A weight analysis for the replication accuracy improvement of injection-molded microlens arrays

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Microlens arrays are essential components used in various optical devices. In this paper, a weight analysis aimed for the replication accuracy improvement has been proposed. The effects of processing parameters on the part weight have been investigated by numerical simulations as well as experiments. It is found that the data of part weight from experiments and simulations are of the same order of magnitude. The part weight increases with the increase of the melt temperature and the mold temperature. It increases with the increase of the injection time at first, and reaches its peak value at 0.8s, then decrease with the increase of the injection time. The part weight increases with the increase packing pressure. With increase of packing time, it is rapidly increased at first and then slightly varied, which reaches its peak value at 0.8s. The differences between the experimental and the simulation results are further discussed. It was validated that the weight analysis method can be used to evaluate the replication accuracy in a simple and practical way.

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Keywords: Replication accuracy, Microlens array, Injection molding, Weight analysis, Processing parameter

1. Introduction

Microlens arrays are widely and commonly used in optical systems and devices, such as digital cameras, mobile screens, computer screens and TV projection systems. Injection molding of plastics for micro- and micro-featured products has shown great commercial potential and is regarded as one of the cost-effective mass-production methods to produce microlens arrays for its excellent reproducibility and productivity (Lee et al. 2004, Chang et al. 2006).

Replication accuracy is a term often used to describe the fabrication precision of molded micro-features. Low replication accuracy gives rise to poor performance, as well as deteriorating the optical and mechanical properties of molded products. Many researchers tried to find a proper way to evaluate the replication accuracy of molded micro-features. Despa et al. (1999) and Sha et al. (2007) chose the filling depth of microstructures as an evaluating index. Schift et al. (2000) using the height of V-grooves to evaluate the replication accuracy. Alessandro D'amore et al. (2004) chose the aspect ratio of V-grooves as an index. Regarding the molded micro-channel width, Chen et al (2011) used gas-assisted mold surface heating to improve the replication accuracy of micro-featured molding. The dimensions along one direction of micro-features were chosen to evaluate the replication accuracy qualitatively in above mentioned researches. This method can be used to evaluate the replication accuracy for regular and simple parts with the help of some instruments, such as Scanning Electron Microscopy (SEM), Scanning Probe Microscopy (SPM) and Quick Vision System (QVS).

In this study, one objective is to find a simple and practical way to evaluate the replication accuracy of injection molded microlens arrays. It was reported that there's some kind of relationship between the part weight and the quality of molded parts (Zhao et al. 2003, Harry et al. 1991, 1992, Musa et al. 1999). In this paper, part weight will be used to evaluate the replication accuracy of injection molded microlens arrays. Based on the part weight analysis, another objective of this paper is to investigate the effects of processing parameters on the replication accuracy. This study provides a simple and practical quantitative method to optimize micro injection molding processing parameters with the aim of improving the replication accuracy, shortening the trail-and-error period and reducing the production cost.

2. Weight analysis

'Replication accuracy' or 'Replication fidelity' are often appeared in the literatures to describe the geometry accuracy of injection molded parts (Wu et al. 2007, Maria et al. 2010). Here we try to give a clear mathematic definition of it. Let Ω_c and Ω_p be the geometrical regions of the mold cavity and the molded product, and let $\Omega_c \cup \Omega_p$ be the overlapped region of the cavity and the product. Then the replication accuracy is defined in this study as following;

$$RA = \frac{\Omega_c \cup \Omega_p}{\Omega_c} \times 100\% \quad (1)$$

If the two regions Ω_c and Ω_p coincide, the replication accuracy is 100%. That means the molded product is perfectly replicated. Higher value of RA means high geometry accuracy of the injection molded products.

It is clear that excessive shrinkage of product and short shot of microstructures are two main causes that will bring low replication accuracy. Shrinkage of a point can be calculated by the following equation (Wang *et al* 2004):

$$V_i = \frac{\rho(T_{room}, P_{atm}) - \rho(T_i, P_i)}{\rho(T_{room}, P_{atm})} \quad (2)$$

where $\rho(T_{room}, P_{atm})$ is the mass density of polymer relaxed to room temperature at atmospheric pressure, $\rho(T_i, P_i)$ is the mass density of polymer at a point in temperature T_i at pressure P_i. From Equation (2), it is obtained that shrinkage decreased with the increase of the mass density $\rho(T_i, P_i)$ If microstructures are fully filled during the molding process, the volume of replicated structure (V_p) will be equal to the volume of cavity (V_c) at the end of filling, i.e. $V_p = V_c$. If microstructures are short-shot, the volume of replicated structure (V_p) would be less than the volume of cavity (V_c) at the end of filling, i.e. $V_p < V_c$. After packing, the gate is frozen at the frozen time (t_{gf}), the value of part weight is fixed and can be obtained:

