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The use of variotherm systems for micro injection molding

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ABSTRACT

Micro injection molding (μIM) is a fast-developing technology which is used to produce polymeric micro components or components with micro/nano scale features, such as are used in many fields including microfluidic diagnostics, micro needle drug delivery devices, micro gears and micro switches. The capabilities and performance of the micro-injection molding process can be improved by incorporating a variotherm system. This leads to improved component quality, especially for high aspect ratio features. It can also help to increase the polymer flow path, improve feature replication, reduce residual stresses and molecular orientations, and also can eliminate weld lines. This paper reviews the use of different variotherm systems in μIM, and describes how simulation of its use can provide insight when designing a mold cavity or a component with challenging micro features. The paper highlights important problems, challenges and areas for further

research. An increased understanding of these issues will provide opportunities to enhance further developments in the μIM process.

Key words: *Molding; Thermoplastics; Morphology; Microfluidics*

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Quanliang Su is a PhD student in UCD School of Mechanical and Materials Engineering. His research concerns polymer micro-injection molding, especially the influence of process conditions on filling and demolding, the morphology of molded parts and simulation of the demolding process.

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1 INTRODUCTION

The micro injection molding process is an enabling technology for manufacturing polymeric micro components and components with micro/nano scale features. In this process, molten polymer is injected into a mold cavity. After pressurized packing and cooling, the solidified polymer is ejected out of the mold cavity to complete an injection cycle, which then repeats continuously. During a single cycle, the polymer melt needs to be cooled and solidified in the mold cavity. This requires that the mold temperature should be lower than the heat deflection temperature (HDT)/glass transition temperature (T[illegible] [illegible]) of the semi crystalline/amorphous polymers. In the conventional injection molding process, there is normally a heater that maintains a constant mold temperature. This has advantages, such as being relatively inexpensive for producing commodity polymer components, being easy to control, and providing fast cycle times that typically range from seconds to less than one minute. However, the consequence of the temperature difference between the mold surface and the oncoming melt is that when the hotter melt contacts the cooler mold surface, a frozen layer will be formed. This will lead to a difference in the actual mold surface temperature and its pre-set temperature. In turn, the frozen layer can increase the difficulty of polymer melt filling for high aspect ratio structures, can reduce the quality or glossiness of the surface finish of components, and can cause an increase in residual stresses. Thus, the optical and mechanical properties of finished components are influenced by this temperature difference. Increasing the mold temperature during the filling stage prevents a frozen layer from adversely affecting the quality of molded components but it can also increase the cycle time, which is not ideal for mass production of polymer components.

Micro components weighing a few milligrams or large parts having micro/nano scale surface features share a common characteristic of having a high surface to volume ratio, up to 10^3-10^6 m^{-1}. Thus, the corresponding cooling rate increases by the same order of magnitude[1]. Because of the intrinsic low thermal conductivity of polymer materials, a notably high thermal gradient exists across the part thickness. Premature solidification always causes problem of insufficient filling, particularly for small features with high aspect ratios. Additionally, in the conventional process, in order to fill such small features, high temperatures and high injection speeds are applied to reduce melt viscosity by shear thinning and these materials experience correspondingly high stresses and shear rates. Such a variable thermomechanical environment influences the nucleation and growth rate of crystalline entities and forms a special hierarchical microstructure for microinjection moldings, which differs significantly from the conventional process. The corresponding process window becomes much narrower and limits the opportunity for optimization and controlling the final properties of a part.

The ideal molding condition is to have a hot mold during the injection stage and a cold mold during the cooling stage: this is the basic principle of a variotherm system. Such process conditions can simultaneously increase and decrease the molding cycle time. In reality, however, while changing mold temperature rapidly does improve the quality of molded components, it is also associated with many specific issues which have restricted the wide use of this technology.

Investigations on the rapid heating and cooling of mold began in the 1960s, which greatly contributed to the early development of variotherm systems. Boistad[2] invented a mold apparatus which had an additional electric heating source for the mold cavity; it provided heat along a mold surface as required. It was proven that this mold apparatus could substantially shorten the injection molding cycle. Thiess[3] invented an apparatus for manufacturing ceramics with electromagnetic induction heating or electric resistance heating. This apparatus provided an improved high strength, lightweight and high temperature, porous mold for manufacturing ceramic ware which could economically and quickly shrink parts within the mold for fast release from the mold, and which could be re-used without reconditioning. With the development of micro-electromechanical systems and biomedical industries, high precision requirements became increasingly necessary for many optical and medical components, with the result that most research on variotherm systems began to appear after 1990. However, early researchers focused on the whole mold volume or a large portion of the mold system when heating with a variotherm system. Obviously, rapidly heating and cooling such a large volume is time-consuming and wastes significant energy. More recent research has sought to heat only the surface portion of a mold prior to the filling process. Many different heating methods have been developed, such as electric heating, induction heating, gas heating, flame heating and infrared heating. Kim[4] developed a multilayered mold structure for hot surface molding in a short cycle time, in which an insulation layer provided on each of the mold cores retained heat at the molding surface, thereby increasing surface quality of the finished part. Yao et al[5] developed a rapid heating and cooling system consisting of one metallic heating layer and one oxide insulation layer; this system could raise surface temperature from 25 °C to 250 °C in 2 s and cool back down to 50 °C within 10 s. Wang et al[6] developed an electric heating mold structure with electric heating rods and cooling channels for a 32-inch LCD panel, their test production results showed that the dynamic mold temperature control systems could efficiently and accurately control the mold temperature. The LCD panels produced with this new variotherm injection molding process had a high surface gloss, without defects such as weld lines, sink marks, flow marks, etc. which usually occur in conventional molding. Wang et al[7] investigated a new electric-heating rapid thermal response mold with floating cavity/core for rapid heat cycle molding; results indicated the temperature distribution uniformity of the cavity surface was improved greatly with the optimal cavity structure and layout of heating rods. Chen et al[8] researched induction heating combined with coolant cooling for controlling mold surface temperature via ANSYS software simulation and verified their simulation results by experiments: their results indicated that surface weld lines marks were eliminated, and the associated weld line strength was enhanced. Kim et al[9] investigated incomplete filling of nanocavities with the aid of an induction heating system. Experimental results indicated that the nanocavities were successfully filled when the surface temperature reached 250 °C, but mold release caused drag damage on the nanogratings. Chen et al[10] used hot gas to heat a mold cavity surface; their results showed that hot gas heating can improve the filling process and achieve 91% of the high aspect ratio microgrooves (about 640.38 μm of the maximum of 700 μm). Wang et al[11] conducted feasibility experiments using two different dynamic mold temperature control methods with steam heating and electric heating, respectively. The results showed that the insulation layer could increase the upper limit temperature of rapid heat cycle molding (RHCM) with steam heating and improve the heating speed of RHCM with electric heating. Chen et al[12] also used a gas-assisted mold temperature control (GMTC) system to study injection molding of parts with fiber additives. Their results showed that when GMTC was applied to this process, the part surface was clearly improved. Jansen[13] and Chen et al[14] made some progress on electric heating by improving it with an insulation layer. Jansen[13] studied heat transfer in injection molding systems with insulation layers and heating elements. His results showed that measurements compared reasonably well with the predicted temperature response. Chen et al[15] used thermally insulated polymer film for mold temperature control to improve surface quality of microcellular injection molded parts. They found that the surface quality of parts can be improved greatly without any significant increase in cycle time when compared with parts molded without polymer film; meanwhile, the flow marks of gas bubbles on the part surface can be removed completely at a film thickness of 0.188 mm. Additionally, variotherm systems are also used to assist filling of micron and submicron size features and to adapt internal morphology to have better properties. For example, Chen et al[16] studied a micro injection molding process for biochips with micro-channel arrays via a gas-assisted heating system; their results showed that replication accuracies reached 99.8% when molding at a mold temperature of 150 °C and improved 21.4% over injection molding at the regular mold temperature of 80 °C. Sato and Kurosaki[17] investigated the influence of infrared radiation from an external source by heating the surface of the resin: it proved to be feasible for submicron replication and birefringence reduction by some tens of seconds irradiation. Yu et al[18] studied the effect of an infrared mold surface rapid heating system on micro-injection molding; the results showed that the mold cavity surface must be heated to above a critical temperature before molding, and the critical temperature was close to the glass transition temperature and it decreased with an increase of the packing pressure. Kolesov[19] investigated the mechanical behavior and optical transparency of polyamide 6 with different morphologies formed by variations of the pathway of crystallization. Resulted revealed that melt-crystallization at low supercooling led to the formation of lamellar α-crystals and spherulites, while at high supercooling the nodular mesophase was formed and the absence of spherulites in cold-crystallized PA 6 films led to high optical clarity.

