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Optimization of Multiple Quality Characteristics in Conformal Cooling Channel Fabrication Utilizing Taguchi Method

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Abstract. This paper points out the significancy of developing an optimization solution of designing conformation cooling system in injection molding tooling. The focus of this study is the on the model, development, and optimization which have will benefit manufacturer, especially the importance in shorten cycle time and better quality since compared with traditional cooling systems, conformal cooling can greatly reduce the warpage defect and shorten the cooling cycle time. This paper introduces a case study that an experiment is conducted to improve shrinkage as the quality characteristic of an injection molding product (automotive seat housing) by optimizing conformal cooling channel design using the Taguchi method.

Keywords: conformal cooling channel, optimization, Taguchi method

1. Introduction

The Plastic Injection Molding (PIM) process is a constant, repetitive process to obtain molded products by injecting molten plastic pellets into a mold follow by cooling and solidifying. Feeding plastic pellets to the heated barrel through a hopper, mixing the plastic by a rotating and using a helical screw, injecting into a mold cavity, packing the molten plastic, cooling, and hardening to the configuration of the cavity and subsequently ejection of the solidified plastic part. The procedure is therefore divided into 3 or 4 phase (Khan et al., 2014, Kitayama et al., 2016, Park and Dang, 2017) which include filling, packing, cooling, and ejection, altogether to form a complete injection molding cycle.

While five stages are involved, cooling occupies the largest percentage of an injection molding cycle, generally between 70 and 80%, meaning the cooling phase takes up over two-thirds of the cycle time, thus become the key factor influencing production efficiency(Park and Dang, 2017, Wang et al., 2015). It is as well the foremost important phase because the cooling holds a significant impact on product quality and reduce thermal stress. Deficient cooling times will generally result defects like volumetric shrinkage and warpage.

Since Professor Sachs (Sachs et al., 1997, Sachs et al., 2000) from Massachusetts Institute of Technology advocate the conformal cooling technology for injection molds, a few studies have demonstrated the exceptional attributes of conformal cooling channels for improving temperature uniformity, shortening cooling time and reducing warpage (Venkatesh et al., 2017) compared with the standard straight-line cooling channels.

The contoured cooling circuit of conformal cooling channels that follows the shape of the cavity, have the same thermal conduction distances between the part and the cooling channels. It is not only be uniform but also significantly shorter that traditional cooling channel. As a result, compared with the traditional standard straight-line cooling circuits conformal cooling channels, considerably reduce shorten the cooling cycle time and the warpage defect, (Vojnová, 2016, Wang et al., 2011). Most of those studies have focused on conformal cooling channels within the molds to enhance and speed up cooling (Kuo et al., 2019, Park et al., 2020, Mercado-Colmenero et al., 2019, Shinde et al., 2018, Kitayama et al., 2018, Li et al., 2018, Jahan and El-Mounayri, 2016). Conformal cooling channels are designed to adapt to the layout of the mold cavity. It has been shown that this procedure enables the mold temperature to achieve the operating temperature more rapidly than in molds with standard cooling channels (Dalgarno et al., 2001, Xu et al., 2001).

Successful cooling performance improvement of conformal cooling systems has been proved by several studies. However, nowadays, the fabrication of such channel is generally still dependent on the engineers' related experiences in practical field or through experimental designs and trial and error methods. These practices are likely be costly in terms of time and money, and the resulted parameters are not quite often optimal.

Author's intention of this paper presents an application of Taguchi method to optimize the fabrication of conformal cooling channel in the insert core of an injection tooling of automotive seat housings. The conformal cooling parameters were selected by in broadly range. Under Taguchi method, the simulation experiment was deployed. By the computer aided engineering (CAE) method, the quality characteristics including warpage and product length were found. Follow by the simulation experiments by using the Taguchi method and data analysis of cooling channel fabrication parameters. Also, the Signal-to-noise ratio method is used to identify the most substantial process parameters for the optimal combinations. In the following, the Taguchi method for obtaining optimal combination of parameters is discussed.

