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Research on temperature and pressure responses in the rapid mold heating and cooling method based on annular cooling channels and electric heating

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ABSTRACT

Rapid heat cycle molding (RHCM) is an advanced injection molding technology for producing spraying-free plastic products with excellent appearance. Rapid mold heating and cooling is the key technique of RHCM. Despite widely used in practice, the regular rapid mold heating and cooling methods still have some obvious defects. Thus, the authors developed a new rapid mold heating and cooling method characterized by electric heating and annular cooling, and this study experimentally investigated its temperature and pressure responses in the heating and cooling periods. The results show that the tool surface temperature increases almost linearly with the heating time after a short response time. The larger the heating power or the smaller the distance from heater to tool surface, the faster the heating rate. Introducing air bubbles into working fluid can remarkably reduce the pressure growth of working fluid without affecting the heating rate. In the investigated range of flow rate, the cooling rate firstly increases significantly with the flow rate, and then reaches a plateau, while the running pressure of working fluid increases linearly with the flow rate in the whole range. The optimum flow rate is around 6.0 L/min corresponding to the Reynolds number of 6700. The heat transfer coefficient in cooling period increases sharply at the initial stage, and then reduces gradually, and finally reaches a plateau. The larger the Reynolds number the higher the heat transfer coefficient. In particular, the heat transfer coefficient and the Reynolds number show a linear relationship on the double logarithm scale. Finally, a mathematical model was developed for predicting and controlling the temperature fluctuation range of tool surface. Thus, this study can benefit the industrial application of the new rapid heating and cooling method.

1. Introduction

Rapid heat cycle molding (RHCM) is an advanced injection molding technology that was developed about ten years ago to overcome the inherent defects of the regular injection molding (RIM) process [1]. In RIM, mold temperature is controlled by circulating coolant through the cooling channels in injection mold. Generally, the coolant temperature is kept at a preset value to maintain the desired mold temperature over the whole molding cycle [2,3]. In order to shorten the cooling stage which normally occupies more than half of molding cycle [4,5], the set mold temperature is thus much lower than the required ejection temperature of product. This rather cold mold causes the hot melt to freeze in advance during melt filling, which brings a series of appearance defects of product, such as silver mark, weld mark, rough surface, and fiber streak. Unlike the static mold temperature control method in RIM, a dynamic mold temperature control method based on rapid mold heating and cooling is adopted in RHCM. The injection mold is rapidly heated to a high temperature right before melt filling while it is rapidly cooled after melt filling to shorten the molding cycle. In this case, the premature solidification of polymer melt once touching the cold cavity wall can be avoided, and hence the surface defects appearing in RIM product can be reduced or even eliminated [6–10]. Moreover, thanks to the high mold temperature during filling, the micro/nano features of mold cavity can be accurately replicated by polymer melt [11,12]. In particular, it has been reported that the high mold temperature during filling can also help to improve the surface appearance of foamed product by removing silver/swirl marks in foam injection molding [13,14]. More importantly, the enhanced cooling after filling in RHCM can effectively shorten the cooling time, thus reducing the

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adverse effect of high mold temperature on process economics [15,16].

Rapid mold heating and cooling plays a pivotal role in RHCM process. While the regular cooling method by circulating coolants through cooling channels is commonly used in different rapid mold heating and cooling methods, various rapid mold heating methods have been explored in the past two decades [7,8,17]. Generally, the current mold heating methods can be divided into two categories: passive heating and active heating. In the former one, metal mold cavity is coated with a thin layer of insulation material which can prevent heat diffusing from the hot polymer melt to the cold metal mold, and subsequently the mold cavity surface is heated by the hot polymer melt itself [18,19]. Although the passive heating does not need any additional heating device, the complicated coating process and the weak strength of coating layer limit its application in industry. In the later one, extra heating devices or sources based on induction heating [20,21], infrared heating [22,23], hot-gas heating [24,25], resistance heating [26,27], or steam heating [28,29] are needed for rapid mold heating. Among the existing heating methods, the resistance heating method using cartridge heaters and the steam heating method by circulating high-temperature steam through heating channels are the most widely used two technologies in industry. In fact, the RHCM process based on the two rapid mold heating methods has almost completely replaced the RIM process in some areas for producing high-gloss and weld mark-free plastic products which do not need any secondary processing, such as sanding and painting. The representative industrial products include LCD TV panels [15,27,28], automotive interiors [7], and other exterior pieces [30].