Variotherm systems were first used in conventional injection molding to provide better component quality, e.g. to eliminate weldlines from light-guide plates, which are used widely in optical applications. However, μIM has many fundamental differences from conventional IM processes on account of scale effects. When the features of a polymer component are in the order of micrometers, the shear rate of polymer melt increases by order of magnitudes over mm-sized components. This is also associated with significantly higher mold temperatures. Clearly, using a variotherm system for μIM processes requires significantly different performance specifications than for conventional IM processes.

Although variotherm systems have been developed for research purposes, there are still some restrictions which affect their application in μIM, particularly in simulation of the micro injection molding process with a variotherm system. Simulation can highlight potential problems during the design stage. This can help to identify design changes required before the first tooling trials, thereby avoiding costly mold modifications. It can also assist in establishing an acceptable processing window. However, the micro injection molding process is not just a scaling down of the conventional injection molding process; it requires a rethinking of each step of the process, which indicates special requirements for the injection pressure, mold temperature, vacuum of cavity, shot size, cooling speed and demolding system. Additionally, there are many challenges associated with simulating micro injection molding: conventional sensors are large in comparison with micro parts, the molding process occurs at high speed which changes the rhelogical conditions for polymer melts, and various physical phenomena that are sensitive to scale effects will influence the accuracy of simulation results (such as wall slip, heat transfer across the polymer/mold surface, surface tension, and three-dimensional micro geometries). In addition, it is also difficult to validate such simulations.

Simulating μIM with a variotherm system can assist the use of this manufacturing technology in industry and in research. However, simulating the μIM process is quite different from a conventional macro scale IM process: no commercial software can simulate μIM directly, boundary conditions cannot be represented properly, and various physical phenomena such as wall slip are not considered. Such simulations are either undertaken using special commercial software or general CFD (computational fluid dynamics) software. Most μIM simulations only consider one or two factors or process variables and it is not possible to account for all factors simultaneously. This is the main reason why the results of simulation predictions differ so much from physical experiments, and it is also one of the main challenges of current research.

This review focuses on three aspects of variotherm systems and the micro injection molding process: (i) the introduction of various heating methods, (ii) the influence of the variotherm process on the performance of micro injection moldings, and (iii) progress on design and simulation for micro injection molding with the variotherm process. We will also share our perspectives regarding micro injection molding, the variotherm process and future applications.

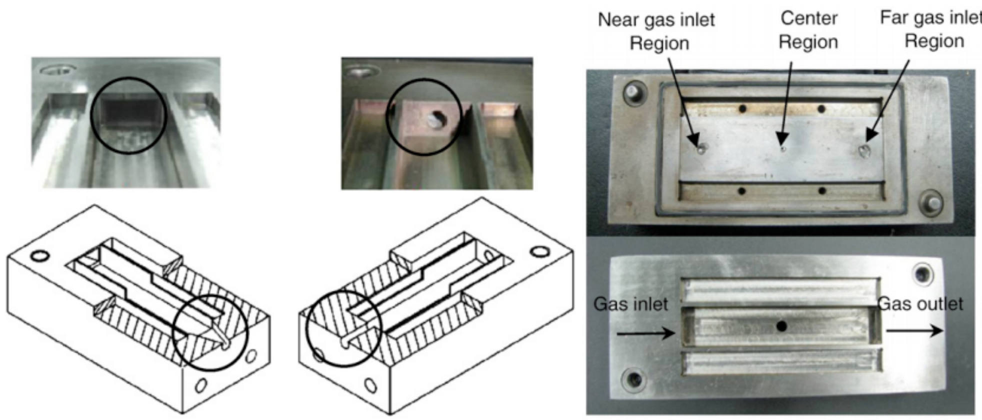
2 VARIOUS HEATING METHODS FOR VARIOTHERM PROCESS

In the variotherm process, mold surface temperature should be higher than the polymer no-flow temperature (T_g) during injection, and then cooled down rapidly to below the heat deflection temperature for precision injection molding. The heating method used in a variotherm system depends on the particular requirements for the micro injection molding process. The mold heating methods can be classified into four categories, depending on the type of heat supply.

2.1 Mold Heating by Convection

For mold heating by convection, a distinction is made between direct and indirect heating of the cavity surfaces. Dry hot air can be blown directly into a mold and fluids are used to heat the mold indirectly via fluid channels such as water, oil or steam.

Different kinds of convective heating methods are used in industry, principally gas and liquid. Heating oil is the most widely used medium in injection molding processes. Fu et al[20] conducted experiments which showed that microstructures of higher aspect ratio such as 60 µm diameter × 191 µm height and 40 µm diameter × 171 µm height could be injection molded with complete filling and demolded successfully using an oil heating variotherm system. Hanemann et al[21] also showed that many polymer-based micromolding technologies for manufacturing molds included the design of oil heating channels. However, the efficiency of these heating systems is quite slow and takes more than several minutes to provide a 100 °C change of temperature; this is because of the low thermal conductivity and low boiling temperature of oil. For this reason, high-temperature gas, hot air and steam are alternative convective media in variotherm systems; in particular, the steam heating method has recently been used in industrial applications. The advantage of steam compared to water is that there is uniform heat exchange with the mold inserts in the temperature control channels. Fig. 1 shows an example of a gas heating mold[22].



(1) Two gas channel shape designs (2) Experimental mold with gas heating

Figure 1 Design of the injection mold for gas heating[22]

Drummer et al[23] used an alternating temperature technology (ATT) to optimize the process to control a part's properties. The ATT system had two separate circuits in which water was held at different feed temperatures and can actively provide alternating heating and cooling, with the effect that an 80 °C change in temperature can be achieved in the mold inserts in less than 10 s, as shown in Fig. 2. Results showed that ATT optimized not only the rheological characteristics of the process but also the morphology, and hence the overall properties of the molded parts, without increasing the cycle time. Meister[24] investigated the influence of mold temperature of the flow length of a spiral shaped mold, for which the cross-section of the spiral had a dimension of 0.3 × 1.5 mm. The variotherm temperature control system used water as the circulating fluid and had a heating and a cooling circuit-switching device and allowed a fluid temperature of up to 200 °C. The combination of insulation from the master mold and conformal cooling channels enabled particularly rapid temperature changes in the cavity. Results revealed that a higher mold temperature led to a slight increase in flow length, but the effect was nearly constant with increasing injection pressure and it was also observed that transcending the glass or the crystallization temperature of the polymer material with the mold temperature has no effect on the achievable flow length of the material. The mold is convectively heated by the medium flowing through the channels. Further heat transport takes place by conduction and depends on the thermal conductivity coefficients of the steel used[25].

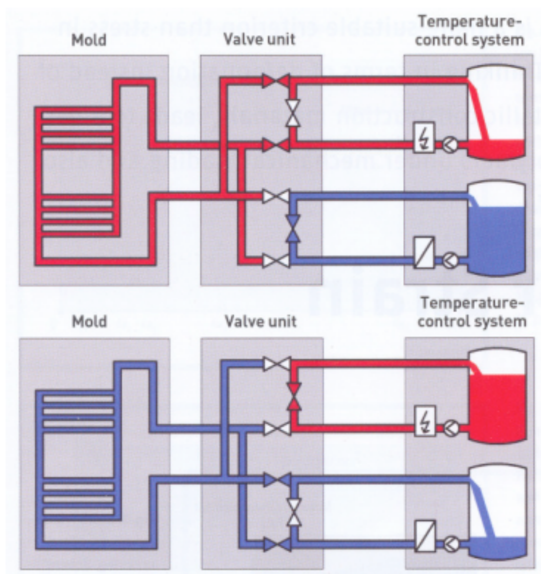


Figure 2 Alternating temperature control system cause hot and cold fluid to flow alternately through the temperature control circuit[23]

2.2 Mold Heating by Radiation

Radiation heat is transmitted rapidly to objects in the form of rays and waves. Chang and

