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# Longitudinal ultrasonic-assisted microinjection molding process for improved mold filling

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*Theoretical calculations and simulations have been created to analyze the mechanism of melt flow and can be used to guide selection of process parameters.*

Microplastic parts—such as micro-optical elements (e.g., micro-Fresnel lenses and light-guide plates with microstructures) and micromedical elements (e.g., microneedle arrays)—are usually fabricated with the use of microinjection molding ($\mu$IM). In this effective low-cost method, plastic is melted and then injected into a mold that contains microstructures, where it then cools and solidifies into the final part. During fabrication of plastic parts with high-aspect-ratio structures or complex shapes, however, some defects—such as short shots (i.e., incomplete filling in the last position of the mold—often occur. Improvements to $\mu$IM techniques are therefore required to provide improved molding quality for finished parts.

To date, several approaches have been investigated for the development of ultrasonic-assisted injection molding.[1–3] During these methods, however, the ultrasonic vibration is not directly applied to the polymer melt in the microcavity and the beneficial effects of the ultrasonic vibration on the polymer melt (e.g., improving the filling capability) are therefore not fully fulfilled. Moreover, the ultrasonic vibration causes very complex changes to the polymer melt that significantly affect the filling quality,[4, 5] but these have not yet been clarified in detail.

To overcome the current issues with $\mu$IM techniques, we have been investigating the action mechanism of the transformation that is caused by the ultrasonic vibration energy. To that end, we have proposed a novel longitudinal ultrasonic-assisted $\mu$IM (LU$\mu$IM) method to improve molding quality.[6, 7] For this work, we require a theoretical model of the melt flow to reveal the detailed action mechanism of the flow properties in the microcavity. This model can also be used to guide the process flow and parameter selection during our LU$\mu$IM method.

In our LU$\mu$IM approach, the longitudinal ultrasonic vibration (whose propagation direction is parallel to the melt-filling direction) acts directly on the polymer melt—through the core—which is integrated with the amplitude transformer of an ultrasonic generator. The energy of the ultrasonic vibration is then divided into two parts, i.e., the mechanical energy transmission and the mechanical energy conversion (see Figure 1). The mechanical energy transmission means that part of the energy is transferred to the polymer melt and causes the longitudinal vibration of the flow frontier particle. In contrast, the mechanical energy conversion means that part of the energy is converted into internal energy (including ultrasonic degradation energy and heat energy), which causes changes to the microstructure and rheological properties of the melt.

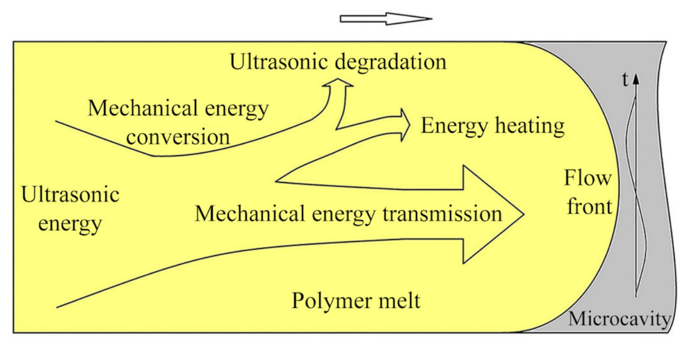


***Figure 1.*** *Schematic diagram of theoretical energy action mechanism during the longitudinal ultrasonic-assisted microinjection molding method. t: Temperature.*

Our theoretical model for the LU$\mu$IM method is based on a general power-law fluid equation. With respect to the mechanical energy transmission, we construct a particle vibration velocity equation for the melt flow front. According to the parameters of our model, the calculated absolute value of the flow-frontier particle-vibration velocity amplitude can become very large for $\mu$IM. This means that the viscosity of the polymer melt can be greatly reduced. In addition, the size of the melt's frozen layer is reduced, and the fluidity and filling capability of the melt improve. It is thus possible to achieve a high filling quality.

