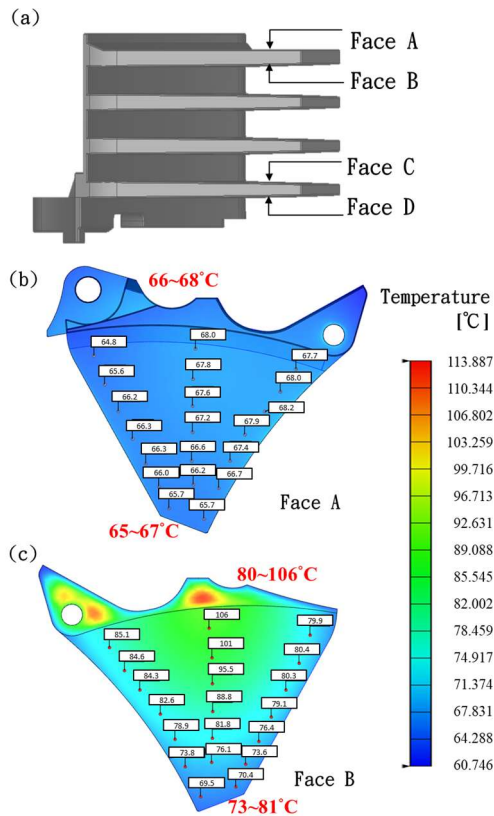


Figure 3. Temperature distribution of the fins of the deflector. (a) location description, (b) temperature distribution of Face A, and (c) temperature distribution of Face B

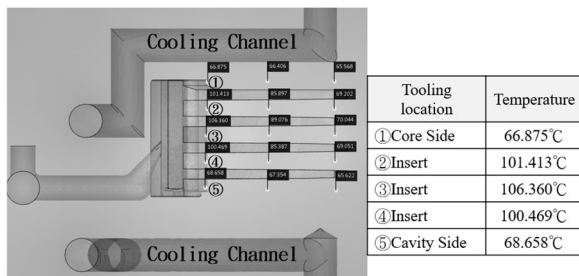


Figure 4. Temperature of mold and slider inserts.

1.3 Model calibration

In order to ensure the accuracy of the experiment, the actual injection molding is compared with the results of the mold flow analysis, and the comparison includes the injection pressure, mold cavity pressure, and fin position. The injection pressure comparison is to compare the pressure curve of the injection machine with the pressure curve of the mold flow analysis, as shown in Figure 6. The upper solid line is the measured value of the real injection machine, while the dotted line is the simulated value, and the two are very similar from the curve in Figure 6. The solid line on the top is the actual injection measurement, and the dashed line is the simulated value. The curves show that the two are very similar, which means that the

actual injection parameters can be presented in the simulation, thus making the simulation results initially close to the real results. The two curves at the bottom of Figure 6 show the simulated and measured values of the mold cavity pressure. The pressure in the mold cavity cannot be obtained directly from the machine, so it is necessary to install sensors in the mold to collect the data. The mounting position of the sensor is shown in Figure 7 (a), where the pressure sensor is mounted under the ejector pin. The actual mounting position is shown in Figure 7 (b). The numerical results in Figure 6 show the same trend, but it is clear that the simulated pressure in the mold cavity is higher than the measured value.

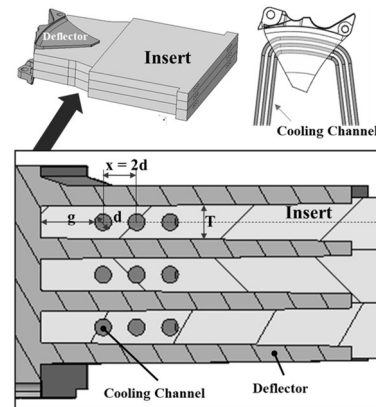


Figure 5. Conformal cooling channels design on the deflector slider insert.