Hwang[26] investigated a low cost and practical infrared rapid heating system for injection molding, and managed to raise the temperature of a mold's center surface from 83 °C to 188 °C in 15 s. Saito et al[27] used an external infrared radiation source for some tens of seconds to heat a mold surface: this reduced the birefringence that remained in the molded part. Yao and Kim[28] found that the filling length of a thin wall injection molding part increased significantly when using an infrared heating system. Yu et al[18] used infrared heating to heat a mold cavity temperature locally and achieved good replication of micro-features and observed that heating for more than 10 s could result in complete filling of the micro-features when the mold temperature was 80 °C. For example, a mold surface can be heated rapidly by an infrared heater through electric magnetic radiation. Similar to an induction heating coil, infrared lamps can be installed into a lamp holder that can be moved in and out of the space between the two half mold plates[26,29]; this principle is shown in Fig. 3. One problem using this heating method is that the temperature uniformity of the mold surface is not so good, due to the relatively large size of a typical lamp and the discrete nature of the heating source. Chang and Hwang[26] also used a reflector to focus the infrared energy to localised areas of a mold, such as the sprue, runners, gates or microfeatures. Wissmann et al[30] developed a new low-cost laser molding process for micro- and nanostructured components. A micro- or nanostructure feature in a mold was transferred to a thermoplastic polymer product based on a high power diode laser radiation (wavelength 940 nm) in different mold inserts made of silicon, glass or nickel and different thermoplastic polymers: polymethylmethacrylate, polystyrene, cyclo-olefin copolymers and polyether ketones. This work showed that moldings in a range of 100nm-300μm with an aspect ratio from 1 to 10 were possible by laser molding and this new process was flexible in using different mold inserts and molding materials and sizes. Hopmann and Schongart[31] employed an external high power diode laser scanner to the heat mold surface. The laser parameters, heating time, area-related energy density and the spot diameter, influenced the temperature profile during the heating period. A short heating time with high energy density was recommended for heating and this new innovative system proved to have a high heating rate.

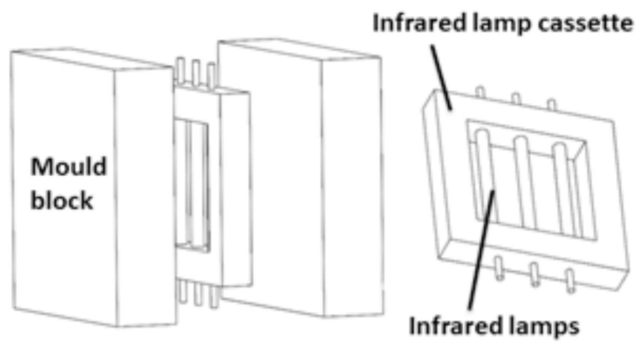


Figure 3 Mold heating by external infrared lamps

Based on the proximity effect, this method is similar to induction heating, as shown in Fig. 4. Yao et al[32] used high-frequency proximity heating to heat a mold with a cavity of 25 mm × 50 mm. The mold cavity could be heated rapidly from room temperature to 240 ºC in 5 s with an apparent heating power of 93 W/cm^2. Neither method requires an electric insulation layer beneath the mold surface compared with the electric resistive heating method. At the same time, proximity heating does not need an electric coil either in or close to the mold, which means that the mold can be heated even if it closes during injection. However, proximity heating is not suitable for uniformly heating a complex mold surface due to its poor flexibility.

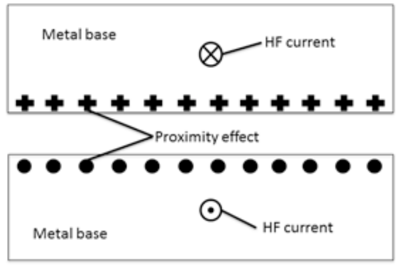


Figure 4 Principle of high frequency proximity heating

Based on dipole rotation, dielectric heating is used to heat a dielectric material, for example a polymer, through high frequency electromagnetic radiation. Akopyn[33,34] investigated uniform heating of a uniformly thick piece in a conventional microwave by selecting a dielectric mold material which has a relative thermosensitivity equal to that of the working material. Erwin and Suh[35] described a new molding material for dielectric heating, it was concluded that this process could eliminate the heating and cooling time associated with the conventional injection molding process; heating and cooling were accomplished in a time period of the order of 1s. When dielectric heating is used to rapidly heat a mold, the mold should be made from a dielectric material, which limits the development of this form of heating. However, this method is able to heat polymer and a metal mold at the same time and is a good complement to induction heating. Moreover, not so many polymers are suitable for the dielectric heating process, unless some additives are used.

2.3 Thermal Conduction with Heating Elements

Electrical resistance heating and heating cartridges are directly integrated into the injection mold; the generated heat reaches the cavity surface by conduction. Of the many heating methods, electrical resistive heating is the most widely used in variotherm systems, as illustrated conceptually in Fig. 6. For various reasons[29], low voltage and high current are required for this method, so proper resistance is the key to this design; the resistance should be neither too high nor too low in order to achieve efficient heating. Yao and Kim[28,36] investigated the use of flat shell molds with two different temperature plates to rapidly heat and cool a mold; they reported that an aluminum shell mold with a thickness of 1.4 mm could be heated from room temperature to 200 °C in around 3 s when the hot plate is at 250 °C. Moreover, from the perspective of mold geometry, having a material with an appropriate resistance is not easy to find, and there needs to be a metallic heating layer in the structure. For this reason, Chen et al[15] used specialized 82%PET+18%PC composite polymer films with very low thermal conductivity as thermally insulated material and stuck them on the surface of the mold cavity. The surface roughness decreased from 5.6 to 1.8 μm when the polymer film thickness increased from 0.125 mm to 0.188 mm, the surface quality could be improved greatly without a significant increase in cycle time. However, this method of sticking films on a mold surface is not suitable for a complex geometry mold surface. Godwin et al[37] improved the mold manifold and hot runner nozzle using thin film elements disposed along a melt channel between the manifold inlet and the hot runner nozzle, the thin film element may comprise a thin film heater in direct contact with molten resin and may be positioned to aid in the heating and flow management of the resin within the melt channel. Jansen[13,38,39] analyzed and tested a model for heat transfer with insulation layers and heating elements in injection molding systems. The assumption that the capacity of the insulation and heater may be neglected resulted in a small overprediction of the surface temperature by only 2-3 °C and the birefingence was removed most effectively by heating briefly before and during the injection stage. Kim and Niemeyer[40] applied an insulated and removable mold insert in the mold cavity; this insulation layer could retain heat at the molding surface and thereby increased the surface smoothness of molded parts.

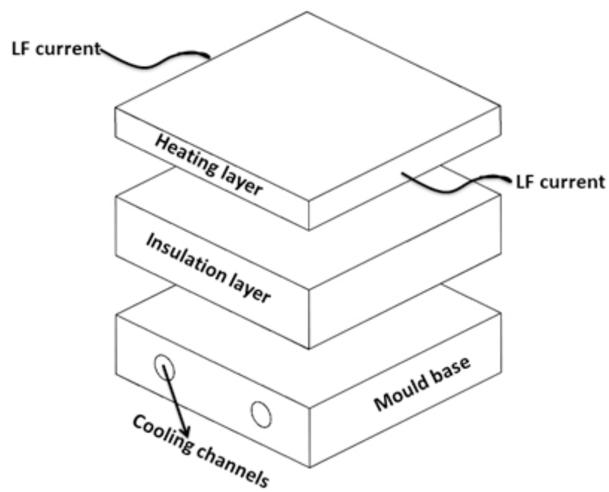


Figure 5 Electrical resistive heating schematic: LF indicates low frequency

The insulation layer can also be replaced by heaters depending on the mold layout requirements. This method has advantages over the oil heating usually used in conventional injection molding, such as being cheaper, faster and easier to implement, especially when injecting a thin-wall cavity. However, there are some disadvantages when using this method to heat the mold, because the heating channel or the heating layer exists in the mold interior, which means that the whole mold is heated, which requires additional machining and operating costs and long cooling times. If not designed properly, the fixed heating layout may not give a balanced uniform temperature profile, which is required for precision injection molding. Moreover, the heating layer can be destroyed easily after thousands of injection cycles through directly using the thin metal layer as a heating electrode.

As mentioned above, the mold surface temperature can be controlled by regulating the heating power prior to and when filling the mold, while the mold can be cooled by using a water coolant. It is quick and energy efficient to control the mold surface temperature in this way. However, heat conduction is a diffusion process, heating a thick mold would take considerable time, so this method is only suitable for heating thin shells, in which the geometry is simple and the mold material has a high thermal conductivity. For this reason, an insulation layer is incorporated into a conduction heating system as an integral part of a mold that is to be heated [41]. However, it is not safe, the lifetime of the insulation layer is limited and coating it is also difficult for a mold cavity that has a complex shape [42].

