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Heating/cooling channels design for an automotive interior part and its evaluation in rapid heat cycle molding

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ABSTRACT

Rapid heat cycle molding (RHCM) is a recently developed innovative injection molding technology. Rapid heating and cooling of the injection mold is the most crucial technique in RHCM because it not only has a significant effect on part quality but also has direct influence on productivity and cost-efficiency. Accordingly, Heating and cooling system design plays a very important role in RHCM mold design. This study focuses on the heating/cooling system design for a three-dimensional complex-shaped automotive interior part. Heat transfer simulation based on finite element analysis (FEA) was conducted to evaluate the thermal response of the injection mold and thereby improve heating/cooling channels design. Baffles were introduced for heating/cooling channels to improve heating/cooling efficiency and uniformity of the mold. A series of thermal response experiments based on full factorial experimental design were conducted to verify the effectiveness of the improved heating/cooling channels design with baffles. A mathematical model was developed by regression analysis to predict the thermal response of the injection mold. The effects of the cavity surface temperature on weld mark and surface gloss of the part were investigated by experiments. The results show that the developed baffle-based heating/cooling channels can greatly improve thermal response efficiency and uniformity of the mold. The developed mathematical model supplies an efficient approach for precise predication of mold thermal response. As the cavity surface temperature raises to a high enough level, automotive interior parts with high gloss and non-weld mark surface can be obtained.

1. Introduction

Injection molding process is one of the most widely used methods for manufacturing plastic product due to its high efficiency, high performance and also net-shape manufacturing of complex shaped parts. A typical injection molding process incorporates filling, packing, cooling and ejecting. Generally, cooling stage takes up more than half of molding cycle. Since the cooling time is mainly dependent upon mold temperature for a specific plastic material and product, mold temperature has a significant effect on molding cycle and productivity. The lower mold temperature is, the higher molding productivity is. However, a lower mold temperature usually means lower part quality in conventional injection molding (CIM) process. In CIM, mold temperature is usually kept at a constant level during the whole molding cycle although in fact it fluctuates in a relatively small range due to the commonly used continuous cooling method by circulating the coolant through cooling channels. To achieve rapid solidification of plastic melt and acquire high productivity, mold temperature should be much lower than the transition temperature of the plastic material. Such low mold temperature makes it inevitable that polymer melt solidifies prematurely in filling stage once it contacts the cold mold wall. The premature solidification of the polymer melt leads to a frozen layer formed at the cavity wall during filling, which results in many inherent defects on the finally molded products, such as weld mark, flow mark, silver mark, large residual stress, and short shot [1–3].

To solve the inherent defects in CIM, an innovative injection molding process based on dynamic mold temperature control was developed in recent years [4]. In the new molding process, the injection mold is alternatively heated and cooled rapidly to achieve rapid thermal cycle. That is why it was called rapid heat cycle molding (RHCM). In RHCM, the mold cavity will be heated to a preset high level, usually higher than transition temperature of the plastic material, therefore premature cooling of the melt and the resulted frozen layer during filling stage can be completely prevented. After finish of filling, the mold and plastic melt is cooled

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rapidly to shorten molding cycle. According to mold temperature variations, RHCM process incorporates heating, high-temperature holding, cooling and low-temperature cooling. Heating and cooling stages take up most parts of the whole molding cycle. Coupling with good heating and cooling system design, RHCM can achieve isothermal filling without sacrificing the molding cycle. Therefore, rapid mold heating and cooling plays a very crucial role in RHCM. For rapid mold heating, researchers have developed diverse methods, including surface heating methods such as flame heating [5], inductive heating [6], infrared heating [7], and resistive heating [8], and massive heating methods such as convective heating by circulating hot fluid through channels in the mold [9] and electric heating by equipping electric heating elements in the mold [10]. For rapid mold cooling, the most efficient and simplest method is to cool the injection mold by circulating low-temperature coolant rapidly through the cooling channels.