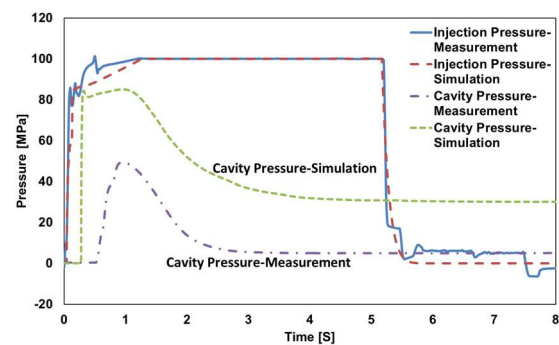


Figure 6. Measurement vs. simulated curves for injection pressure and cavity pressure.

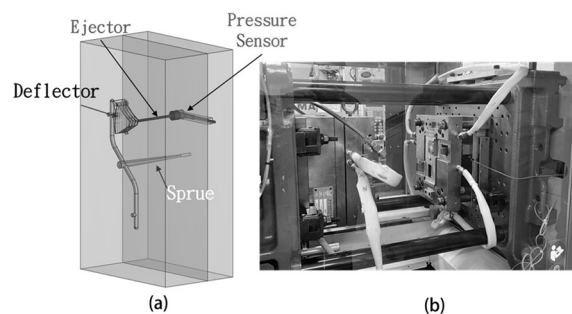


Figure 7. Cavity Pressure Measurement (a) Measuring position, (b) Actual installation

The comparison of the fin position is based on the four faces in Figure 3(a), and the measured values are: Face A = 12.56 mm, Face B = 11.50 mm, Face C = 3.70 mm, and Face D = 2.88 mm. The simulated results are: Face A = 12.91 mm, Face B = 11.86 mm, Face C = 3.50 mm, and Face D = 2.69 mm. The correlation between the measured and simulated results is shown in Figure 8. Based on the comparison of injection pressure, mold cavity pressure, and fin position, the model shows sufficient accuracy for further analysis. The R^2 value of 1 indicates a perfect linear correlation, with all data points lying on the regression line. This confirms that the simulation results closely match the measurements across all surfaces (Face A–D), demonstrating the model's reliability.

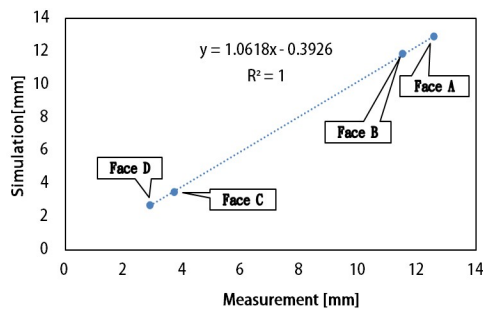


Figure 8. Comparison of correlation between measured and simulated positions of deflector fins.

1.4 Simulation

Mold flow analyses are performed to determine if a CCC constructed according to 2.2 will provide adequate cooling and reduce warpage. In addition, the mold flow analysis is used to understand the cavity pressures during the molding process and to input the pressure results into the structural analysis for use. First, a 3D model of the mold is imported, including the core and cavity, sliders, cooling channels, and deflector, and the gate location and type, runner sizes, and cooling channel inlet and outlet locations are set. Then, the setup model is meshed, and the meshed model is shown in Figure 9. Then the injection conditions are set with reference to the plastic material properties and mold design, the injection machine and material are selected, and finally the analysis scope and project are defined, and then the mold flow analysis is carried out.

Based on the results of the mold flow analysis, cavity pressure curves can be obtained for setting structural stress conditions and performing structural analysis of the insert. The molding process consists of three stages: filling, packing, and cooling. After injection filling, the molten plastic is pressurized and filled to ensure that the mold cavity is completely filled and to limit the extent to which cooling shrinkage affects the shape. The cavity pressure in a mold is highest at the injection gate end at approximately 130 MPa and lowest at the flow end at approximately 60 MPa. There

are three inserts in the slider, which are of the same structural design, and considering the time required to perform the simulation analysis, only one of the inserts with more demanding process conditions is selected for structural analysis.