2.4 High Heating Rates with Induction Heating

Induction heating is the result of eddy current losses in the (conductive) metal mold cavity, which are generated with an alternating current field. The heat is generated directly in the mold; very high heating rates are possible. Induction heating combined with water cooling is also used widely in the variotherm systems in micro injection molding. The biggest difference from electric resistive heating is that this method is much more flexible when heating the mold, the heating coil does not contact the mold surface, and its energy is also focused onto the mold surface rather than the mold base. There are two different solutions for induction heating: the inductors can be located externally or internally[25,43] from the mold. Locating a coil internally is considerably more difficult and it is more common to use an external coil to heat a mold surface. Doing so imposes a limit to the pre-heated temperature before the mold is closed. Chang et al[44] applied an external multiple-turn induction coil to heat a mold surface with high aspect ratio micro features, this coil could raise the mold surface temperature at a rate of about 20°C/s. Results showed that micro channels with an aspect ratio of more than 10 were successfully replicated. Chen et al[8,45] used induction heating with coolant cooling to achieve dynamic mold surface temperature control, which eliminated the surface marks of weldlines. This method is particularly useful for replicating high-aspect ratio features by micro injection molding. Chen et al[46] also investigated the efficiency of induction heating on a micro-featured mold with a micro channel array of 30-50 μm in width and 120 and 600 μm in depth, corresponding to aspect ratios ranging from 2.4 to 12.0. It was found that rapid mold surface heating with temperature rising from 60 °C to between 100 and 140 °C by induction heating takes some 2-3.5 s, while the mold temperature returned to 60 °C in about 70-110 s. Raising the mold temperature via induction heating did improve the replication accuracy of high aspect ratio micro-feature parts without significantly increasing the cycle time. Kim et al[9] heated a nickel stamp with nanoscale-grating structures via induction heating from 25 °C to 258 °C in 2.7 s; experimental results indicated that the nanocavities were successfully filled when the surface temperature reached 250 °C. The method is shown schematically in Fig. 6.[25]

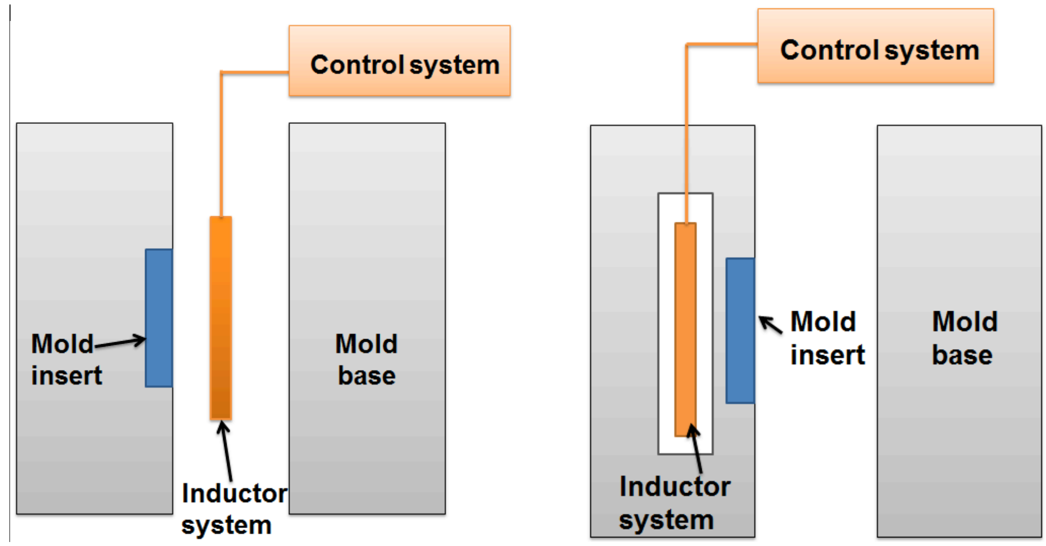


Figure 6 Schematic of external and internal induction heating[25]. Left: External system for induction heating; Right: Integration of an inductor into a mold insert.

Care must be taken when designing the mold and coil geometry, and selecting the current frequency and control system for the induction heating. When the mold cavity is nearly flat, it is a better choice than other heating methods, because when using induction heating on the mold surface, it reaches a preset temperature more quickly. Chen et al[14] successfully moved the induction coil in and out prior to injection and mold closure occurred within only 4 s. Huang and Tai[47] heated the surface of a mold for light-guided plates by induction heating to obtain the required molding temperature in only 3 s. Park et al[49] obtained a maximum of 143 °C on the mold surface through 3 s of induction heating. Tseng[49] developed an external induction heating mold control system, which helped to fill the micro cavity of an ink-jet printer's plate successfully; each nozzle plate was 7×4×0.05 mm and it had 60 micro through-holes. However, the induction heating coils used to heat the mold surface need to be designed carefully to reach a uniform temperature distribution. The diameter and shape of the coil can significantly affect the heating efficiency and both of them depend upon the mold cavity. In addition, the mold needs to be heated and cooled, these cycles take much more time than the regular ones. How to reduce this time has become one of the most studied topics. The other disadvantage is the reduced lifetime of the mold due to thermal fatigue.

In addition to these variotherm technologies, a micro molding process based on the use of ultrasonics[51] for polymer melting has recently been designed specifically for manufacturing small and precise plastic parts. Ultrasonic molding on a Sonorous 1G machine, using shot weights from 0.05 g to 2.0 g, was successfully capable of processing most polymers including standard polypropylene and high density polyethylene.

Table 1 provides a summary comparison between different methods of rapidly heating a mold based on the type of heat supply and other characteristic properties.

3 EFFECTS OF VARIOTHERM SYSTEM ON μIM AND PRODUCT PROPERTIES

The frozen layer is either reduced or disappears when a variotherm system is used in the micro injection molding process, because the mold surface temperature is higher than the freezing temperature of a polymer. This has the advantages of increasing the flow path of polymer melt, improving feature replication, reducing residual stresses and eliminating weld lines.

3.1 Reducing Flow-induced Molecular Orientation

The mold surface temperature is a very important factor, which has an influence on the relaxation of molecular orientations, and consequently affects component properties, such as birefringence and residual stresses. Flow-induced molecular orientation in a frozen layer deteriorates the optical and mechanical properties of molded components. Much previous work has focused on the reduction of molecular orientations. Yao et al[32] injected polymer into a 500 μm thick cavity with the help of a high-frequency proximity heating method. Their results showed that when the heating temperature reached 265 °C, which was the same as the injection temperature, birefringence was almost eliminated, as shown in Fig. 7. Satio et al[27] and Sato and Kurosaki et al[17] found when they used infrared radiation as a variotherm system to heat a mold surface, the birefringence decreased in proportion with the increase in radiation intensity. Park et al[51] investigated the effects of rapid mold heating on the birefringence distribution through experiments and simulation; their results showed that when an amorphous polymer was injected into a mold cavity that had a mold temperature higher than the polymer glass transition temperature, the birefringence level decreased due to the molecular relaxation from the shear and elongated orientation state in the much lower cooling rate. Jansen and Flaman[38,39] studied the effects of the heating time, the instant of heating, and the heating power on the birefringence distribution of a polystyrene resin via high-performance mold surface heaters. Their results showed the birefringence was removed most effectively by heating briefly before and during the injection stage. Chen et al[52] developed a rapid thermal response (RTR) molding technology, by means of a thin metal heating layer and an oxide layer; their results showed that birefringence almost disappeared when injecting a polystyrene flat strip specimen (80×35×3 mm) at a RTR temperature of 180 °C.

3.2 Increasing Length of Flow Path

The frozen layer has a significant influence on melt flow resistance. With the help of a variotherm system in micro injection molding processes, the flow resistance can be reduced and the fluidity of polymer increased. This is very useful for filling of high aspect ratio micro features. An illustration of the effect of variotherm on increasing flow length is shown in Fig. 7. In addition, Yao and Kim[36] investigated the polymer flow length in a thin strip-type cavity using the variotherm system. They found that the injection pressure in a heated isothermal mold cavity decreased as the injection speed decreased. McFarland et al[53] studied polystyrene cantilever beams using variotherm to heat a mold to 205 °C: a thickness of 10 μm and an aspect ratio exceeding 170 of a case was successfully molded when other process parameters remained fixed. Chang and Hwang[54] studied the effect of infrared heating on the flow path length using a thin and long spiral flow pattern in their experiments. From the results of the experiments with PP, the heating ability of a spherical reflector and centralized lamp configuration is the best (flow length increased by almost 50% after only 20 s of heating) when using infrared heating in the injection molding process. Lin et al[55] investigated the effects of the processing parameters on the filling of nano structures analytically and experimentally. Nano structures on the mold insert had the dimension of 400nm wide and 650nm deep and an infrared heating system was introduced to the injection molding machine to dynamically heat the mold cavity surface. Both the theoretical calculations and experimental results showed that the rising melt temperature and filling distance increased almost linearly with the melt temperature and that the increase of mold temperature had a more profound effect on the filling distance for nano structures.