2. Methodology

2.1. Product Geometric Design

This study applied conformal cooling channels to the PIM part which is a housing for switch and PBC in automotive car seat (Fig. 1)

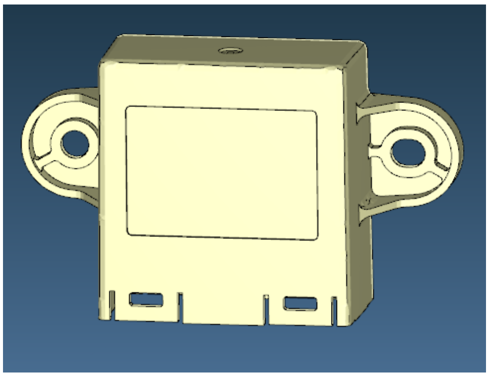

Fig. 1: Outlook of the car seat housing.

Fig. 2: Three-coordinate measuring machine.

2.2. Experimental Materials

The extra-rigid quality of glass fiber reinforced polypropylene resin PPH GF5030HCVT2, produced by Polykemi Sweden, was used. This polypropylene with s extra-rigid quality because of 30% glass fiber reinforced, was chosen due to its characteristics of low density and high chemical resistance, and greater resistance to high temperature.

2.3. Definition of Warpage and Shrinkage

A three-coordinate measuring machine (CMM) coordinate measuring instrument was used for measuring the warpage and shrinkage of the plastics housings manufactured using different cooling channel design and methods. The product nominal length was 10.00 mm. The ideal warpage value was 0 mm as expected. Three-coordinate measuring machine (B&S GLOBAL Silver Performance) is used with a range of 500 mm and precision of 0.0015mm which shown in Fig. 2.

2.4. Defect Study

Fig. 3 shows the predicted location of the deformation. The red color is the area that perpendicularity is in positive value with maximum value of 0.395mm. This red area can make housing defect and form a warpage inner wall. Warpage is due to the design of the part which has a deep structure. Temperature of the two top corners shown in Fig. 3 is high compared to the rest of the part due to the rib limited the distortion space. The temperature of the resin along the locations of on the top should be as even as possible after melt filling, in order to eliminate defect,

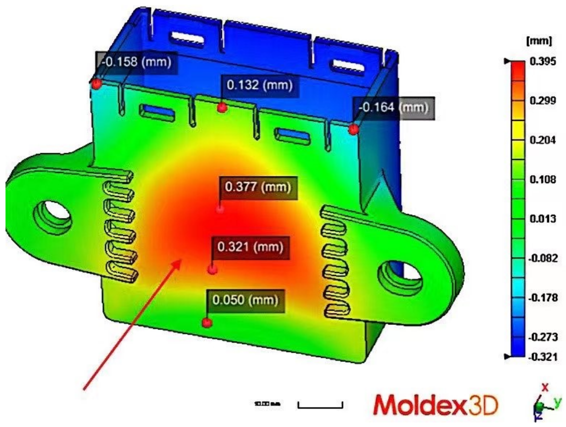

Fig. 3: Predicted location of deformation on car seat housing.

2.5. Experimental Setup

In the first stage, in case of the complex shaped automotive seating housing, as shown in Fig. 1, a mold filling analysis is conducted in order to predict the warpage region. The commercial analysis software Moldex3D CAE was utilized to conduct this analysis. The parameters related to the design of the cooling channel, such as the channel diameter (d), number of channel (N), and Reynolds number (Re) are will be selected by simulation method in widely range. For the simulation experiments and data analysis the Taguchi method was employed. Followed by the S/N ratio method and ANOVA, which were used to identify the most significant process parameters for the initial optimal combinations.

In this investigation, the selected CCC design parameters studied were the channel diameter (d), number of layer (L), and Reynolds number (Re) at two levels as the control factors. The DOF for the two levels was 1 (DOF = number of levels−1). Thus, the L4 (2^3) Taguchi standard orthogonal array (OA) was employed for determining the effect of three process parameters as shown in Table I.

TABLE I. EXPERIMENTAL LAYOUT USING AN L4 ORTHOGONAL ARRAY

Test Number	Channel diameter (d)	Number of Layer (L)	Reynolds number (Re)
1	1	1	1
2	1	2	2

3	2	1	2
4	2	2	1

Then, the Taguchi method was utilized for the data analysis and simulation experiments, followed by ANOVA and the S/N ratio method, which were used to identify the most significant process parameters for the initial optimal combinations. The flowchart of the proposed method is shown in Fig. 4.

