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Thermal optimization of deterministic porous mold inserts for rapid heat cycle molding

Luca Crema, Marco Sorgato, Giovanni Lucchetta *

Department of Industrial Engineering, University of Padova, via Venezia 1, Padova, Italy

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ABSTRACT

In this work a porous mold insert with a regular deterministic geometry was developed and its design was optimized by means of numerical simulations to maximize the heat exchange in Rapid Heat Cycle Molding (RHCM) between water and the cavity surface, without impairing the mold structural integrity. Compared to previous fluid convection technologies, such as steam heating and pressurized water in metal foam inserts, the optimized porous inserts performance is significantly higher, having a maximum heating rate of 7 °C/s and a mean heating rate of 6 °C/s. A testing mold with the optimized porous inserts was developed to validate the numerical simulations and to characterize the RHCM influence on the surface quality of fiber-reinforced polypropylene parts. Parts surface roughness decreases increasing mold temperature, packing pressure and injection rate. Moreover an increase of mold temperature attenuates the effect of injection rate on roughness. Therefore, with this RHCM technology it is possible to obtain a high quality fiber-reinforced part even at low injection speed.

1. Introduction

Injection molding is one of the most widely used processing technologies in the plastics industry. The mold temperature control technique adopted in conventional injection molding is the continuous cooling method: water is circulated in the cooling channels at constant temperature to cool the mold and the polymer melt. As a result, a solidified layer develops at the cavity surface and it progressively thickens, increasing the flow resistance and decreasing the mold-filling ability of the polymer melt [1]. This well-known phenomenon is used to explain some of the most critical injection molding defects, such as weld lines [2], sink marks and short shots [3]. Moreover, molding micro features is even more critical because the higher the feature surface-to-volume ratio the faster the polymer solidification [4]. In molding fiber-reinforced thermoplastics with the conventional process (CIM), the poor surface aesthetic of the product significantly limits its application where the product appearance is fundamental [5]. To overcome these limitations, the Rapid Heat Cycle Molding (RHCM) technology, also known as Variotherm [6], has been increasingly used in recent years [7]. In RHCM, before injecting the melt, the mold is firstly heated to a preset temperature, which is kept constant during the filling and packing phases. When the gate solidifies the mold is rapidly cooled to allow the solidification of the polymer melt [8]. For amorphous polymers, the cavity surface is usually heated up to a temperature that is slightly higher than the polymer glass transition temperature (T_g) [4].

Among all available RHCM technologies, electrical resistive heating is the most widely used for rapidly heating the mold. In this technology, electric resistances are positioned inside the mold to heat the cavity surface, while the cooling is performed with conventional cooling channels [9]. Alternatively, mold temperature can be rapidly varied using high-frequency proximity effect induced heating, combined with water-cooling [10,11]. Infrared radiation was also applied for heating the cavity surface [12]. However, these technologies require high initial investments in mold making [13]. Therefore, a more economical approach to thermally cycle the cavity surface temperature, which consists in alternatively circulating hot and cool water in the mold cooling channels, is often preferred. The use of pressurized water as operative fluid simplifies the whole system and it allows to reduce the initial investment and the operating cost [14]. Conformal channels are used to ensure a high thermal exchange and a uniform temperature along the mold cavity [15–19]. Li et al. have numerically investigated the heat transfer in RHCM, optimizing the temperature distribution uniformity [16]. They noticed that the optimization of the distance between heating channels greatly increase the uniformity of the mold temperature. Wang et al. have carried out numerical simulations for heat transfer and fatigue analysis

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* Corresponding author.
E-mail address: giovanni.lucchetta@unipd.it (G. Lucchetta).

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to investigate the effect of the conformal thermal control system on cycle efficiency, structural strength, and mold fatigue life [17]. Comparing with conventional injection molds, the working conditions of RHCM molds are relatively worse due to the thermal stress resulted from cyclic mold heating and cooling. Zhao et al. showed that thermal stress, deformation and fatigue life can be systematically analyzed using the finite element method (FEM) [20,21].

A more efficient water-based solution was recently developed using a modular mold, where bearing ball-slots are located in proximity of the cavity wall and connected in series with the cooling channels [22]. Fiorotto et al. have replaced bearing balls with inserts made of open-cell aluminum foam, which allow high thermal diffusivity and high surface-to-volume ratios for heat transfer [4]. However, some disadvantages limit the implementation of this solution, such as the low stiffness and the high purchase cost of the open-cell foams. Furthermore, the aluminum foam structure is completely defined by its density and it cannot be varied by design. Therefore, it is not possible to increase the thermal and structural performance varying the design of aluminum foams.