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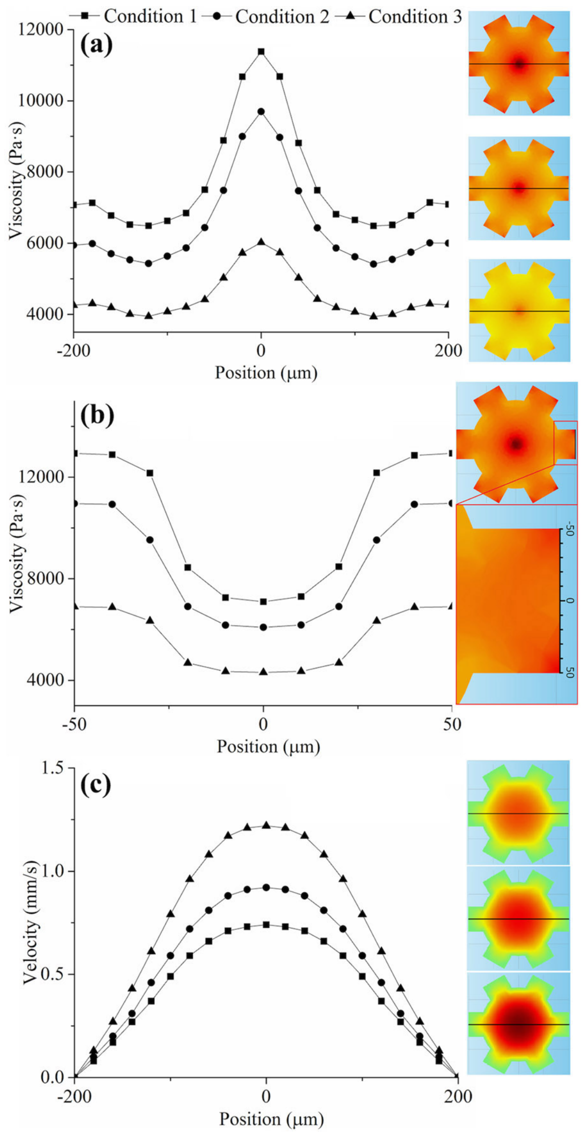


***Figure 2.*** *(a) Simulated viscosity distribution curves (left) for a polymer melt within a spline-shaft-shaped microcavity. The curves show the centerline viscosity (as illustrated by the black lines in the three cross sections on the right) under three different conditions, where condition 1 is the field without ultrasonic assistance, condition 2 is the field just with the effect of vibration energy transmission, and condition 3 is the field influenced by both energy transmission and energy conversion. (b) Simulated viscosity distribution curves (under the three conditions) for the part of the microspline tooth where a high-viscosity boundary layer and short shot often occur. (c) Velocity field distribution curves for the centerline (shown right) of the polymer melt under the three conditions.*

We obtain the theoretical model for rheological behavior by combining the action equations for ultrasonic degradation and energy heating with the general power-law fluid equation. From our theoretical equation we have thus shown that ultrasonic vibration has a specific influence on the rheological behavior because it changes the molecular weight and temperature of the melt. We have also used our theoretical equation to calculate viscosity-change curves. The functional relationship between processing factors and viscosity indicates that the ultrasonic frequency is the dominant factor for increasing the fluidity of the polymer melt (followed by the ultrasonic amplitude and the duration of the ultrasonic pulse).

To validate our theoretical results—i.e., ultrasonic vibration has a strong effect on microinjection molding of plastic parts with high aspect ratios and complex geometries—we have simulated the LU$\mu$IM process for a spline shaft. The viscosity and velocity field results (see Figure 2) show that both fields can be improved with longitudinal ultrasonic vibration. The filling speed, filling capability, and viscous uniformity in the spline-shaft-shaped microcavity can thus be improved with the use of ultrasonic vibration. Furthermore, this approach could reduce the viscosity and chance of a frozen layer occurring in the corners of the molded parts.

In summary, we have investigated the use of a novel longitudinal ultrasonic-assisted microinjection molding approach. In particular, we have created theoretical models that can be used to analyze the flow properties of polymer melts in our proposed LU$\mu$IM method. These theoretical models can also be used to guide the selection of process parameters. The results of our analyses and simulations show that the ultrasonic vibration can be used to achieve higher velocity, lower viscosity, a more uniform viscosity field, and a better filling performance than in standard $\mu$IM methods. Our approach can thus be used to obtain a better mold-filling quality. In the next stages of our work we will demonstrate the variation in the physical properties of plastic parts that can be achieved with our LU$\mu$IM method.

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