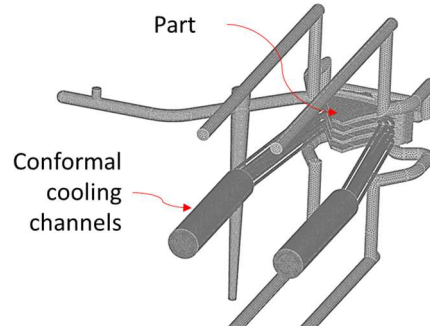


Figure 9. Mold flow simulation model with conformal cooling channels.

2. RESULT AND DISCUSSION

2.1 Result of mold flow simulation

The results of mold flow analysis are compared for five different CCC designs to compare the cooling efficiency, the effect on part temperature, and the improvement of overall part warpage after cooling. In addition, it is necessary to analyze and compare the pressure in different filling areas in the cavity during the injection molding process to understand the pressure distribution of the inserts from both filling and packing, so as to facilitate the subsequent structural analysis.

As shown in Figure 10(a), the deflector mold is divided into 5 layers, and 12 probes are set up in each layer as shown in Figure 10(b). As can be seen from Figure 10, the channels pass underneath probes 1-6. The results of the mold temperature for each layer with different channel diameters are shown in Figure 11. Figure 11(a) shows the results without cooling channels, and it can be found that the temperature difference between probes 1-6 is huge, with the temperature ranging from 65 to 110 °C; Figures 11(b)–(f) show the results for different cooling channel diameters, and it can be clearly found that the temperature range is between 58 and 65 °C. The temperature of the CCC is controlled between 58 and 62 °C through the 2-4 layers.

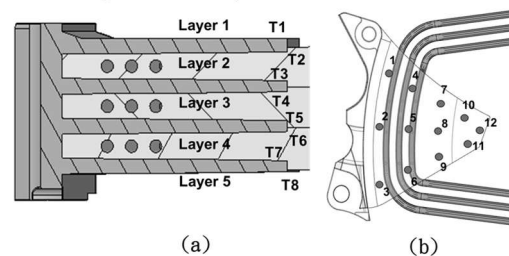


Figure 10. Data acquisition location (a) layered description, (b) probe position per layer.

The four fins of the deflector have 8 surfaces, T1-T8 from top to bottom, as shown in Figure 10(a), and there are 12 probes on each surface, as shown in Figure 10(b). The surface temperature results of each deflector fin at different channel diameters are shown in Figure 12. The temperature trend in the graph is similar to that in Figure 11. From the temperatures of the mold and the deflector, it can be seen that the temperature decreases slightly when the channel diameter increases from 0.6 mm to 0.8 mm, but the temperature difference is negligible in the diameter range of 0.8 mm to 1.4 mm. Hence, 0.8 mm is the most effective as far as cooling effect is concerned. The results of the deflector warpage analysis are shown in Table 2. The results show that the warpage is significantly improved for all five different diameter channel designs compared to the no-cooling channel, but the cooling effect starts from 0.8 mm, and the

increase in diameter does not improve the warpage, and even an increase in warpage occurs.

2.2 Result of structure simulation

The results of the structural stress analysis of five different diameters of CCC models are shown in Figure 13 to illustrate the stress distribution at the cross-section of the slider insert. The maximum stress for the 0.6 mm diameter CCCs during injection is 243 MPa, for 0.8mm is 308 MPa, for 1.0 mm is 340 MPa, for 1.2 mm is 404 MPa, and for 1.4 mm is 472 MPa, and the yield strength of the mold steel used as the material for the slider insert is 1,188 MPa. It can be seen that in the injection process of this multilayer thin-shelled product, even with a diameter of 1.4 mm, the strength requirement can be met with a cavity pressure of 80 MPa.