At present, one of the most widely and successfully used rapid mold heating and cooling technology in injection molding industry is based on high-temperature steam heating and low-temperature water cooling. Steam and water are controlled to alternatively pass through the same or separate channels in the mold to heat and cool mold cavity. The heating/cooling channels design is of great significance for rapid and uniform heating and cooling of mold cavity, thus improving part quality and productivity. In the field of optimization design of heating/cooling channels, researchers have conducted some works in recent years. By integrating response surface methodology (RSM) and genetic algorithm (GA), Li et al. [11] developed an optimization design method for heating/cooling channels to improve heating efficiency and uniformity of the cavity surface. Based on RSM and particle swarm optimization (PSO), Wang et al. [12,13] developed an optimization design method for heating/cooling channels to acquire the optimal heating/cooling efficiency, heating/cooling uniformity and also mold strength. Three optimization strategies were proposed to meet different requirements for efficiency, uniformity and mold strength. To improve heating efficiency and temperature uniformity, an optimization method by integrating multi-objective evolutionary algorithm and multi-attribute decision-making method was developed by Wang et al. [14] to optimize the positions of heating/cooling channels. Although these developed optimization design methods for heating/cooling channels can improve heating/cooling efficiency and uniformity effectively, they are mainly focusing on the plastic product with relatively simple shape and the heating/cooling channels in the related RHCM mold only have a two-dimensional distribution. For RHCM mold with three-dimensional complex cavity structures, conformal heating/cooling channels should be considered for rapid and uniform heating/cooling of mold cavity. Conformal heating/cooling channels are the heating/cooling channels conforming to the surface of the mold cavity. They can be fabricated by U-shape milled groove using computer numerical control (CNC) milling machine [15] or three-dimensional (3D) printing [16–19]. It is worth mentioning that 3D printing has been developing rapidly in recent years. It can be used to fabricate heating/cooling channels with arbitrary 3D structures [19–21]. Simultaneously, the fabricated mold tooling also has high enough strength to meet the requirements for high-volume production of injection molding. However, the manufacture cost by 3D printing, especially for the large injection mold, is still too expensive, which limits its wide application at present. Based on the conventional machining process of straight drilling, convention strait-line heating/cooling channels coupling with baffles or bubblers is also capable of producing complicated conform heating/cooling channels [22,23].

The main objective of the current research was focused on the design of the heating/cooling channels for a three-dimensional complex-shaped plastic part produced by RHCM based on steam heating and water cooling. Baffles were introduced in the heating/cooling channels to improve heating/cooling efficiency and uniformity. Thermal analysis tools were utilized for evaluation and optimization of the heating/cooling design. A series of thermal response experiments with different heating/cooling time settings were conducted to analyze the thermal response characteristics of the injection mold and verify the designed heating/cooling channels. A polynomial mathematical model was developed by regression analysis to predict thermal response of the mold and facilitate heating/cooling parameter settings. Finally, an experimental system based on the designed RHCM mold and heating/cooling equipment was built to investigate the effects of RHCM process on part quality.

2. Original design

As shown in Fig. 1 is the structure of the automotive interior plastic part. This part has a complex three-dimensional structure and three through holes. Since the polymer melt will firstly separates and afterward converges around these through holes during filling stage, the weld or meld lines on the final molded plastic part surface are generally inevitable in CIM. That is one of the reasons why RHCM process was used for this plastic part. The plastic material used for the part is polycarbonate (PC) typed LEXAN Resin 123R supplied by SABIC Innovative Plastics in USA. It has a density of 1.2 g/cm^3 and a melt mass-flow rate of 17.5 g/10 min. Its glass transition temperature is as high as 155 °C, which indicates a very high cavity surface temperature during filling is needed for elimination of weld marks in RHCM. The recommended processing parameters by the manufacturer are given in Table 1.

Since the automotive interior part requires a high standard of appearance, submarine gates were selected, as shown in Fig. 2. The tip size of the submarine gates is Φ 2.0 mm. By considering filling balance, injection pressure and manufacturing cost, two submarine gates were utilized. To avoid jetting marks, the part region adjoining one of the submarine gates, the purple region in Fig. 2, is properly thickened by 1.0 mm. For another gate, a small splicing area, as shown in the blue[1] area in Fig. 2, is added to prevent gate mark occurring on the outer surface of the part. To reduce plastic waste and improve part quality, hot runner systems are used. For rapid heating and cooling of the mold cavity side, a series of straight line-drilled heating/cooling channels in the original design case were used, as shown in Fig. 3. All the heating/cooling channels have the same diameter of 8.0 mm. The distance between the centers of the adjacent heating/cooling channels is about 18 mm, which is about 2.3 times of the channel diameter. Owing to the irregular outer surface of the cavity surface, the distances from the centers of the heating/cooling channels to the cavity surface are not even, about 2–3 times of the channel diameter. Since the inner surface of the plastic part does not require a high surface quality, convention continuous cooling method was used for the corresponding core side of the mold. The cooling channels with baffles in the core side of the injection mold are shown in Fig. 4.

As aforementioned that one of the reasons for using RHCM process is to eliminate the weld marks on the part surface, prediction of the positions of the weld marks in advance are of great significance to guide heating/cooling channels design. For this reason, the commercial analysis software for injection molding, Autodesk Simulation Moldflow insight, was utilized to simulate the filling process and predict the possible positions of weld marks. Fig. 5 shows the predicted weld mark positions. Corresponding to the

[1] For interpretation of color in Fig. 2, the reader is referred to the web version of this article.