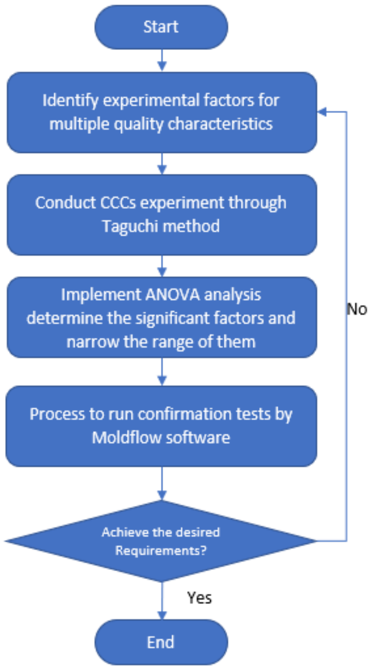

Fig. 4: Flowchart of proposed method.

3. Results

To eliminate or reduce warpage, the Taguchi optimization method was used to design the optimal cooling system. Three cooling parameters were considered for Taguchi optimization. The number of layer (L), diameter (D), and Reynolds (R) are parameters related to the design of the cooling system.

TABLE II. L4 (23) ORTHOGONAL ARRAY FOR COOLING CHANNEL DESIGN

Test Number	Channel diameter (d)	Number of Layer (L)	Reynolds number (Re)
1	2	6	40000
2	2	7	45000
3	3	6	45000
4	3	7	40000

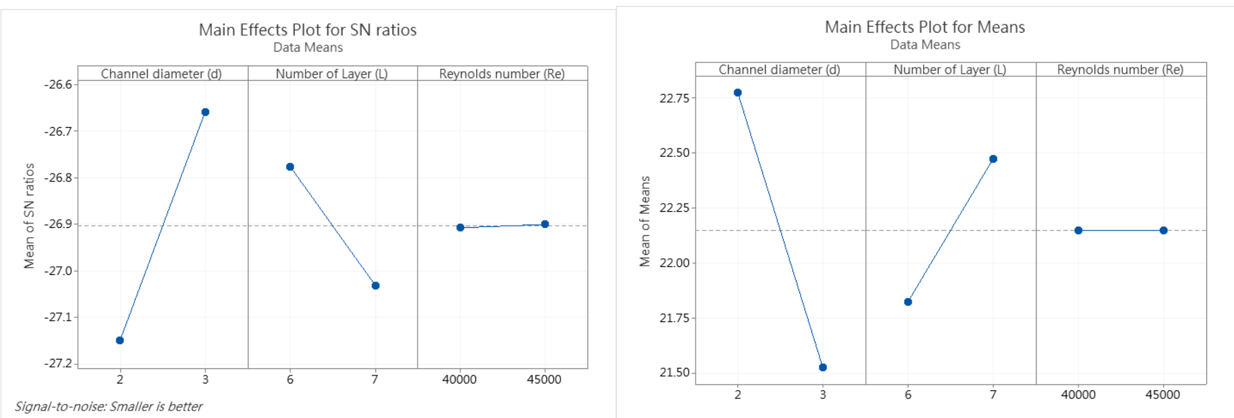

Fig. 5: Plots of CCC parameter effects on cooling time.

The DOF for the two levels was 1 (DOF = number of levels−1). Thus, the L4 (2^3) Taguchi standard orthogonal array (OA) was employed for determining the effect of three process parameters as shown in Table I. The values of these parameters were separated into two levels. As shown in Table I, an L4 (23) orthogonal array was used, which implied carrying out nine heat transfer analyses with three factors of two levels. According to Taguchi optimization technique shown in Fig. 5 and Table II, III mm Channel diameters, 6 Number of Layers, and 45000 Reynolds numbers were selected for the optimal cooling channel design parameters.