Although the steam heating and electric heating methods have been widely used in industry in recent years, they each have some shortcomings. Regarding the steam heating, a high-pressure and high-temperature steam boiler, and the supplementary pipelines and valves for steam transportation are required [31]. This will not only significantly increase the cost of equipment, but also bring some potential security issues. Moreover, it is difficult to recycle the steam running out of the injection mold, which leads to a lot of energy waste. In contrast, the electric heating method has a rather simple heating system which is more compact, safer and cleaner. However, it involves a much more complex mold structure because many heating elements should be mounted into the injection mold, particularly considering the interference between them and the cooling channels. Moreover, it is hard to take these elements out of the injection mold because they are usually stuck strongly in the long mounting holes. In this situation, the replacement of heating element becomes very troublesome once it is damaged. Furthermore, as the heating elements have to be placed between the mold cavity surface and the cooling channels, the distance from the cooling channels to the mold cavity surface is subsequently enlarged [15,31], and it thus leads to a relatively low cooling efficiency. To solve the above problems, we developed a new rapid mold heating and cooling method by combining the advantages of the steam heating and electric heating methods [17]. In the new method, the cartridge heater is inserted into the mounting hole with a diameter larger than the heater's diameter, and the annular space between the heater and the mounting hole is used as cooling channel. Thus, it becomes very easy to insert or take out the heater, and meanwhile the distance from the cooling channel to the mold cavity surface can be shortened to achieve a high cooling efficiency. In addition, thanks to the elimination of extra cooling channels, not only the hole-drilling workload can be reduced, but also the mold stiffness and strength can be improved. Due to these advantages, the new rapid heating and cooling method shows a promising future not only in the field of rapid heat cycle molding but also in other industrial areas where an efficient heat exchange is needed.

In our earlier work [17], the temperature response behavior of this new rapid mold heating and cooling method has been investigated by numerical simulation. The focus of that work was to clarify the factors affecting heating efficiency and temperature uniformity, and also to check the feasibility of the new rapid mold heating and cooling method in industrial applications. The objective of the current study is to experimentally investigate the thermal response behavior of the new rapid heating and cooling method. Special attention is paid to the pressure response of working fluid in the closed annular channel because it is found that the pressure rises rapidly during heating. Furthermore, an effective method is proposed to reduce the pressure growth and hence prolong the heating time, and thus the tool can be heated to a much higher temperature. Moreover, the coolant flow rate is regulated to investigate its influence on cooling efficiency. Consequently, a reasonable range of coolant flow rate is specified by balancing the cooling efficiency and the pressure drop as the coolant passing through the annular channels. Finally, a full factorial experiment design is conducted to investigate the influence of the heating time and the cooling time on the temperature response of tool surface in cyclic heating and cooling process. A mathematical model is further created for regulating the temperature response of tool surface. The findings of this study helps to promote the practical application of the new rapid heating and cooling method.

2. Experimental setup and procedure

To investigate the thermal and pressure responses of the new rapid mold heating and cooling method based on annular cooling channels and electric heating, a special experimental facility was developed as schematically shown in Fig. 1. The whole facility can be divided into three parts: the rapid heating and cooling system composed of a cartridge heater and a coolant circulation pipeline, the control system based on programmable logic controller (PLC) and human machine interface (HMI), and the data recording system composed of a high-speed data acquisition card and a personal computer (PC) which is installed with the software for data recording.

For rapid heating, the cartridge heater with a diameter of 8 mm and with a length of 480 mm was used, and it has a total power of approximately 2000 W under the rated voltage of 400 V. The cartridge heater was inserted into a tubular steel tool. As the mounting hole had a diameter (Φ10 mm) larger than the cartridge heater's diameter, an annular channel with a thickness of 1 mm was thus created between the heater and the steel tool, as Fig. 2 shows. In order to speed up heat diffusion and enhance heating rate, the annular channel was filled with working fluid (pure water in this study). In the heating period, the working fluid is enclosed in the annular space by using two air pneumatic reversing valves (valve I and valve III in Fig. 1). By doing so, heat loss caused by the flow of working fluid can be minimized. However, the pressure of working fluid will definitely increase gradually during heating due to thermal expansion, which is not desirable. For this reason, one of the major objectives of this study is to investigate the pressure response of working fluid, and to find an effective way to reduce the pressure growth during heating. After heating, the two reversing values are opened to circulate the working fluid through the annular channels so as to cool the steel tool. After cooling, the valve I and valve III are turned off sequentially to enclose the working fluid in the annular channel, and meanwhile the valve II is turned on to transport the water from the pump directly to the coolant tank. Afterwards, it enters the second thermal cycle, and the heater is turned on again to heat the tool.

For the temperature measurement, two fast-response thin film thermocouples (ST-50, Nippon Rika Kogyosho, Japan) were sticked