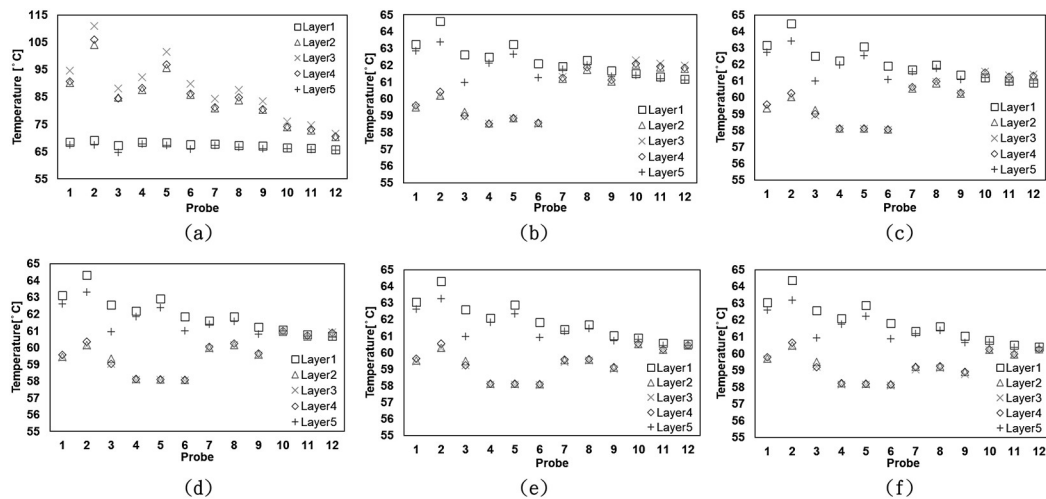


Figure 11. Temperature of each layer of the mold for different channel diameters (a)no cooling channels; (b)0.6mm cooling channels, (c)0.8mm cooling channels, (d)1.0mm cooling channels, (e)1.2mm cooling channels, and (f) 1.4mm cooling channels.

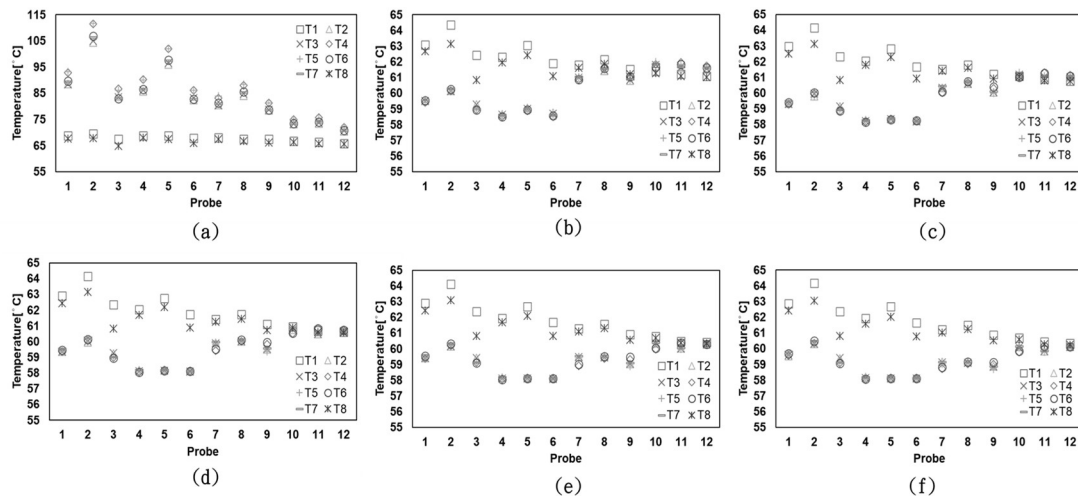


Figure 12. Temperature of each surface of the deflector for different channel diameters (a)no cooling channels; (b)0.6mm cooling channels, (c)0.8mm cooling channels, (d)1.0mm cooling channels, (e)1.2mm cooling channels, and (f) 1.4mm cooling channels.

