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Research Article

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Flow characteristics of microchannel melts during injection molding of microstructure medical components

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ABSTRACT

It is shown by modifying and simulating the macro-molding Cross-WLF viscosity model and adopting polymethylmethacrylate (PMMA) to test and verify the flow characteristics of microstructure-formed microfluidics that, the mold temperature has the greatest impact on the flow characteristics of microchannel melts; when the mold temperature rises to 120°C, the condensate layer disappears, and the flow of melts is no longer affected by the mold temperature; when the ratio of the peak-valley size of microchannel surface roughness to the size of microchannel reaches 0.30, the microchannel is almost blocked by the condensate layer; when the contact angle θ of the surface tension of melts is smaller than 90°, the resistance of the surface tension to the flow of melts decreases with the decrease of θ; these unwanted effects could be eliminated by adopting the variotherm injection molding technology.

Keywords: microchannel; flow characteristics; microstructure; injection molding; medical components

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INTRODUCTION

With the development of micro-system technologies, the plastic microstructure parts have been more and more widely applied in the medical field, for example, miniature metering devices in medical practice, medical products for surgery (operating forceps), plastic medical parts to be implanted into the human body, etc.[1]; however, as the size of plastic microstructure parts, the sizes of their channel and mold cavity and their injection capacity are small, some factors that may be ignored under conventional scale may have great impact on the flow behaviors and flow characteristics of melts during microstructure injection molding (e.g. scale effect, surface roughness of mold cavity, mold temperature, surface tension, wall slip, etc.), making the capacity of plastic melts to fill the mold cavity during the filling process of plastic microstructure parts worse than that of conventional injection, yet it is difficult to produce high-precision and high-quality plastic microstructure parts by using the conventional injection molding method. Scholars at home and abroad have conducted theoretical studies on the flow behaviors and flow characteristics of melts during injection molding of plastic microstructure parts, for instance, Yu L D *et al.* from the Ohi University of USA had studied the heat transfer phenomena between polymer melts and microchannel wall surface and put forward the convection heat transfer coefficient between melts and microchannel wall surface [2]. Young W B had adopted the two-dimensional simplified numerical algorithm to simulate and analyze the flow behaviors of melts in the mold cavity of microstructure parts and found out that they were related to the flow rate of melts, the feature size of microstructure and the cooling rate [3]. Yu Tongmin *et al.* had analyzed the filling flow characteristics of melts and convection heat transfer during microstructure injection molding and established the surface tension model of melt flow in the microchannel [4-5]. SHENYK *et al.* had performed numerical simulation on the flow behaviors of melts during injection molding of plastic microstructure parts [6-8]. Rogall *et al.* had put forward the concept of “temperature variation process” of microinjection molds to solve the flow questions of melts during injection molding of microstructure parts [9]. Piottery *et al.* had suggested that, the molding quality of plastic microstructure parts should be achieved by increasing the mold temperature [10]. Moreover, researchers at home and abroad had also studied the effects of channel cross-section shape and injection molding process on the flow properties of microfluidics [11] and performed validation via numerical simulation [12]. To a certain extent, these studies have answered some theoretical and process questions related to the flow behaviors and flow characteristics of melts during injection molding of plastic microstructure parts, however, they could not accurately characterized the viscosity model of rheological properties of melts under micro-scale and the velocity field, temperature field and stress filed measured by numerical simulation are not accurate enough, thus the precision of prediction of quality of plastic microstructure parts is affected. The current study analyzed the impact of microchannel characteristics on the flow behaviors of microfluidics during microstructure injection molding, adopted the flow conditions of microstructure injection molding to modify the viscosity model of macro melt flow behaviors and came up with the viscosity model of flow behaviors of melts during microstructure injection molding. On this basis, the effects of scale effect, surface roughness of mold cavity, mold temperature, surface tension, wall slip and other factors on the microstructure variotherm mold temperature injection molding were discussed.

