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Gas-assisted powder injection molding: A study on the effect of processing variables on gas penetration

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ABSTRACT

Parts of polypropylene and of a stainless steel powder feedstock were molded by means of gas-assisted injection molding in epoxy cavities made by stereolithography. The design of the experiment method using the Taguchi L_9 array was implemented to test the effect of gas pressure, gas delay time, shot size and melt temperature on gas penetration depth and residual wall thickness. Simulations were conducted and compared with direct experimentation. Simulation predicted that the shot size was the only significant factor when processing polypropylene and the powder metal feedstock. The experiment showed that shot size and gas delay time were significant when processing polypropylene; and shot size, gas pressure, and melt temperature were significant factors when processing the powder metal feedstock. The residual wall thickness could not be controlled by the processing variables used in this study as the S/N ratios calculated were very small.

1. Introduction

Injection molding is a versatile and important operation for mass production of plastic parts with complex geometry. The injection molded parts typically have excellent dimensional tolerance and require almost no finishing. The process is also being extended to such materials as fibers and powders of metals, ceramics, and carbides with polymeric binders [1]. Powder injection molding (PIM) reduces manufacturing cost and savings of 20–40% are possible over traditional metal and ceramic processing technology [2]. However, the size of a typical PIM part is limited by the high cost of the powder. Economics also limits the part thickness because it defines both the time required for cooling and also the time required for debinding and sintering. For this reason gas-assisted powder injection molding (GAPIM) a combination of PIM and gas-assisted injection molding (GAIM) which produces powder metal parts with hollow cores is of interest. It provides cost effectiveness through considerable savings in debinding and sintering times [3].

GAIM technology utilizes injected gas to form hollow cores in the thicker sections of the part [4,5]. Fig. 1 shows the process of GAIM in four stages. In the first stage, a fixed amount of the plastic melt is introduced into the cavity as a "short shot" (less than the full volume of the cavity). In the second stage, the nitrogen gas is introduced and it takes the path of least resistance ideally along the center section of thicker channels that are at a relatively high temperature. In the third stage, the gas pushes the plastic melt from the thick section of the part to the unfilled extremities of the vented cavities, thereby filling the part and leaving a hollow section in the channels. The gas continues to apply pressure as the plastic cools, solidifies, and packs more efficiently. The pressure that is applied against the walls of the mold cavity is lower than the packing pressure used in conventional molding. Further, the gas is compressible and so applies a uniform pressure on the inside surface throughout the part. These result in better packing, thus minimizing sink marks and surface blemishes and lead to a more aesthetically pleasing part [6–8]. In the fourth stage, the part is completely cooled and the gas is vented before the mold opens.

A uniform material packing is one of the main advantages of gas-assisted injection molding and this is of particular value when using stereolithography cavities. Since nitrogen gas displaces some of the volume that is normally filled by feedstock, the total amount of heat that must be dissipated per part is smaller. The part cooling time is a function of the maximum distance from the surface to a point within the melt. Since the gas core diminishes the wall thickness in the thickest sections, the part cooling time is further reduced. It must be noted that the part design must be modified when using GAIM to accommodate thicker gas channels, but this can usually be achieved with some reduction in part weight [9]. Thus, GAIM likely leads to lower part weight and lower cycle times and less damage to the mold caused by temperature and pressure. Qingfa [10] also found that one

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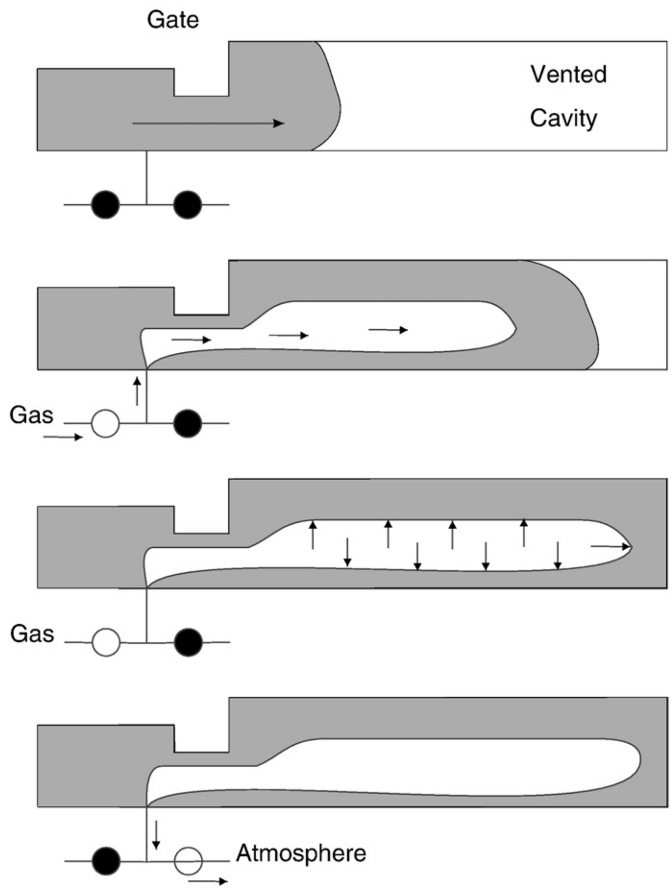

Fig. 1. Schematic diagram of GAIM.

of the most significant benefits of implementing GAIM to PIM is the quantity of material saved and the expansion of the component size limit.