Table 2. Warpage of the deflector for different channel diameters.

Unit: mm	No cooling channel	0.6mm	0.8mm	1.0mm	1.2mm	1.4mm
T1	0.118	0.023	0.010	0.009	0.011	0.011
T2	0.118	0.023	0.010	0.009	0.010	0.011
T7	0.066	0.020	0.010	0.009	0.013	0.015
T8	0.066	0.021	0.010	0.010	0.014	0.015

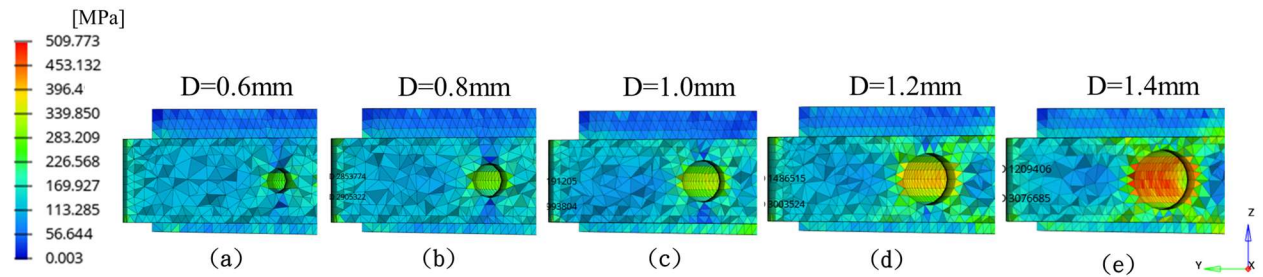


Figure 13. Slider with cooling channels cross-section (a)When $D=0.6\text{mm}$, the maximum stress is 243MPa; (b) When $D=0.8\text{mm}$, the maximum stress is 308MPa; (c) When $D=1.0\text{mm}$, the maximum stress is 340MPa; (d) When $D=1.2\text{mm}$, the maximum stress is 404MPa; and (e) When $D=1.4\text{mm}$, the maximum stress is 472MPa.

Table 3. Temperature difference between the two sides of fins of different cooling channel diameters.

Unit: °C	No cooling channel	0.6 mm	0.8 mm	1.0 mm	1.2 mm	1.4 mm
T7 and T8	38.3	3.4	3.9	4.0	3.9	3.8
T1 and T2	34.8	4.2	4.4	4.5	4.5	4.5

2.3 Discussion

Mold flow analysis was performed by defining each layer of the mold and measuring the temperature of each layer with 12 probes in order to compare the mold temperatures affecting the deflector warpage in layers 2 and 4. Figure 14(a) shows the temperature distribution of different channel diameters in layer 2. The temperature of the five channel diameters close to the gate location (probes 1-3) is the same, while the 0.6 mm channel diameter in probes 4-6 has a higher temperature and the larger channel diameters in probes 7-9 and 10-12 have a lower temperature. The comparison in Figure 14(b) shows that the results of Layer 4 are consistent with those of Layer 2. In terms of cooling efficiency, the larger the diameter, the lower the mold temperature, the better the cooling efficiency. However, for the portion of probes 1 to 6, the channel diameter is cooled and saturated from 0.8 mm. Table 3 compares five different CCC diameters that reduce the temperature difference between the two sides of the fins to within 5°C compared to a mold with no cooling channels in the slider. As shown in Table 2, comparing the five different CCC diameters, the warpage of the molded part is significantly improved to within 0.025 mm.