EXPERIMENTAL SECTION

1.1 Experimental Material

Polymethylmethacrylate (PMMA): glass transition temperature 103-106°C, melting point 240°C-270°C, decomposition temperature 270-275°C.

1.2 Test Equipment

The injection molding equipment adopted is the Germany BOY12A injection molding machine, with the diameter of screw being 18 mm, the maximum injection speed being 240 mm/s, and the maximum injection pressure being 179.5 Mpa.

1.3 Mold Structure

The mold core is prepared by adopting the UV-LIDA technology commonly used in micromachining to meet the precision requirements of mold manufacturing. The fan gate is adopted to meet the requirements of gentle melt flow and flow balance. The DS18B20 SCM temperature control system is adopted as the temperature control system to achieve the variotherm mold temperature dynamic control during the injection molding process of microstructure parts.

1.4 Process Parameters

Injection pressure 120 Mpa, injection speed 100-220mm/s, mold temperature 50-120°C, melt temperature 230°C - 240°C, pressure holding time 10s.

2 Experimental Results and Discussions

2.1 Micro-scale Effect

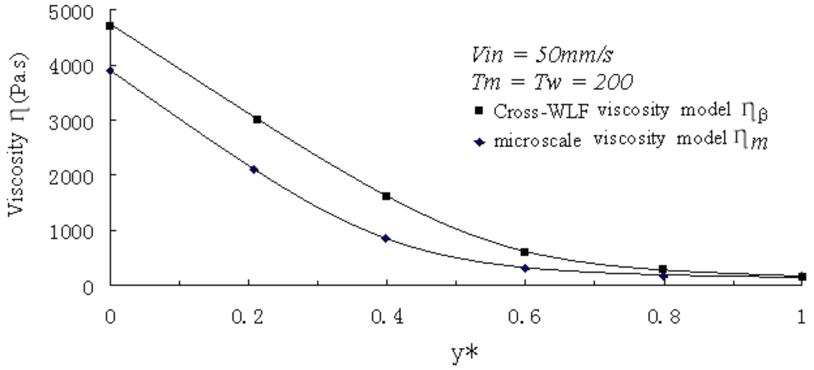
As the plastic melts may be affected by the temperature, shear rate and pressure during the general injection molding process, the Cross viscosity model related to temperature could be adopted as the viscosity model [13-15]:

Where, n is the power law index; r^* is the shear stress level obtained by converting the Newtonian viscosity to the power law viscosity; $\eta_0(T)$ is the zero shear viscosity that could be described with the Arrhenius equation [16]:

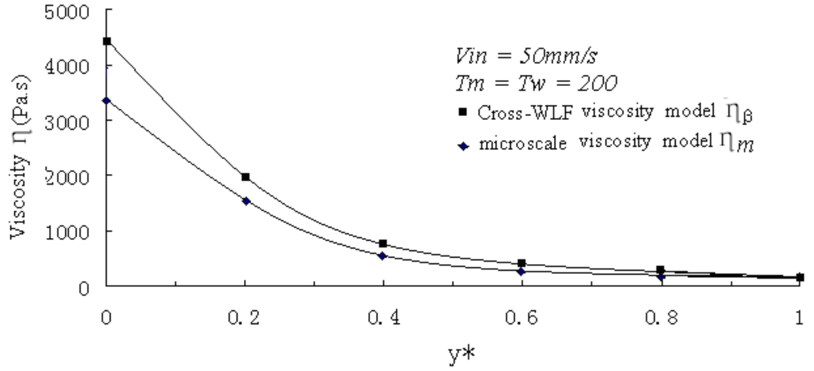
As the structural size of plastic microstructure parts manufactured by injection molding is small, the size of flow channel is miniaturized and the ratio of the channel's surface area to its volume (surface area/volume ratio) has been increased greatly, some factors that may be ignored under macro-scale play important roles in the injection molding of plastic microstructure parts, for example, when the feature size of microstructure injection molding flow is decreased from the cm magnitude to the μm magnitude, the surface area/volume ratio will be changed from the 10^2/m magnitude to the 10^6/m magnitude, and the heat transfer and mass transfer processes related to the surface and the flow behaviors of melts will also be changed enormously with the increase of the surface/volume ratio. In general, if the physical parameters of melts remain unchanged, the heat dissipation rate will be increased 10 times with the feature size decreased by one order of magnitude, as a result, the melt temperature drops rapidly during the mold filling process of plastic microstructure parts, consequently leading to the change of melt viscosity and the uneven gradient distribution of the whole microchannel section, and then the fluid viscosity around the wall surface of microchannel is 60%-80% higher than that of its volume. Due to the change of viscosity, the flow of melts is blocked in the microchannel, meanwhile, the shear rate is continuously changing from the center to the wall surface, especially when the feature size of microchannel is small, the shear rate is changing greatly, the molecular orientation along the flow direction is clear and the apparent viscosity of melts is increased, all of which will cause the deviations from the macro viscosity model. In this topic, the Cross-WLF seven-parameter model is used as the basis to fit and modify the viscosity model of macro melt flow behaviors under the micro-scale conditions (the process not described here), and get the viscosity model of melt flow behaviors during microstructure injection molding:

Where, η_0 is the zero shear viscosity (Pa.s), D_1 is the coefficient of zero shear viscosity under the glass transition temperature, A_1 is the flux in correlation with the temperature that is usually within 1-100, A_2 is the flux in correlation with the temperature that is usually within 1-1,000, T is the real time temperature (°C), and T^* is the reference temperature (°C) that often refers to the glass transition temperature of the material used.

The Formula (3) has characterized the rheological properties of melts changing with the changes of the temperature, shear rate, pressure, feature size of microchannel and radius of gyration of polymer molecular chain in the microchannel during microstructure variotherm mold temperature injection molding. In general, the zero shear viscosity field is the constant not changed with the change of the shear rate $\dot{\gamma}$, however, when the melts of microstructure injection molding are flowing in the microchannel, the shear rate is continuously changing from the center to the wall surface, and especially when the feature size of microchannel is tiny, the shear rate is changing greatly.



(a) a = 500μm



(b) a = 300μm

Figure 1Distribution curve of melt viscosities in different microchannels at x=5mm cross sections

Figure 1 is the distribution curve of melt viscosities in different microchannels at x=5mm (anywhere along the flow direction) obtained by simulating with the traditional Cross-WLF viscosity model and the micro-scale viscosity model, where the abscissa y* is the normalized distance from the core of section to the wall surface of microchannel, $y^* = y/(a/2)$. It can be seen from Figure 1 that, the maximum melt viscosity is reached at the core of section of microchannel, and the melt viscosity is relatively small and the shear rate is relatively bigger at the wall surface of microchannel.

2.2 Mold Temperature

Figure 2 shows the relationship between the mold temperature and the thickness of condensate layer for microstructure parts formed by PMMA injection molding. As the melt viscosity of PMMA is relatively high and the cooling rate is great, if the mold temperature is set at the traditional temperature 50°C, the melt temperature drops rapidly, the thickness of condensate layer on the wall surface of microchannel will increase rapidly, and the microstructure mold cavity will not be filled; when the mold temperature is set at 100°C, the microstructure mold cavity still can’t be fully filled; when the mold temperature rises to 120°C, the condensate layer on the microchannel surface basically disappears, the mold cavity is fully filled, and the plastic microstructure parts formed are of great quality. When variotherm mold temperature injection molding is adopted, the temperature on the inner wall of microchannel increases with the increase of mold temperature, and the distribution of viscosities of plastic melts tends to be even and uniform at the whole microchannel section, which effectively eliminates the advanced condensation phenomena of plastic melts during injection molding and guarantee that the mold cavity is completely filled with plastic melts. That is to say, by dynamically controlling the mold temperature, the microstructure variotherm mold temperature injection molding keeps the plastic melts always under an even, low-viscosity molten status before the mold cavity is completely filled, eliminates the advanced condensation phenomena of melts and achieves high-quality injection molding.

