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A novel gas-assisted microcellular injection molding method for preparing lightweight foams with superior surface appearance and enhanced mechanical performance

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ABSTRACT

This paper proposed a novel gas-assisted microcellular injection molding (GAMIM) method by combining the gas-assisted injection molding (GAIM) with the microcellular injection molding (MIM). Firstly, under the assistance of the high-pressure gas from the GAIM, the amount of the polymer melt required for fully filling the mold cavity is reduced in the GAMIM compared with that in the MIM, thus leading to a high weight reduction of the foamed part. Secondly, the high-pressure assisted gas from the GAIM can dissolve all the cells generated in the melt filling stage back into the polymer melt, thus improving the molded part's surface appearance by eliminating the surface sliver marks. Thirdly, the secondary foaming process in a steady state triggered by releasing the high-pressure assisted gas makes the foamed part have a fine cellular structure and a compact solid skin layer, which can help to enhance the part's mechanical properties. In order to verify the effectiveness of the GAMIM, comparison experiments of the MIM and the GAMIM were conducted. The results demonstrate that the GAMIM can not only significantly increase the weight reduction, but also greatly improve the surface appearance and mechanical properties of the foamed part.

1. Introduction

Microcellular plastic is a kind of lightweight material which has many advantages including cost saving, good energy absorption and excellent insulation performance. It has presented wide applications in many industries such as packaging, construction and automotive. Microcellular plastic was first developed by Suh in 1980s [1,2]. Then its fabrication techniques were developed from the original batch foaming to the continuous foaming such as extrusion foaming [3,4] and microcellular injection molding (MIM) [5–9]. Compared with other foaming techniques, the MIM is the only technique that can produce foamed plastic parts with complicated three-dimensional geometries. Despite its advantages, the MIM still has some distinct shortcomings such as a limited weight reduction, inferior appearance, and poor mechanical properties, which seriously restrict its large-scale application.

In the regular microcellular injection molding, the foaming process is confined in a closed mold cavity. To fully fill the mold cavity, a relatively high injection pressure should be exerted on the polymer melt. This high pressure in the confined space significantly inhibits cell growth, and therefore leads to a limited weight reduction of the foamed part. Generally, the maximum weight reduction of the foamed part for the MIM is less than 15% in most cases. In order to increase the weight reduction, the most effective way is through increasing the expansion space for foaming. Based on this strategy, a foam injection molding process combining the microcellular injection molding with the breathing mold (core-back or mold opening) technology was developed [10–15]. In this combination process, foaming is triggered by opening the injection mold with a certain distance after melt filling and packing stage. The opening distance of the mold can provide a large extra space for foaming, and thus the expansion ratio of the foamed part can be greatly increased. However, the breathing mold technology requires a special injection machine or specially designed mold with the function of mold opening. This significantly restricts its application in practice. Moreover, it is very difficult to precisely control the opening distance, which leads to the variation of the part's dimensions. Additionally, this combination process is also not fit for the product with a complicated geometry.

Foaming occurs in the melt filling stage for the regular microcellular injection molding. The deformed or ruptured cells at the melt flow front will be pushed to the cavity surface under the action of the fountain flow. At the relatively cold cavity surface, the deformed and ruptured

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cells will be further elongated due to the shear action, then solidify and form the common surface defects (silver marks) on the foamed part's surface [16]. Fundamentally, there are two approaches to solve the surface defects. One is reducing the deformed and ruptured cells at the melt front by using the gas counter pressure [17,18] or decreasing the gas concentration [19]. Another is improving the flow ability of the melt [20] at the cavity surface to dissolve the sliver marks back into the melt by using the rapid heat cycle molding [17,21–23]. For the first approach, using the gas counter pressure and decreasing the degree of gas supersaturation are all harmful to cell nucleation and growth, and thus are harmful to the weight reduction of the foamed part. For the second approach, although the sliver marks on the surface of the foamed part can be almost eliminated and the part with high glossy surface can be gotten, there are still sliver marks at the melt flow end and near the weld line [22], which are difficult to eliminate within the current technology level.

The cellular structure plays an important role in affecting the mechanical properties of the foamed part [24–26]. In the regular microcellular injection molding, the foaming process is coupled with the melt filling process. In this case, some of the growing cells will be significantly deformed, and are prone to rupture and coalescence to form large cells under the shear action of the fountain flow. This will lead to a non-uniform, irregular and inferior cellular structure. Such undesirable cellular structure is harmful to the mechanical properties of the foamed part. To improve the mechanical properties of the foamed part, the most widely applied approach is via enhancing the polymer matrix by modification with additives [13,27,28]. However, this approach does not essentially solve the weakening of the non-uniform cellular structure to the polymer matrix.

To solve the current shortcomings of the microcellular injection molding, this paper proposed a novel gas-assisted microcellular injection molding (GAMIM) method by combining the microcellular injection molding (MIM) with the gas-assisted injection molding (GAIM). A GAMIM system was specially designed and built for the experiments. Both the MIM and GAMIM experiments were conducted to verify the effectiveness of the GAMIM. The weight reduction, cellular structure, surface appearance and mechanical properties of the foamed samples were characterized for comparison of the MIM and the GAMIM. The results demonstrate that the developed GAMIM method can significantly increase the weight reduction, improve the cellular structure and surface appearance, and also enhance the mechanical properties of the foamed part.