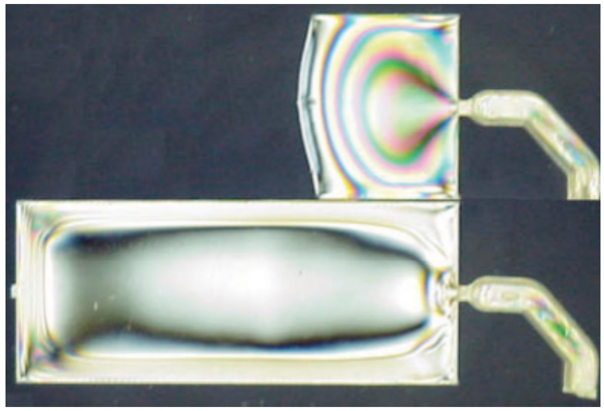


Figure 7 Comparison of the flow length and birefringence for molded 0.5 mm thick polycarbonate parts with and without proximity heating. The top specimen was conventionally molded and the bottom specimen was molded with high frequency proximity heating[32]

3.3 Minimizing Weld Lines

Weld lines form during the filling stage when two or more melt fronts contact each other. They decrease the strength and increase the danger that a molded component will crack. Clearly, it is necessary to eliminate or minimize the formation of weld lines in polymer components. When using a variotherm system during the injection process, this defect occurs less frequently[56], as shown in Fig. 8. Chen et al[46] found that, for the double-gated tensile bar used in their experiments, its weld lines were eliminated with an increase in the heating temperature. Park et al[48] applied high-frequency induction heating to eliminate weld lines in an injection-molded plastic part, and experimental observation indicated that weld depth was reduced from 2.943 μm to 0.298 μm and the weld line on the heated region was almost eliminated with the aid of induction heating.

Figure 8 Comparison of specimens produced (a) employing the RHCM system and (b) by conventional injection molding[56]

3.4 Improving Replication Quality of High Aspect Ratio Features

Currently, the dimensions of micro channels for microfluidic devices range from 10 to 100 μm and even extend to the submicron and nanometer scale for manipulation and measurement of individual molecules[57,58]. Polymer microfluidic devices require high levels of flatness and low levels of residual stress[59] to ensure high performance bonding and to avoid possible delamination. This requires high precision molding with a balanced performance and the variotherm process provides a good solution for such challenges. In addition, the complete replication of high aspect ratio micro features is a challenge during micro injection molding. A common physical phenomenon called the hesitation effect[60] (as shown in Fig. 9) should be taken into account in the micro world. This phenomenon can occur during polymer filling when the thicknesses of a substrate and micro features are different. The polymer melt tends to flow more easily into the cavities of a substrate with lower flow resistance while it can stagnate at the entrance of micro cavities; the result is that the melt does not completely fill micro cavities before it fills a substrate. Such a time delay can lead to a melt solidifying prematurely at the entrance of a small feature, causing problems of insufficient filling. Under a variotherm process, usually in conjunction with vacuum venting[61], a polymer will still remain in its molten state after complete filling of the substrate, which allows further filling of micro features and avoids this hesitation effect[56]. Rytka[62] investigated the filling differences for micro to nano scale features using four different processes including variotherm injection (compression) molding. Results showed that high aspect ratio microstructures could be replicated with high accuracy using variotherm injection (compression) molding only in combination with a polymer that had a sufficiently low melt viscosity and, thus, a low filling resistance in the cavity.

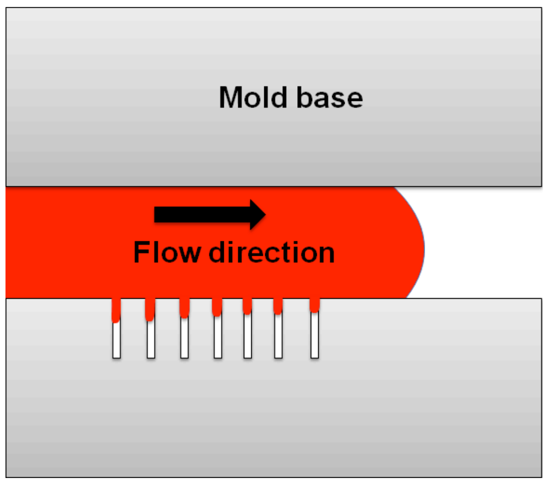
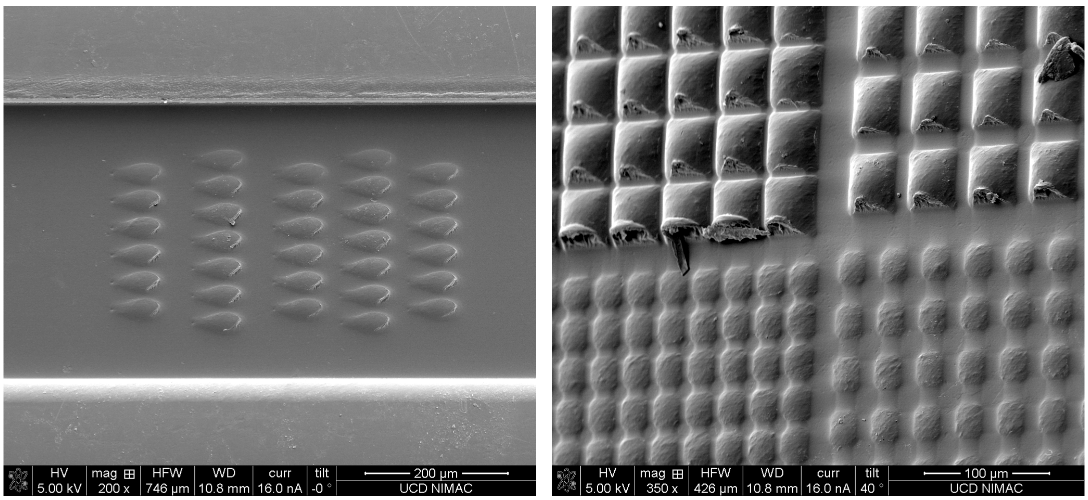
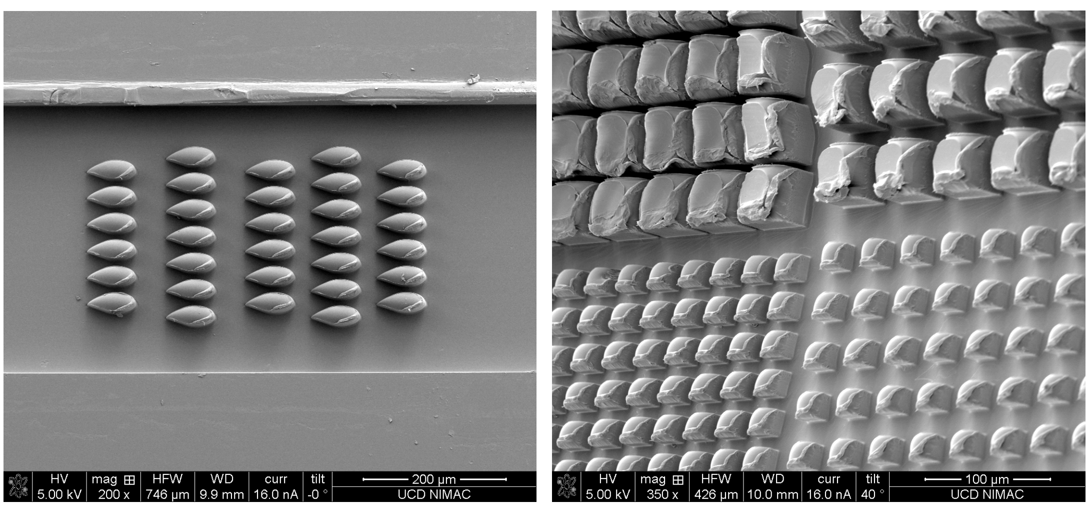


Figure 9 Hesitation effect when filling of micro features in micro injection molding

Temperature selection is critical to the variotherm process. Figure 11 shows our recent work on replication of microfluidic features using Cyclic Olefin Copolymer (COC 5013L10). We compared replication using a warm circuit temperature of 130ºC and 150ºC under the same process condition using a Single ATT (Alternating Temperature Technology; c.f. Figure 2) system. It is obvious that filling under a higher temperature gives much better filling for both water droplet shaped features and square pillar features. Feature filling is aspect ratio dependent and feature spacing does not show any significant difference. Such a difference is related to the real mold temperature. As shown in Figure 11, the real mold temperature is higher than the warm circuit temperature. No-flow temperature is generally used to determine whether the polymer flows or is solid, which is estimated as $T_{no}=T_g+30$ ºC[63]. In our case, although the real mold temperature (~144 ºC) is above the glass transition temperature of COC5013 (~130 ºC)[64] at the 130 ºC warm circuit, it is still lower than the no-flow temperature and results in poor replication. When the warm circuit temperature increases to 150 ºC, the associatedcavity temperature is ~10ºC higher than the polymer no-flow temperature and good filling can be achieved.