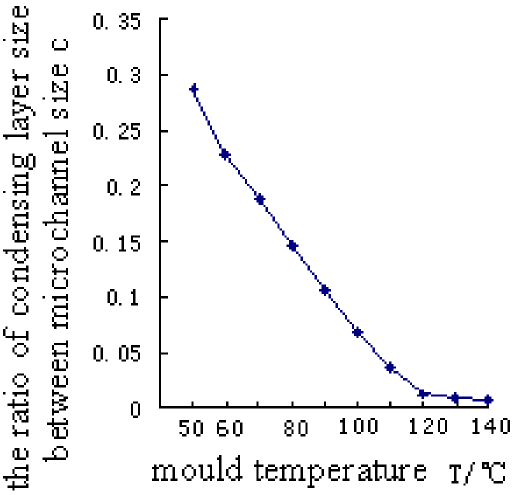


Figure 2 The relationship between the mold temperature and the thickness of condensate layer

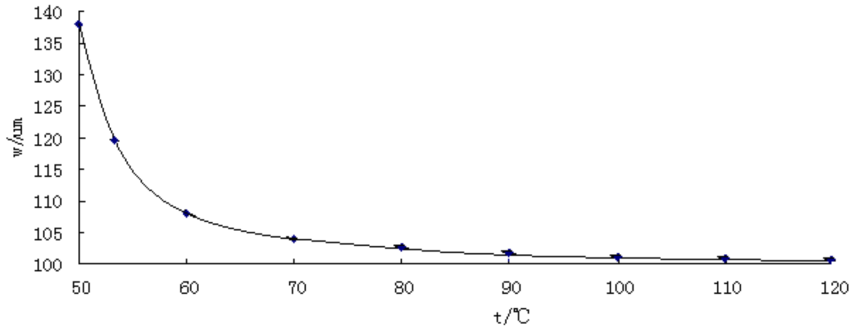


Figure 3 The relationship between the mold temperature and the microchannel opening width

It can be seen from Figure 3 that, the melts' capacity to fill the mold cavity increases with the elevation of mold temperature, but the microchannel opening width decreases instead; when the mold temperature rises to 70°C, the opening width is significantly decreased; when the mold temperature rises to 120°C, the decrease tendency of opening width basically flattens out, and the opening width is no longer decreased with the elevation of mold temperature.

2.3 Surface Roughness of Microchannel

Figure 4 shows the relationship between the surface roughness of microchannel and the thickness of condensate layer for polypropylene (PP) of a certain brand at the heat diffusion rate $\alpha=5.9\times10^{-8}m^2/s$. It can be seen from the figure that, when the ratio of the peak-valley size of microchannel surface roughness to the size of microchannel reaches 0.30, the condensate layer is about 6 μm thick, and the total thickness of condensate layer is almost equal to the size of microstructure, indicating that the effects of surface roughness of mold cavity on the microfluidic flow process during microstructure injection molding are mainly manifested in the ratio of the surface roughness size of mold cavity to the size of mold cavity (micron-scale feature size). As the micro peak-valley on the wall surface of microstructure mold cavity not only increases the surface area of mold cavity, but also increases the surface area/volume ratio of micro-mold cavity, making the effect of heat transfer on the wall surface of mold cavity on the energy change of microfluidics more significant and also causing the condensate layer on the wall surface of mold cavity to thicken rapidly during the flow of microfluidics, consequently affecting the flow of microfluidics. By dynamically controlling the mold temperature, the variotherm injection molding technology makes the surface temperature of mold cavity higher than the glass transition temperature of PP, the condensate layer on the wall surface of mold cavity is very thin and even cannot form a solid condensate layer on the wall surface of mold cavity, subsequently ensuring the smooth flow of microfluidics in the microchannel.