In terms of stress distribution, the draft angle of

the insert is set to 2° to ensure smooth ejection. As shown in Figure 15, in the analysis, the downward force is set to be the force perpendicular to the insert plane direction F . The force acting on the contact surface with the insert with the draft angle is actually $F \cdot \cos 1^{\circ}$. At the end of the insert, the shear force τ is generated by the horizontal component $F \cdot \sin 1^{\circ}$ of F acting on the insert plane, which also indicates that the stresses at the top and bottom corners of the end are higher compared to the surrounding area, as shown in Figure 13, but the values of the shear stresses at the corners are the same since the design of the draft angle is the same for all five CCC diameters. In addition, Figure 13 shows that the highest stresses are concentrated on the left and right sides of the channels, the reason for which has already been shown in the study by Kirsch (1898) on the phenomenon of stress concentration in materials. When forces are transferred vertically, the material exhibits a geometrically discontinuous situation, and the stress concentration occurs in the horizontal direction of the discontinuous geometry. In the insert design, the force is transferred above and below the insert, so that a stress concentration occurs on both sides of the circular channel.

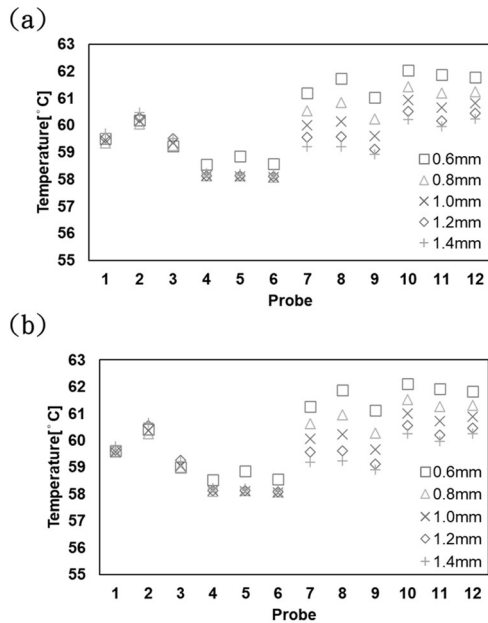


Figure 14. Temperature of the different channel diameters of different layers (a) layer 2; (b) layer 4

According to Saint Venant's Principle (2006), the stresses induced in a body by a load are only related to the combined forces and moments of the loads at points a short distance away from the loaded area, while there is a distinctly different distribution of stresses near the loaded area. This principle explains why the larger the channel diameter is, the thinner the wall thickness of the channel at the upper and lower ends and the mold cavity, and the higher the value of the stress in that area. Because of the draft angle, the upper and lower wall thicknesses of the three channels show a gradual thickening from left to right, so the first channel is thinner and has the highest stress value, and the second and the third are gradually decreasing. Moreover, for the 3-piece inserts, the cavity pressure is uniformly applied in the vertical direction, and the pressure inside the channel is supported externally, which is one of the reasons why the stress inside the insert with different channel diameters is lower than that of the yield stress.