(a) (b)



(c) (d)

Figure 10 Comparison of micro feature replication (water droplet shape and square pillar features) using variotherm system: (a) and (b) under warm circuit temperature of 130 ºC; (c) and (d) warm circuit temperature 150 ºC.

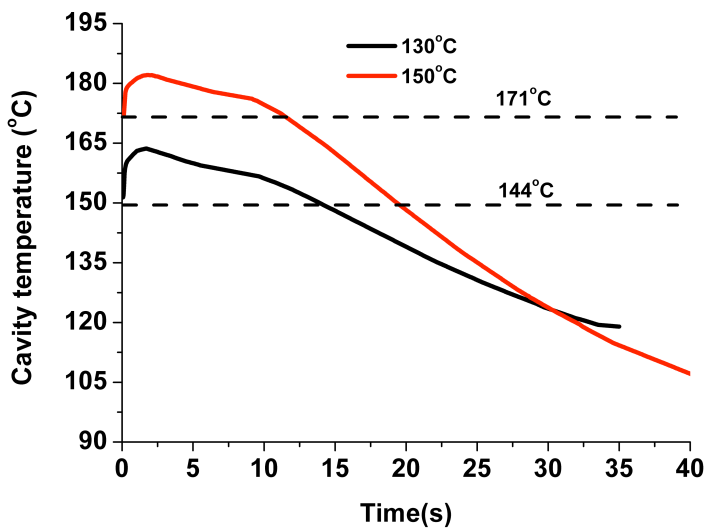


Figure 11. Cavity temperature evolution when warm circuit temperature is set at either 150 ºC or 130 ºC.

3.5 Morphology Control

During the filling stage of injection molding, complex flow fields are involved in plastic parts (shear and elongation). Moreover, the low thermal conductivity of polymers implies the presence of important thermal gradients within the flow thickness. For semicrystalline polymers, these variations of thermomechanical conditions affect the crystallization phase. Flow and cooling conditions change the nucleation and growth rates of crystalline entities[66]. The final microstructures are then different from those created under quiescent conditions, leading to an anisotropic morphology, named 'skin-core', within the part thickness[67]. This skin-core morphology is, in fact, made up of four distinct layers within the thickness: skin layer, shear layer, fine-grained layer and core[67-71]. When the thickness of a micro feature decreases to a few hundreds microns, the molten polymer and micro cavities will encounter higher temperatures, speeds and pressures, and the rheological behavior of flow in the micro cavities can differ from in a conventional cavity[72]; the wall-slip effect occurs and extensional viscosity increases in the micro channels. In the case of semi-crystalline polymers, these specific processing conditions can also affect the various stages of crystallization, i.e. nucleation and growth of crystalline lamellae[73,74]. Whiteside[75] investigated the effects of micro scale processing on the rheological, mechanical and tribological properties of engineering and commodity polymers. They found a typical skin-core morphology. We have systematically studied the morphology of a micro part under extreme process conditions[68] and various thicknesses from 500 μm to 100 μm[1]. Our results indicate that when part thickness decreases from 500 to 100 μm, the volume ratio of the skin layer increases from ~10% to ~67% and the corresponding molecular orientation factor increases from ~0.37 to ~0.6 due to the increase of highly oriented structures contained in the skin layer, as shown in Figure 12. The reduction of thickness increases the cooling rate and causes an increase of shear stress, which leads to a high percentage skin layer. For a fixed 400 μm thick part, the thickness of the oriented skin layer decreases with increasing injection velocity and mold temperature due to the suppressed cooling rate. Although higher injection velocities increase the density of nucleation, the filling time (shear time) is shortened, causing a decrease in the amount of oriented nuclei and the associate oriented skin layer. For poly(ether-block-amide), we found that the cooling rate is more significant than velocity in the formation of highly oriented skin structures. Additionally, the overall molecular orientation increases with increasing skin thickness. The Young's modulus, strain at break, and yield stress generally increase with an increase of the skin ratio. Based on these findings, we have indicated that shear stress is a good candidate for characterizing the onset of oriented structures during the molding process, which would allow the percentage of oriented morphology, and consequently the product performance, to be controlled. Using variotherm to control shear stress using cooling rate can, therefore, provide a good way to optimize the final properties of a product.

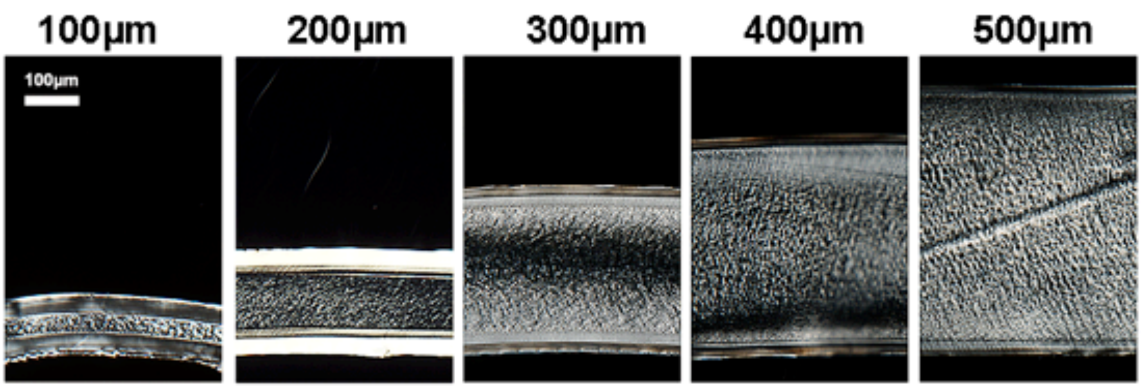


Figure 12 Increasing skin layer with reducing part thickness when injection molding Poly(ether-block-amide). The skin layer is ~67% when the part thickness reduces to 100 μm.

The internal morphology of the μIM parts with some common pure polymer materials has been extensively investigated and is well understood. However, more attention should be paid to the morphology and corresponding performance of the micro parts with the addition of various fillers, especially under when using a variotherm process; this issue remains unaddressed.

4 SIMULATION OF VARIABLE HEAT TRANSFER

Numerical simulation of μIM is becoming more important for a variety of reasons, including the need to optimize process conditions, to estimate cycle time and to identify possible manufacturing problems. When the features are in the order of micrometers, there are several effects that can greatly influence the filling of micro cavities, some of which are not necessarily important on the macroscale. Therefore numerical simulations should consider various important aspects of the micro injection molding process due to scaling issues in miniaturization of injection molded parts, such as wall adhesion, surface tension, wall slip, micro scale viscosity and the stark lack of rheological data from microscopic experiments[76-80]. This means that existing simulation software cannot represent all of the information needed to describe the μIM process. In addition, there are many key issues should be considered carefully so as to achieve good simulation results, examples of such issues include:

1) Define the flow process and the last-filled sections of a mold; this is usually done via short-shot methods in which different amounts of material are injected into the mold cavity. This can help to identify defects such as incomplete filling, weld lines and voids.

2) Optimize the design of a mold for a lower cost and shorter cycle time. This can help to improve important mold structures such as cavity geometry, and the sprue and gating system before manufacturing a mold.

3) Properly estimate the actual thermal conditions of polymer flow during the filling and cooling stages and possible detects caused by part demolding, which is helpful when calculating the cycle time and identifying processing bottlenecks, particularly for any part with high aspect ratio features.

4) Establish some initial and proper combinations of process parameters so as to improve design of experiments.

5) Predict post-processing properties including residual stresses, shrinkage and warpage, which have a profound influence on part quality, especially for parts with high aspect

ratio features.