2. Gas-assisted microcellular injection molding

Fig. 1 illustrates the principle of the gas-assisted microcellular injection molding method. The whole process can be divided into four stages.

In the melt filling stage, a certain amount of high-pressure polymer/super critical fluid mixture in the barrel is injected into the low-pressure mold cavity, just like that in the regular microcellular injection molding. Due to the rapid decline of the pressure, cell nucleation and growth occur during the melt filling stage. Consequently, some of the cells are deformed significantly under the shear, extension and compression of the strong shear flow with a fountain effect at the melt front.

In the high-pressure assisted gas filling stage that follows, the pressurized gas from the gas-assisted control system is injected into the interior of the melt through the gas pin to push the melt filling the whole mold cavity. Thus, the amount of the polymer/super critical fluid mixture required for fully filling the mold cavity can be greatly reduced, and the weight of the foamed part can be further reduced compared with that in the regular microcellular injection molding.

After fully filling the mold cavity, the high-pressure assisted gas is held to build up a high and uniform cavity pressure which is then kept for a certain time. The high cavity pressure can crush all the cells either inside the polymer melt or on the surface of the polymer melt by

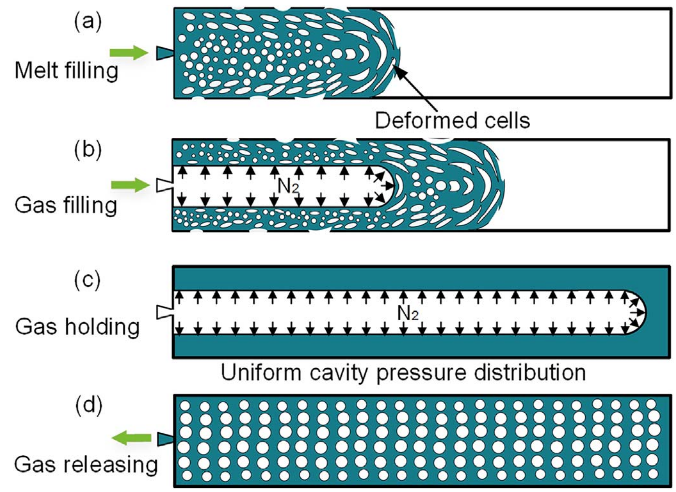

Fig. 1. The principle of the GAMIM: (a) melt filling; (b) high-pressure assisted gas filling; (c) high-pressure assisted gas holding; (d) assisted gas releasing and foaming.

dissolving the gas in the cells back into the polymer melt. Thus, the surface appearance of the foamed part can be improved by eliminating the sliver marks caused by the cells on the surface of the polymer melt.

In the last stage, the high-pressure assisted gas in the interior of the hollow polymer melt is released immediately to trigger a secondary foaming process. Because the secondary foaming process has no relation with the polymer melt filling process and occurs at a steady state, it can produce a finer and much more uniform cellular structure than the first foaming process in the melt filling stage. Moreover, the melt temperature can be easily controlled by varying the holding time of the high-pressure assisted gas to improve the melt strength, which plays a very crucial role in cell nucleation and growth, particularly for the semi-crystalline polymer. Additionally, the drop rate of the pressure can be easily controlled by changing the assisted gas's pressure and releasing flowrate. All these factors will benefit cell nucleation and growth, and contribute to a fine and uniform cellular structure.

Based on the GAMIM's principle, this paper constructed a gas-assisted microcellular injection molding system, as shown in Fig. 2. The injection machine, Borch BS800-III, has a clamping force of 8000 kN and a maximum injection pressure of 209 MPa. The control device of the super critical fluid, provided by Trexel Company, is used to accurately inject the physical blowing agent into the polymer melt with controlled pressure and flowrate. A shut-off nozzle is equipped at the front of the barrel to maintain the polymer/super critical fluid mixture within the barrel. The GAIM controller, supplied by Beijing Chn-top Machinery Company, offers the pressurized gas which is injected into the interior of polymer melt to form a hollow section of the part.

To verify the effectiveness of the proposed method, on the basis of a mold used for microcellular injection molding, we modified it into a mold for gas-assisted microcellular injection molding. Fig. 3(a) shows the cavity structure of the modified mold. It has a hot sprue in mold cavity center, two cylinder cavities, two rectangular cylinder cavities, four plate cavities, and six material storage wells. Considering the balance of melt flow, a block was used to block up the upper left of the mold, as shown as the blue enclosed area in Fig. 3(a). Four inlets of the high-pressure assisted gas were set on the lower right side wall of the mold. Four gas pins were respectively placed at the gates of the two cylinder and two rectangular cylinder cavities for injecting the pressurized gas into the polymer melt.

After injecting by using the gas-assisted microcellular injection molding mold, the injected parts with the shape shown in Fig. 3(b) were obtained. The cross section dimensions of the two cylinder samples are Φ10 mm and Φ15 mm, respectively. The cross section dimensions of the two rectangular cylinder samples are