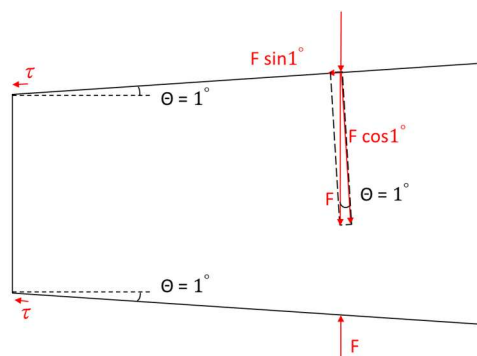


Figure 15. Influence of draft angle on cavity pressure transfer

3. CONCLUSION

In this study, the CCC design is carried out for multilayer thin-shell products. In injection molding, thin-shell products are susceptible to ambient temperature variations and cooling system effects, which result in inconsistent cooling rates and different degrees of product shrinkage, and this uneven shrinkage causes internal stresses that ultimately lead to warpage. In this study, we break through the CCC design criteria given in previous literature and propose a CCC design for multilayer thin shell products to reduce the amount of warpage and at the same time maintain the strength of the mold. For the same volumetric flow rate, the smaller diameter results in a higher flow velocity, and the cooling channel carries the heat away from the mold more efficiently through thermal convection. However, for the same thickness of the slider insert, the distance between the smaller diameter channel and the mold cavity is larger, and the heat conduction efficiency in removing the heat from the molten plastic is lower. For products with multiple thin shells and small spacing such as the deflector, the five different CCC diameters can effectively reduce the temperature difference between the slider insert and the core and cavity sides, so that the temperature difference between the inner and outer sides of the fin can be reduced to less than 5 °C. All five types of cooling channels can control the warpage within 0.025 mm, with 0.8 mm and 1.0 mm diameters having the smallest warpage of 0.01 mm.

Injection molding has the highest in-mold pressure during the packing stage, and the pressure increases the closer you get to the gate. Due to the multiple fins, the deflector is mainly subjected to pressure in the up and down direction, so the stresses are mainly concentrated on the transverse sides of the circular cross-section of the channel, rather than on the top and bottom sides. In a slider insert of the same thickness, the larger the cooling channel diameter and the smaller the wall thickness of the mold cavity, the greater the value of the stresses on the transverse channel sides. In this case, the risk of mold failure due to plastic deformation is higher. Among the five different CCC diameters, only the 0.6 mm diameter CCCs meet the design specification of 1.5 times the channel diameter for the distance between the center of the channel and the cavity, and have the lowest maximum stress, which is relatively good for the strength of the structure; the designs of the 0.8, 1.0, 1.2, and 1.4 mm channel diameters are lower than the design specification of 1.5 times the channel diameter, but the calculations show that the structure does not show any plastic deformation. These channel designs are below the design code for a distance of 1.5 times the diameter of the channel. The 0.8 mm diameter design would be a better choice if the cooling efficiency of the CCCs on the mold, the amount of warpage, and the structural strength of the mold are

also taken into consideration. In this study, the design of conformal cooling channels for multilayer thin-shell products has broken the established design criteria, and its structural strength has been theoretically verified to be sufficient to improve the warpage of such molded parts, and also to provide solutions to the plastic deformation problems that may occur in the injection molds, thereby expands the scope of application of conformal cooling channels.

In future research, further investigation can focus on optimizing the CCC layout using dimensionless analysis, enabling broader applicability across different part sizes and geometries. Moreover, the current study is based on simulation; thus, experimental validation using real molds and temperature/pressure sensors will be essential to confirm the accuracy of the simulation results. Additional studies may also explore alternative mold materials or localized reinforcement techniques to enhance mold strength when larger-diameter CCCs are used in thinner mold inserts. Lastly, integrating multi-objective optimization algorithms, considering warpage, cooling efficiency, and mold durability simultaneously, could provide more systematic design guidance for CCCs in complex thin-shell products.