The use of gas-assisted injection molding for rapid tooling is limited to those parts that can accommodate additional gas channels [11]. Surface defects due to the interaction between the polymer melt and the gas are possible [12]. In addition, new processing variables are introduced to the molding process control, and these include delay time, gas pressure, and gas time [13–15]. However, these disadvantages of GAIM are relatively minor compared with its significant advantages mentioned previously.

Michaeli et al. [16] studied GAPIM with various ceramic powder feedstocks. He found that specific thermal properties of materials used were of main concern in GAPIM. This is due to the high thermal conductivity of the powders compared to plastics. The thermal conductivity exhibited by ceramics was five times higher compared to PP. He also studied residual wall thickness and its distribution along the melt-flow path. Gas delay time was a parameter that exhibited importance with regards to residual wall thickness due to material high thermal conductivity. Results demonstrate that the wall thickness increased with a longer gas delay time. As a consequence of high melt, less material was pushed in the inner core. It was pointed out that gas delay time is the most significant parameter for influencing the residual wall thickness.

2. Methods and procedures

2.1. Processing materials

For the GAIM experiment, unfilled 13T10Acs279 polypropylene (PP) from Flint Hills Resources (Odessa, TX) was used. The stainless steel powder feedstock (SSPF) material used for GAPIM is a 316L stainless steel powder with a wax-polymer based binder from CetaTech (Sacheon, South Korea). The SSPF contains 59% 316L stainless steel powder in volume.

2.2. Part and mold design

In this study the effect of GAIM processing variables on gas penetration is of primary interest. The residual wall thickness (RWT) is also investigated. The geometry depicted in Fig. 2 consists of a hook shaped part with a 6.35 mm diameter cylindrical cross section that has a sequence of angular turns of 45°, 90°, 90° and 45°. Two cavities were built by stereolithography (SLA), one for GAIM and the other for GAPIM, as shown in Fig. 2.

2.3. Processing equipment

The mold cores and cavities were fabricated with DSM Somos® ProtoTherm™ 12120 resin. The molds were mounted into a Master Unit Die quick change insert with an 84/90 ALU 210 mold frame. Injection molding was performed through a 30 ton Boy 30 M injection-molding unit. The unit has a maximum stroke of 95 mm with a maximum barrel capacity of 37 G and a screw diameter of 28 mm. The fixed processing conditions for the experiment are listed in Table 1.

Nitrogen supply for GAIM was obtained through a nitrogen generator from Gain Technologies (GT-N2GA). Membrane separation technology separates compressed air into streams of 99.5% nitrogen and mixed oxygen with carbon dioxide traces. A gas control system from HEA International was used.

An embedded K-Type Omega TT-J-30-SLE wire thermocouple placed 2 mm below the surface of the part cavity was used to measure the mold temperature. Real time data from the mold was recorded using a National Instruments data acquisition board. The temperature monitoring system was calibrated with Omega HH21A temperature meter with 0.5 °C resolution. Mold temperature at the start of the shot was maintained at 30 °C. The mold temperature was monitored by the installed thermocouple and the cooling time was set to maintain constant mold temperature from shot to shot.

2.4. Design of experiments

The processing parameters under investigation are: melt temperature, shot size, gas pressure, and gas delay time, as these are known to be the most significant parameters for GAIM [5,13,15,17]. The processing windows were determined after preliminary molding experiments. Low, medium and high values that were chosen within the processing windows are shown in Table 2.

Process parameter variation was done through design of experiments (DOE) approach. In this study we adopted a 3^4 factor L_9 orthogonal array, which is called Taguchi method, as shown in Table 3. This DOE analysis is done in order to reduce the number of experiments while maintaining reliability.

In this study, our target function is to obtain maximum gas penetration depth and residual wall thickness. The statistic signal to noise ratio (S/N ratio) is the ratio of the power of the signal to the power of the noise. A larger-the-better S/N ratio calculation shown below was used to achieve maximum gas permeation:

$$S/N = -10\,log\frac{1}{n}\sum\frac{1}{y_i^2} \quad (1)$$

where n is the number of data and y_i is the measured data. The S/N ratio is used to identify the parameter values for the optimal result.