4.1 Significant Factors in µIM Simulations

Compared with the conventional viscosity of a polymer, the microscale viscosity of polymer which is flowing in a micro channel has been observed to increase by up to 80% near the channel wall. This is believed to result from high intermolecular interactions or the immobility of the molecular layers that are in contact with the solid surface[81,82]. With a dramatic decrease to the micrometer scale, the viscosity variation through the thickness is significant. Secondly, the high shear rate of polymer melt flowing in micro channels may produce the wall slip phenomenon when wall shear stress exceeds a critical value[83,84]. Wall slip can be explained using the the bead-spring model in terms of higher cavity pressure and decreased mold surface roughness after injection molding[80,85]. However, usually, it is a classical no-slip boundary condition which is used in conventional IM simulations. Thirdly, surface tension resulting from unbalanced forces of the molecules at the material surface may have an influence on the microscale flow[86,87]. Lastly, micro-scale elasticity[88,89], variable heat transfer coefficients[90,91] and compressibility effects[92,93] exist in µIM and is different from conventional IM, which needs to be included in any computer simulation analysis in order to obtain a more accurate prediction for flow behavior within micro features.

4.2 Software Available for µIM Simulation

Generally, the simulation of µIM can be implemented via two different approaches regarding the choice of simulation packages: the first approach is to enhance the commercially available software packages for conventional injection molding, in order to accurately simulate micro injection molding, while the second one is to develop bespoke finite element codes specifically for simulating micro injection molding.

Specialist commercial software for μIM is based on software for simulating conventional injection molding, such as Moldflow (which has been merged into Autodesk since 2008), Moldex3D, CADMOLD and SIGMA. When using their 3D module to simulate the micro injection molding process, the simulation results are sometimes correct compared with experiments, particular in the simulation of macro injection molding components with micro features, where micro features occupy a small volume of the whole molded parts, which means that micro features have only a small influence on the accuracy of simulation results. At the same time, some of these companies are improving the simulation accuracy of their commercial software; both Moldex3D[94] and Autodesk Moldflow[95] can be used to simulate micro injection molding with a variotherm system. Yu et al[96] investigated the most influential processing conditions with the help of C-MOLD, which was been merged into Moldflow in 2002. Results indicated that the injection speed, feature width and mold temperature were important for filling in the molding process. Piotter et al[97] simulated the temperature distribution in a tool using Abaqus and found that conventional software that had been designed for macro injection molding processes cannot be used to simulate the μIM process directly: some specific considerations need to be included in the development of software for simulating μIM (e.g. wall slip, heat dissipation, surface tension). C-MOLD was also used to simulate some complex geometry components with high aspect ratio features[98]. Khalilian et al[99] evaluated Moldflow to determine if commercially available injection molding simulation software developed for macro injection molding provided sufficient support to the development of micro-injection molded components. It was concluded that the use of molding simulation software developed for macro molding applications was very useful in reducing the development time of the micro molding process of a micro-pump component. Tseng[49] used Moldflow to analyze the mold-filling phenomena. The numerical calculation demonstrated that the most significant factor for molding thin films with micro through holes was the mold temperature, with a higher mold temperature resulting in a greater volume being filled. These commercial simulation software are easy to use; however, such software provides few user defined functions, limiting their application when developing new process technology.

It is for this reason that many researchers have employed the second computational approach, i.e., general computational fluid dynamics (CFD), which is more flexible in defining user functions, or self-programming codes to conduct simulations of μIM, such as in mathematic models, boundary conditions, mesh element types, numerical solution and coupling of multi-physical phenomena. Kim et al[100] presented two numerical approaches to analyze the filling behavior of micro patterns on micro-injection molding for a non-Newtonian polymer melt based on the Navier-Stokes equation. It was found that the viscosity was related to the temperature drop along the mold wall, which was the key parameter of a micro filling process. Choi and Kim[86] proposed a multi-scale simulation method that can simulate filling during the micro-injection molding process: their results showed that slip and surface tension played important roles in the micro-regime of circular micro-channels. Cao[101] developed a computer code for melt flow in micro-injection molding based on the PTT model, the slip boundary condition and surface tension were added to the mathematical model to describe microscale effects in μIM. Numerical simulation revealed that the melt viscoelasticity plays an important role in the prediction of melt pressure, temperature at the gate and advancement of the succeeding melt front in the cavity. Huang et al[102] investigated the flow characteristics of micro injection molded light guiding plates. Viscous heating, temperature and velocity distribution were utilized to analyze the delay or advancement of the melt front experimentally and the three-dimensional numerical simulation results were very close to those of physical experiments. Kemmann[103] took viscous flow into consideration in the simulation of micro injection molding a test structure with lateral dimensions between 2.5μm and 20μm, which was filled well when POM was used as injection material. Xie et al[104] simulated the micro injection molding process of a micro tensile specimen with specific commercial software (Moldflow) and general CFD software (Comsol Multiphysics). The results showed that specific commercial software (Moldflow) for the normal injection molding process was not valid to describe the micro flow process. However, CFD software (Comsol Multiphysics) showed better qualitative effects in describing micro fluid flow behavior, although neither software could provide a quantitative analysis because of poorly defined boundary conditions and micro fluid mathematical model. Despite this various prior work, current commercial software still lacks accuracy when used to simulate the μIM process. Additionally, they lack reliable quantitative data on constitutive and rheological data and very little literature exists on the simulation of μIM that includes the influence of variotherm systems on μIM[46]. Besides, due to the electromagnetic (EM) field can be generated from induction heating and high frequency proximity heating, the simulation of such complex processes requires at least an analysis of coupled electro-thermal fields, but with supply source simulation taken into account. Electromagnetic analysis includes the electromagnetic field induced from input AC power to a coil, and eddy currents induced in the mold from the electromagnetic field, and Joule heat generated from these eddy currents. Thermal analysis includes modeling the processes of heating, holding, and cooling. The heating process is coupled with the electromagnetic conversion process. In the heating process, the heat conduction effect is the main issue to be considered because the heating cycle is generally as short as several seconds. Due to the temperature-dependent nonlinear properties of materials in the induction heating process, induction heating is a highly non-linear system and analytical solutions are difficult to obtain. The realisation of a reliable simulation process is made difficult by a number of factors, including the credible determination of thermo-electrical material properties (temperature-dependent nonlinear properties), EM wave and the associated currents, and the demand for fast calculation times.

As micro parts continue to have progressively smaller dimensions and more complex shapes, these factors will become ever more challenging when simulating a µIM. Online or real-time inspection techniques have been also attracting significant interest as a way of collecting physical molding data for simulation purposes. Real-time data pertaining to process parameters, e.g. pressure, temperature, time, clamping force, injection speed, and injection stroke, are very important for achieving precise simulation results. Liu et al[105] proposed a novel type of adaptive Kalman filter algorithm based on F-distribution to track the signature of the melt pressure. The simulation experiment results showed that this method could reduce the effect of measurement noise more quickly and effectively and it was proven to be effective for micro injection molding applications. Tosello[106] presented a different strategy optimized for the simulation of a miniaturized part with micro features. Actual experimental data was implemented in the simulation software and a three-dimensional meshing of the whole injection system was applied to optimize the simulation. Results revealed that the use of experimental data from actual molding can greatly improve the quality of µIM simulations. However, considering the small dimensional size of micro cavities and the complex geometry of a mold, on-line data monitoring technology will only become possible when existing pressure sensors are further miniaturized or alternative methods are developed, e.g., using piezoelectric materials as the micro-cavity walls.

4.3 Heat Transfer Process for µIM Simulation

It is believed that mold temperature is mostly responsible for the heat exchanged between a polymer and the mold wall, especially for micro-cavities of high aspect ratio and the heat transfer between a polymer and mold has an impact on filling pressure, cooling performance and shrinkage. When a variotherm system, which changes mold temperature dynamically, is considered in the simulation of micro injection molding, the heat transfer phenomenon between mold surface and polymer should be studied. Therefore a better understanding of the heat transfer phenomenon at the micro-scale is necessary in order to predict the phase change and morphology evolution while a melt fills into a cavity.

Usually suppliers of injection molding simulation software recommend a wide range of values for heat transfer coefficient (HTC); due to the wide range of values it is reasonable to presume that other effects are aggregated in the provided values[107]. Nguyen-Chung et al[108] determined the HTC between the melt and the mold wall from short-shot studies by reverse engineering; the HTC increased with decreasing cavity thickness or injection speed. Yao et al[29] illustrated schematically the heat transfer process in injection molding, showing three contributions to heat transfer, as shown in Fig. 13.