REFERENCES

- Beer, F. P., Johnston, E. R., & Dewolf, J. T. (2006). *Mechanics of materials*. New York: McGraw-Hill.
- Chen, C. P., Chuang, M. T., Hsiao, Y. H., Yang, Y. K., & Tsai, C. H. (2009). Simulation and experimental study in determining injection molding process parameters for thin-shell plastic parts via design of experiments analysis. *Expert Systems with Applications*, 36, 10752-10759.
- Dang, X. P., & Park, H. S. (2011). Design of U-shape Milled Groove Conformal Cooling Channels for Plastic Injection Mold. *International Journal of Precision Engineering and Manufacturing*, 12(1), 73-84.
- He, B., Ying, L., Li, X., & Hu, P. (2016). Optimal design of longitudinal Conformal Cooling Channels in Hot Stamping Tools. *Applied Thermal Engineering*, 106, 1176-1189.
- Huang, Y. Z., Huang, C. F., Peng, B. Y., Chnag, C. W., Cheng, H. C., Lin, Y., . . . Wang, H. (2020). Experimental and Numerical Study Determining the Warpage Phenomenon of Thin-Wall Injection Molding. Wiley, 2020.
- Kanbur, B. B., Shen, S., & Fei, D. (2020). Design and optimization of conformal cooling channels for injection molding: a review. *The International Journal of Advanced Manufacturing Technology*, 106(7), 3253-3271.
- Kirsch, E. G. (1898). Die Theorie der Elastizität und die Bedürfnisse der Festigkeitslehre. *Zeitschrift des Vereines deutscher Ingenieure*, 42, 797-807.
- Kitayama, S., Miyakawa, H., Takano, M., & Aiba, S. (2016). Multi-objective optimization of injection molding process parameters for short cycle time and warpage reduction using conformal cooling channel. *The International Journal of Advanced Manufacturing Technology*, 88, 1734-1744.
- Kuo, C. C., & Chen, W. H. (2021). Improving Cooling Performance of Injection Molding Tool with Conformal Cooling Channel by Adding Hybrid Fillers. *Polymers*, 13.
- Kuo, C. C., & You, Z. Y. (2022). A simple method for enhancing the flexural strength of epoxy-based rapid soft tooling with conformal cooling channels. *The International of Advanced Manufacturing Technology*, 121, 1887-1897.
- Kuo, C. C., Jiang, Z. F., & Lee, J. H. (2019). Effects of Cooling Time of Molded Parts on Rapid Injection Molds with Different Layouts and Surface Roughness of Conformal Coolinf Channels. *The International Journal of Advanced Manufacturing Technology*, 103, 2169-2182.
- Kuo, C. C., Qiu, S. X., Lee, G. Y., Zhou, J., & He, H. Q. (2021). Characterizations of polymer injection molding tools with conformal cooling channels fabricated by direct and indirect rapid tooling technologies. *The International Journal of Advanced Manufacturing Technology*, 117.
- Lai, J. Y., Wu, J. W., Song, P. P., Chou, T. Y., Tsai, Y. C., & Hsu, C. H. (2022). Hybrid mesh generation for the thin shell of thin-shell plastic parts for mold flow analysis. *Engineering with Computers*, 38, 4895-4917.
- Lin, W. C., Fan, F. Y., Huang, C. F., Shen, Y. K., & Wang, H. (2022). Analysis of the Warpage Phenomenon of Micro-Sized Parts with Precision Injection Molding by Experiment, Numerical Simulation, and Grey Theory. *Polymers*, 14.
- Otieno, S. O., Mwema, F. M., Mharakurwa, E. T., & Jen, T. C. (2024). Fuzzy assessment of process parameter interactions on warpage defect modeling in plastic injection molding. *International Journal on Interactive Design and Manufacturing*.
- Park, H. S., & Pham, N. H. (2009). Design of Conformal Cooling Channels for an Automotive Part. *International Journal of Automotive Technology*, 10(1), 87-93.
- Tan, C., Wang, D., Ma, W., Chen, Y., Chen, S., Yang, Y., & Zhou, K. (2020). Design and additive manufacturing of novel conformal cooling molds. *Materials and Design*, 196.
- Wang, W., & Lee, C. (2023). Design and Optimization of Conformal Cooling Channels for Increasing Cooling Efficiency in Injection Molding. *Applied*

Sciences, 13.

- Wang, Y., Yu, K. M., Wang, C. C., & Zhang, Y. (2011). Automatic design of conformal cooling circuits for rapid tooling. *Computer-Aided Design, 43*, 1001-1010.
- Xu, X., Sachs, E., & Allen, S. (2001). The Design of Conformal Cooling Channels in Injection Molding Tooling. *Polymer Engineering and Science, 41*(7), 1265-1279.