In this work, an innovative RHCM system was developed replacing the traditional cooling channels with deterministic porous inserts placed behind the mold cavity surface and geometrically optimized through numerical simulations. The optimization was carried out developing a series of thermal and mechanical simulations with the aim of defining the most suitable inserts geometry to maximize the thermal exchange without impairing the mold integrity. The purpose of this study was to overcome the limitations of the available technologies concerning the cycle time and the mold temperature uniformity. A testing mold was developed with the aim of validating the numerical simulations and characterizing the RHCM influence on the surface quality of fiber-reinforced polypropylene parts.

2. Design of the porous mold inserts

The objective of this work was the development of a new porous insert solution with a deterministic geometry in order to achieve the requested stiffness and further enhance the thermal exchange between the mold cavity and the circulating fluid. To achieve a comparable result with the previous stochastic solution, the same mold used by Fiorotto et al. was used [4]. This mold has two cavities with a flat rectangular geometry (150 × 20 mm) and a uniform thickness of 4 mm.

The design strategy was based on the initial mold constrains. The deterministic porous inserts had to replace the metal foam inserts. Therefore, their overall dimensions were already constrained: a parallelepiped with the base dimensions of 33 × 90 mm and height of 20 mm. The original cavity plate is 9 mm thick while the part thickness is 4 mm. Therefore, the distance between the inserts and the cavity was set to 5 mm, as a tentative design to be verified in terms of both mechanical strength and thermal response efficiency. It is important to emphasize that the optimal distance between the inserts and the cavity depends on the cavity geometry. Larger injection molds for more complex parts might need thicker plates to distribute the filling pressure. However, in this study the distance between the inserts and the cavity was set to 5 mm for the following reasons:

- to compare the results with the previous stochastic solution [4],
- to propose a tentative design that was as similar as possible to a working solution,
- to take advantage of an existing experimental setup.

As a consequence of the mold design, the porous inserts are subjected to the cavity pressure loads induced by the polymer injection. Therefore, they were designed both to increase the thermal exchange between the mold cavity and the circulating fluid and to withstand the filling pressure. To achieve the first purpose, the contact area between inserts and cavity plate has to be as high as possible keeping an elevated surface-to-volume ratio. Besides the thermal properties, the porous inserts have to ensure a high resistance to mechanical stress since they are subjected to an alternate compressive stress.

Therefore, the design of the new porous inserts was guided by the following requirements:

- high contact area between the inserts and the cavity plate,
- elevated surface-to-volume ratio,
- high exchange surface between water and inserts,
- good stiffness and resistance to compression loads,
- good manufacturability.

According to these requirements, the new porous inserts were designed overlapping a series of perforated sheet-metal blanks. The holes were made by laser cutting and had a square shape, as shown in Fig. 1.

Arranging the perforated sheet-metal blanks by overlapping the square holes (Fig. 2(a)), it is possible to obtain a labyrinth structure of channels through which the pressurized water can circulate (Fig. 2(b)). All of the sheets were realized with the same geometry but assembled with a layer-by-layer offset along the water flow direction in order to generate a particular labyrinth structure. This offset between the overlapped sheets was fixed to a half-hole length.

This solution allows a greater design freedom compared with the stochastic metal foams. In fact, there are more degrees of freedom that can be exploit: the shape and size of the holes, the thickness of the blanks and the arrangement of the different layers. Moreover, the fabrication of the proposed porous inserts is fast and economical. As shown in Fig. 1, the blanks were parametrically defined by the holes square side length (L), the rib thickness (t) and the sheets thickness (S). The value of t was fixed to 1 mm while the values of L and S were optimized by means of thermal numerical simulations.

3. Porous inserts optimization

The optimization was carried out through a series of thermal and mechanical simulations with the aim of defining a suitable inserts geometry that maximizes the thermal exchange without impairing the mold integrity.

3.1. Thermal modeling

A series of thermal simulations were developed using Ansys CFX to optimize the porous inserts geometry from the thermal point of view. The model hypotheses were the following:

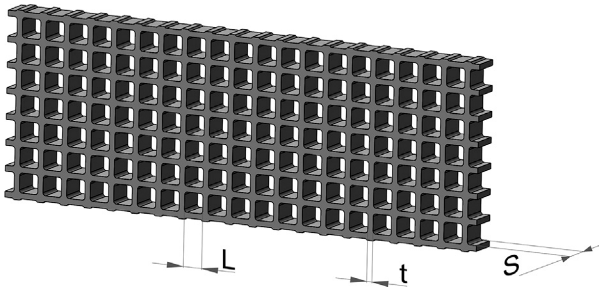

Fig. 1. The dimensional porous insert sheet characterization.