TABLE III. TAGUCHI ANALYSIS RESPONSE TABLES

Response Table for Signal to Noise Ratios

Smaller is better

Level	Channel diameter (d)	Number of Layer (L)	Reynolds number (Re)
1	-27.15	-26.78	-26.91
2	-26.66	-27.03	-26.90
Delta	0.49	0.26	0.01
Rank	1	2	3

Response Table for Means

Level	Channel diameter (d)	Number of Layer (L)	Reynolds number (Re)
1	22.77	21.83	22.15
2	21.53	22.48	22.15
Delta	1.25	0.65	0.00
Rank	1	2	3

4. Experimental Verification

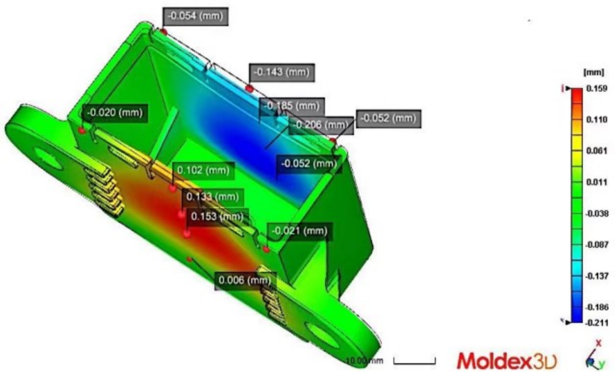

Fig. 6: Conventional channel Part temperature distribution.

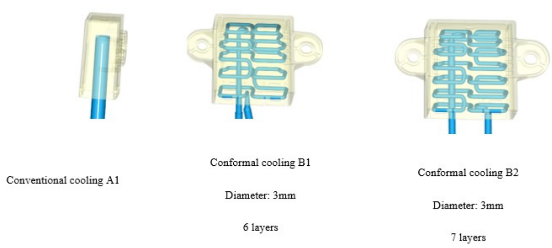

Fig. 7: Cross-section of conventional cooling channel (A1), TypeB1 and Type B2 conformal cooling channel.

This study examined the effects of conformal cooling and traditional on such housing warpage. As shown in Fig. 6. Conventional channel has unbalanced cooling, shrinkage happens which cause noticeable deflection like warpage toward inner side. A Modified cooling is needed and can improve deformation. According to Taguchi analysis in previous section, the results of the two set of cooling channel design parameters were compared using Moldex3D CAE simulation software. Channel designs are shown in Fig. 7. First set of parameters, namely type B1, is the optimal cooling channel design parameters found by Taguchi analysis included 3 mm Channel diameters, 6 Number of Layers, and 45000 Reynolds numbers. Second set of parameters namely type B2, is 3 mm Channel diameters, 7 Number of Layers, and 40000 Reynolds number. Conventional cooling channel, named A1, is also shown for control purpose.

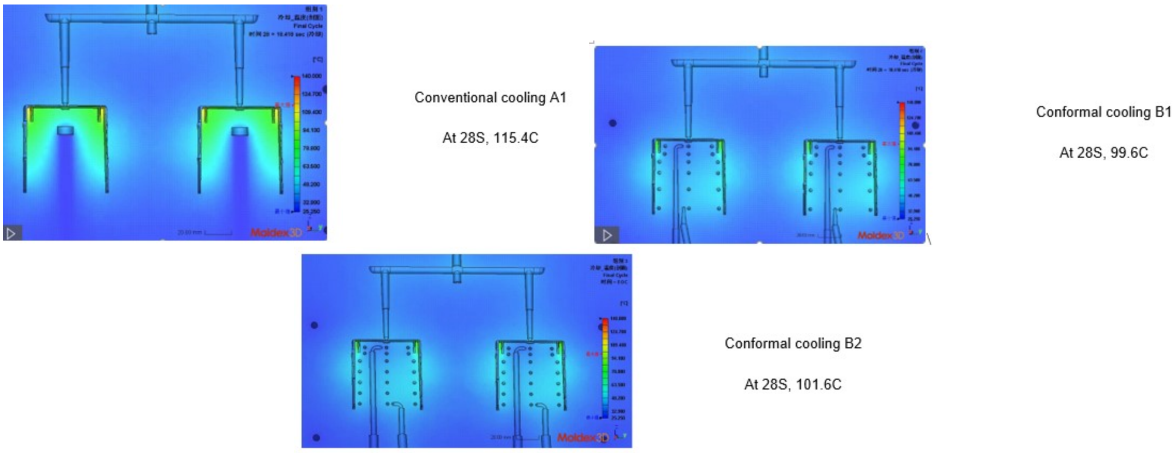

Fig. 8: Temperature during Cooling cycle with cooling channel A1, B1 and B2.