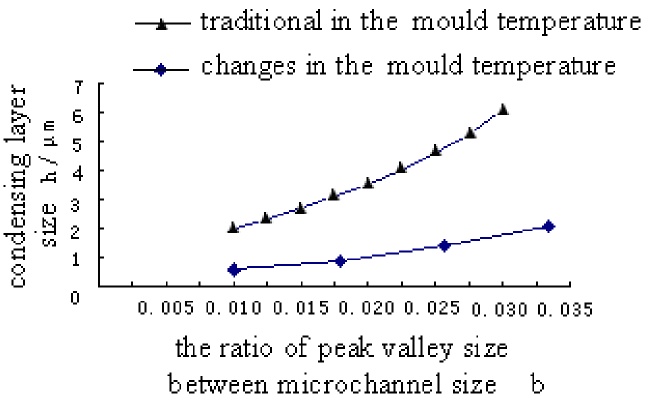


Figure 4 The relationship between the surface roughness of microchannel and the thickness of condensate layer

2.4 Surface Tension of Melts

Figure 5 shows the effect of the size of contact angle on the size of microfluidic flow resistance when the contact angle θ of melt surface tension is smaller than 90°. In microstructure injection molding, the increase of surface area/volume ratio is inevitably related to the effect of the surface tension related to the surface area of microfluidic flow channel. It can be seen from the figure that, when θ is smaller than 90°, the resistance of surface tension to microfluidic flow gradually reduces with the decrease of the contact angle θ; when the contact angle θ decreases from 90° to 80°, the flow resistance of microfluidics reduces by approximately 14%, it is thus clear that the surface tension at this moment promotes the flow of microfluidics and becomes its driving force. This suggests that the surface tension has a great impact on the flow of microfluidics during the microstructure injection molding process, which may be even more important than the effects of gravity and inertial force.

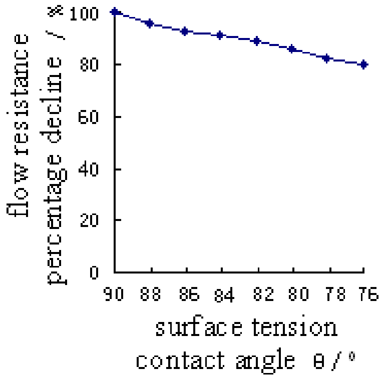


Figure 5 The effect of the contact angle of surface tension on the flow resistance of microfluidics

CONCLUSION

(1) The current study used the Cross-WLF as the basis, fitted and modified the viscosity model of macro melt flow behaviors based on the micro-scale flow conditions, and obtained the viscosity model of flow behaviors of melts during microstructure injection molding, which characterized the rheological properties of melts changing with the changes of the temperature, shear rate, pressure, feature size of microchannel and radius of gyration of polymer molecular chain in the microchannel during microstructure variotherm mold temperature injection molding.

(2) When the mold temperature rises to 120°C, the condensate layer on the microchannel surface basically disappears, the decrease tendency of opening width basically flattens out, and the opening width is no longer decreased with the elevation of mold temperature; when the ratio of the peak-valley size of microchannel surface roughness to the size of microchannel reaches 0.30, the condensate layer is about 6 μm thick, and the total thickness of condensate layer is almost equal to the size of microstructure; when the contact angle θ is smaller than 90°, the resistance of surface tension to microfluidic flow gradually reduces with the decrease of the contact angle θ, and the surface tension becomes the driving force of microfluidic flow.

(3) The variothermo injection molding technology is adopted to achieve the dynamic control of mold temperature, make the viscosities of plastic melts evenly and uniformly distributed in the whole microchannel section and the melts always under an even, low-viscosity molten status before the mold cavity is completely filled, effectively

eliminate the advanced condensation phenomena and ensure that the mold cavity is completely filled with plastic melts.

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