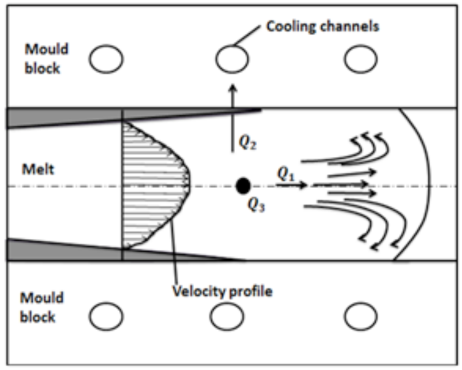


Figure 13 Schematic of heat transfer process in injection molding[29]

There are three different factors which affect the heat transfer process during injection molding[29]: Q_1, convected heat from the melt; Q_2, heat conducted to the mold; Q_3, heat generated inside the thermoplastic. These can be expressed in the following energy equation [29]:

$$\rho c_p\left(\frac{\partial T}{\partial t}+v\cdot\nabla T\right)=\nabla\cdot\left(k\nabla T\right)+\left(\alpha\sigma:\dot{\gamma}+\dot{s}\right) \qquad (1)$$

where ρ is density, c_p is specific heat, k is thermal conductivity, T is temperature, t is the time, $\boldsymbol{v}$ is the velocity vector, $\boldsymbol{\sigma}$ is the total stress tensor, $\dot{\gamma}$ is a strain rate tensor, α is the fraction of deformation energy converted into heat, and $\dot{s}$ is a heat generation source from a nondeformation field. In Eq. (1), $\rho c_p v\cdot\nabla T$ represents the convective energy (Q_1); $\nabla\cdot\left(k\nabla T\right)$ represents the conduction loss to the mold (Q_2); $\left(\alpha\sigma:\dot{\gamma}+\dot{s}\right)$ represents the total heat generation source (Q_3). Analyzing Eq. (1), when the injection speed is increased, the corresponding Q_1 increases, as well as the average temperature of the polymer; when the mold temperature is increased, Q_2 reduces, as well as the temperature gradient. Higher injection speeds can also increase the amount of viscous heating and the polymer temperature. It is possible to build a heat source ( ) inside the polymer, which increases the polymer temperature during the injection process, such as applying a microwave electromagnetic field to generate a dielectric heating source[109].

However, the interfacial temperature between the polymer and mold is not the same as the mold surface temperature. The mold surface temperature is actually instantaneous and can be described by the following equation [41]:

$$\frac{T_p - T_s}{T_s - T_m} = \frac{\left(k\rho c_p\right)_m}{\left(k\rho c_p\right)_p} \qquad (2)$$

where the subscripts *m* and *p* represent the mold and polymer respectively; this equation indicates the passive heating for reducing the heat loss of the polymer during the filling stage. The actual passive heating effect may be higher than the value predicted by Eq. (2)[110]. Bendada et al[111,112] also found that thermal contact resistance between polymer and mold was not negligible and would affect the value of actual passive heating effect via experimental and numerical approaches, respectively.

Simulating injection molding is a significant challenge, because many variables are included in this process and because of the non-Newtonian nature of molten polymer. However, simulation of micro injection molding is more difficult than for macro-scale injection molding since many new concepts are involved when simulating at the micro-scale level[113]. Some factors should be considered carefully before conducting simulation of μIM as following:

1. building a proper 3-D model which contains the effect of side and end surfaces，

especially a part with high aspect ratio features,

2. taking into account the influence of surface roughness, surface tension, viscous friction and cooling of polymer melt front[114], and high shear rate during μIM[113],

3. selecting the element type and mesh density used in a finite element simulation will affect the accuracy of the μIM,

4. special processing conditions including variotherm and vacuum venting should also be considered when simulating μIM.

Mesh characteristics also played a key role in simulation of μIM due to the small dimensional size of micro features. Many important factors concerning mesh quality should be considered for a successful and accurate simulation result, such as the global edge length for general accuracy, the merged tolerance for micro features and the bias ratio for thin sections, especially the maximum aspect ratio when meshing a micro feature, e.g. the aspect ratio should not exceed a value within which successful simulation can be achieved. Otherwise, the simulation process will fail or the simulation process will give inaccurate or wrong results.

Heretofore, one of the main challenges related to the micro injection molding technology has been the possibility of simulating the process. However, qualitative predictions regarding the behavior of either polymer or process can be achieved for micro products, e.g. with high aspect ratio surface structures. Moreover, at present no sophisticated simulation software that exists has the ability to consider all influential factors during μIM as mentioned above. Developing such simulation software will address an increasingly important need which will benefit both academia and industry.

5 DISCUSSION

Mold design and cavity geometry have important influences on variotherm systems depending on different kinds of heating methods, because they will affect the way in which heat is transferred to the mold and polymer. Usually heating methods are chosen in consideration of many existing conditions, especially according to the requirements of specific components, which will be molded by μIM with the aid of a variotherm system. Consequently, mold design should consider the chosen heating method for the associated variotherm system. In other words, mold design should make sure that the mold can be heated and cooled more quickly and efficiently, that the mold volume should be as small as possible, and that the mold material should have low specific heat and low density for better heating and cooling. If it is not easy to implement such a mold design in real experiments or practical applications, an insulation layer and replaceable mold inserts may be necessary and useful in order to avoid the heat loss or to improve the heating efficiency of the variotherm system.

Compared with cooling methods in designing a variotherm system, heating methods are much more challenging. Actually, cooling media which can be utilized in variotherm systems are limited, such as oil, water and cold gas, depending on their advantages and disadvantages, although water is the most widely used coolant both in conventional injection molding and μIM processes. Moreover, compared with the heating stage, the cooling stage can be conducted at a slower rate, which is often sufficient for some thick parts. At the same time, there are different kinds of heating methods that can be used in a variotherm system. This is one of the reasons why most research to date has focused on heating methods rather than cooling methods.

Developments in simulation tools for µIM are still limited for many reasons, such as a limited understanding of the physics, available simulation software for µIM processes and commonly used models for simulating µIM processes. On the one hand, some simulation results can be obtained by modifying conventional models of injection molding. On the other hand, however, such simulation results must be repeated when process parameters change or cannot be verified by experiments. In other words, such simulations do not follow universal rules for µIM processes. Finally, particularly for µIM, process integration of variotherm process, injection compression molding and vaccum venting will be beneficial for the replication of high transparency and high precision components and micro/nano features.

6 CONCLUSION AND RESEARCH TRENDS

In µIM processes, because of the existence of a frozen layer, many molded components are affected by quality problems, such as weld lines, incomplete filling, large residual stresses and imperfect surface smoothness. Obviously, a variotherm system is a useful solution for these problems. Even though variotherm technology has existed for decades and includes many kinds of heating methods, it is still not a proven one for use with µIM. This paper has reviewed the various heating methods and simulation work for variotherm systems. An effective heating method should be chosen according to requirements of the mold cavity and other specific needs; mold design for µIM should consider the heating method used by a variotherm system; simulation of µIM is still limited.

Though there are many heating methods, each has their own disadvantages, with the consequence that one of the research trends is to modify existing heating methods and to develop new heating methods, as well as the cooling system, because the available cooling methods are also limited. Actually, the use of conformal cooling channels is a good choice, but is very expensive. The second research trend is to develop new mold materials for variotherm systems and a better mold design is also very important for improving heating efficiency. It ought to be possible to develop higher aspect ratio molded parts with particular functionalities with the aid of variotherm heating and cooling. Feasible simulation software is urgently required for a wide range of applications of variotherm systems in μIM processes. The third research trend is to develop such simulation software and corresponding models which can consider more factors involved in the μIM processes and can exactly simulate the micro morphology of filling. Such simulation will also require new methods for acquiring real-time data from μIM processes which can be used for simulating μIM processes. Fourthly, particularly for μIM, process integration of variotherm process, injection compression molding and vaccum venting is beneficial for replication high transparency and high precision component or micro/nano features. Finally, variotherm process plus in-line process monitoring may provide a useful way to control part cooling rate; thus, product performance can be controlled directly by automatically tuning mold temperature and process settings.

It is worthwhile noting that although the variotherm process helps feature replication, the adhesion and friction between polymer and micro mold can be increased, because of the larger contact area. For micro/nano molding, this means that tools can be damaged more easily. Development of high performance tools, using materials such as Bulk Metallic Glass for micro/nano inserts as in our recent work[115], becomes critical. Finally, most variotherm systems consume significant quantities of power because of the need for a large variation of temperature ranges, which requires auxiliary equipment.

7 ACKNOWLEDGEMENTS

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