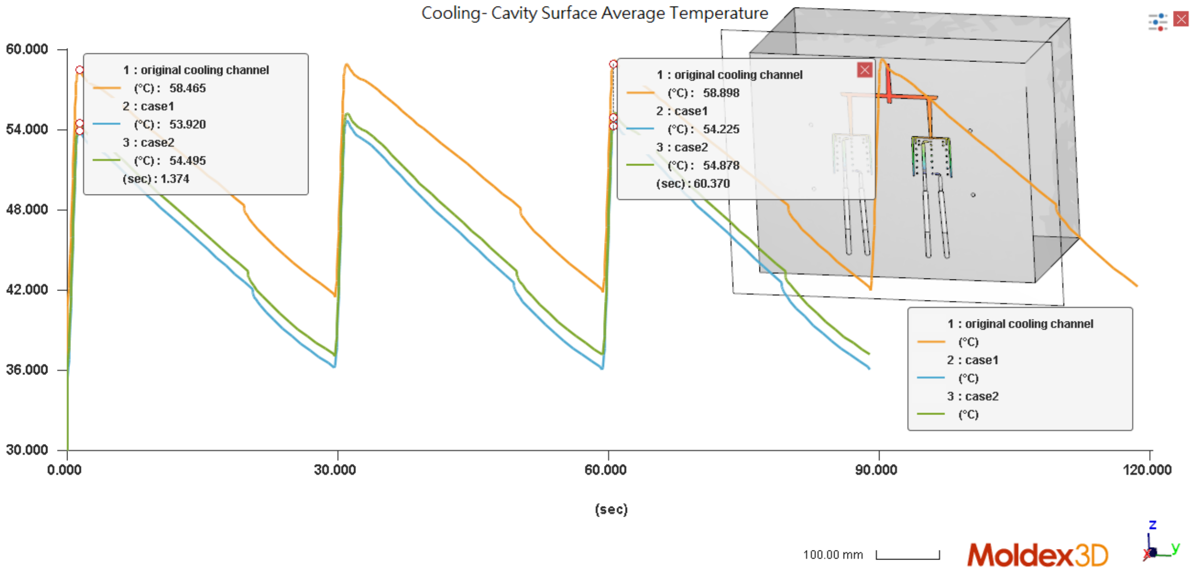

Fig. 9: A comparison chart of average temperature on cavity surface in cooling cycle.

According to Fig. 8 and Fig. 9, conformal cooling channel B1 had the lowest temperature, indicating that the channel absorbed the highest amount of heat during the cooling cycle. The temperature of the conformal cooling channel B2 was the second highest but then was considerably lower than that of B1, followed by conventional channel A1.

Due to the plastic part structure, the inner corner shown in Fig. 10 and Fig. 11 has the poorest cooling performance because of the rib is built very close to the wall. A1 conventional has a highest temperature of 127℃ with the inner angle (Green line) highest temperature of 93.5℃. B1 conformal cooling channel has a highest temperature is The highest temperature is 102℃, the inner angle (Green line) highest temperature is 64℃. B2 The highest temperature is 111℃, the inner angle (Green line) highest temperature is 65.4℃. It's proof that B1 has the optimal cooling performance in the inner corner area.

The products in the experiment demonstrated inward distortion and nonuniform temperature distribution. Figs. 12 show the simulated finish products and the tendency of warpage, respectively.

With CCC B1, the molded product shown the slightest amount of warpage because heat was removed efficiently. On the other hand, the molded product had the largest amount of warpage with Conventional A1 this was because the cooling channel had a temperature closer to the mold temperature, it was unable to disperse heat efficiently.

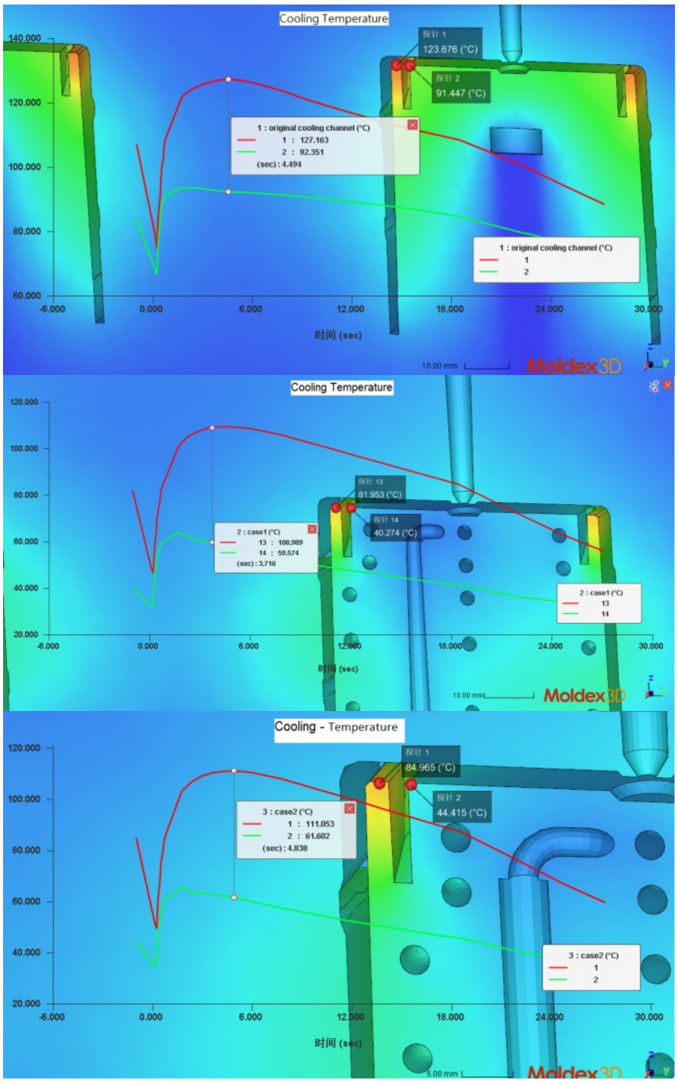

Fig. 10. Part surface temperature of conventional Cooling A1. The highest temperature is 127℃, the inner corner (Green line) highest temperature is 93.5℃.Part surface temperature of conformal cooling channel B1. The highest temperature is 102℃, the inner corner (Green line) highest temperature is 64℃.Part surface temperature of conformal cooling channel B1. The highest temperature is 111℃, the inner angle (Green line) highest temperature is 65.4℃.

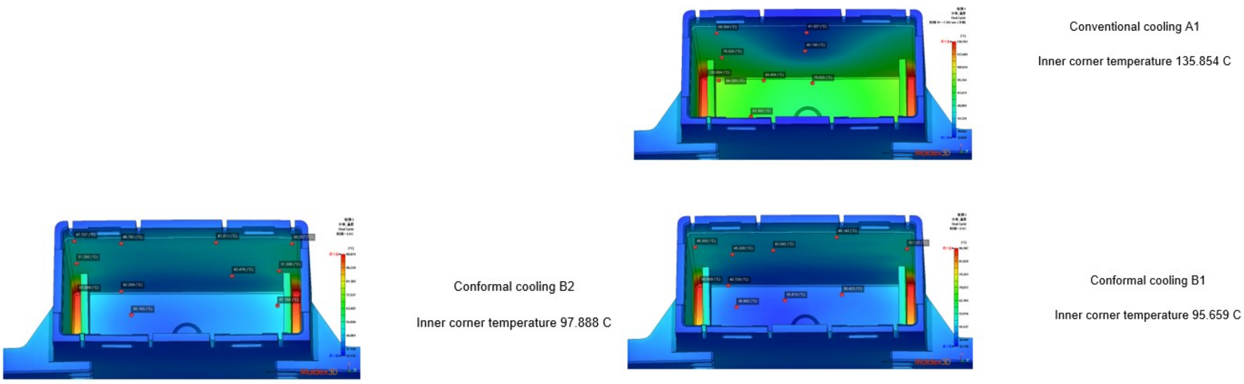

Fig. 11: Bottom top view of different cooling channel influence temperature of the inner corner area.

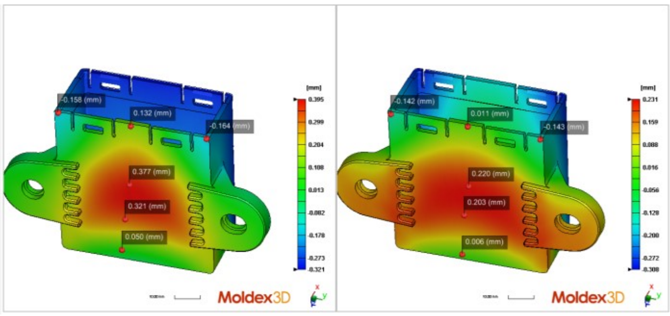

Fig. 12: Warpage analysis under A1 and B1 cooling channel simulation.

The experiment of cooling channel temperature showed that conformal cooling removed more heat than traditional cooling did. The temperature changes of the cooling channels indicated that the conformal cooling channel had considerably higher cooling efficiency than the traditional cooling channel did; it also had higher coolant flow rate and heat transfer performance, resulting in a smaller amount of warpage.

In the simulation, the product had the smallest amount of warpage with CCC A1. The warpage of the product with traditional cooling was 0.395 mm, and that of the product with conformal cooling A1 was 0.231 mm. The amount of warpage was lowered by 71% when conformal cooling was utilized.

As per shown Fig. 13, B1 CCC has the shortest cooling time of 21.1 seconds therefore, it's the most cost saving options with the least machine cost involve and more output than the rest of the options. Conformal cooling type B2 has a slightly longer time of 1.8 seconds in total. The traditional baffle cooling channel has the longest cooling cycle of 30.4 seconds. Total improvement of cooling cycle time saving is 44%.

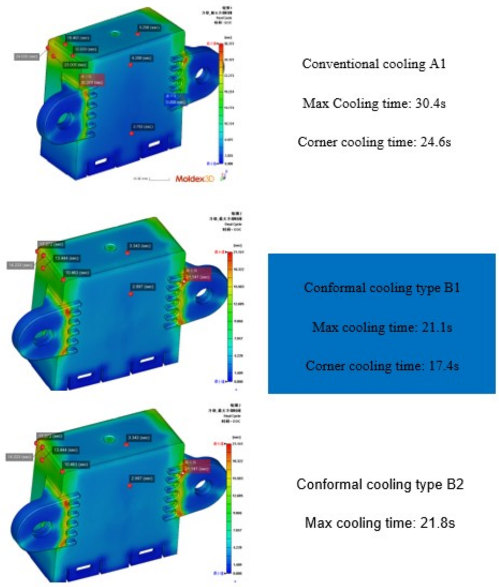

Fig. 13: Maximum cooling time saving under different cooling channel options.

5. Conclusion

Innovative technology of conformal cooling channel allows manufacturer to have the maximum quality assurance and biggest cost saving. This works shown the significancy of optimizations in conformal cooling channel design. In this investigation, the optimization of additive manufactured conformal cooling channel was put forward, and the quality characteristic of shrinkage is concerned using Taguchi method. The obtained results are summarized as follows:

(1) The Taguchi optimization method was utilized to find the optimum levels of design parameters for the cooling channel in insert core. The surface temperature of the insert core can be cooled without additional process time.

(2) The shrinkage on an automotive seating housing can be improved significantly by decreasing the surface temperature of the conformal insert core. The amount of warpage was reduced by 71% when

conformal cooling was employed, and total improvement of cooling cycle time saving is 44%. This result indicates the insert core can efficiently reduce the shrinkage problem.

(3) Because the shape of cooling channel in the insert core can be designed freely, the insert core can be adapted to other complex-shaped products.

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