$$W = \int_{V_p} \rho(x.y.z.t_{gf})dV = \int_{V_p} \frac{1}{\upsilon(x.y.z.t_{gf})}dV = \bar{\rho}_{v_p} \cdot V_p \quad (3)$$

where $\upsilon(x, y, z, t_{gf})$ is the specific volume of polymer at the frozen time. Equation (2) and (3) showed that the part weight contains the information of shrinkage and filling status of microstructures. Smaller shrinkage and higher density lead to larger volume of replicated structure of heavier part weight. The value of part weight, therefore, can roughly indicate the replication accuracy of the injection-molded micro-parts. It has been also showed in some experimental investigations that part weight has a close relationship to dimensional properties and is a good indication of process stability (Musa et al. 1999, Yang et al. 2006, Postawa et al. 2005). So, the part weight will be adopted in this study to evaluate the replication accuracy of injection molded microlens arrays quantitatively.

3. Experimental setup

Considering the fabrication difficulty of mold insert, microlens arrays of different shapes were simplified to micro cylinder array, as shown in Fig. 1. It was a 5×16 micro cylinder array with a substrate length of 12 mm, a width of 5 mm and a thickness of 0.8 mm. The structure of aperture was cylindrical geometrical shape with a diameter of 0.2 mm and a height of 0.3mm. The volume of the designed micro cylinder array was $48.75mm^3$.

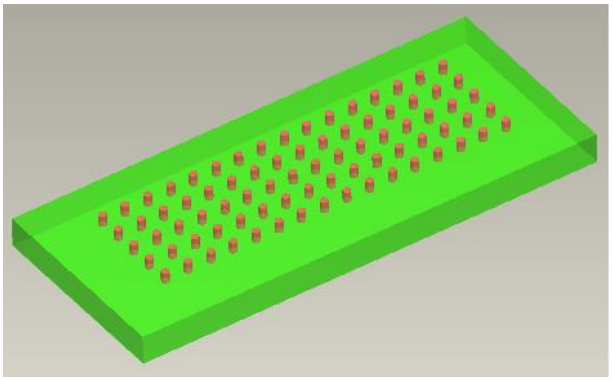

Fig. 1. Structure of designed microlens array.

A modified LIGA process was utilized for the fabrication of mold insert in this study. This process involved five processing steps: coating, exposure, develop, reflow, electroforming and molding. A schematic diagram of this modified LIGA process is illustrated in Fig. 2 (Lin et al. 2003, Yang et al. 2004). The fabricated nickel mold insert using this modified LIGA process is shown in Fig. 3.

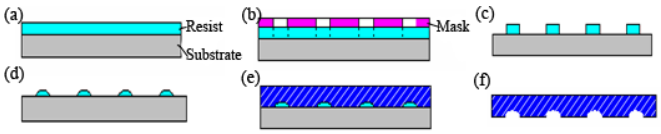

Fig. 2. Processing steps for the fabrication of mold insert with modified LIGA process. (a) Coating. (b) Exposure. (c) Develop. (d) Reflow. (e) Electroforming. (f) Molding.

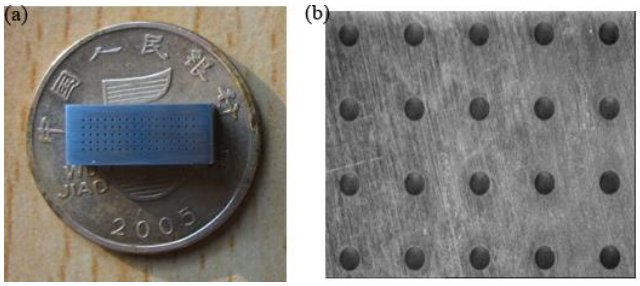

Fig. 3. Fabricated mold insert of micro column array using the modified LIGA process.(a) Nickel Mold insert. (b). Microscope image of microlenses with a diameter of 0.2 mm

Fig. 4 presents the structure of the mold and the assembly position of the mold insert. The fabricated mold is shown in Fig. 5.

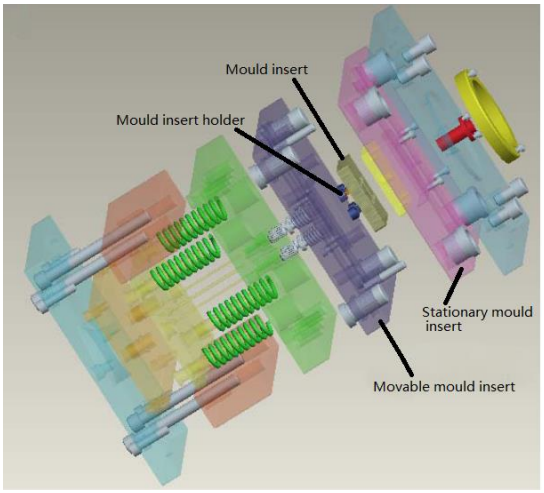

Fig. 4. 3D explosion drawing for the injection mold.

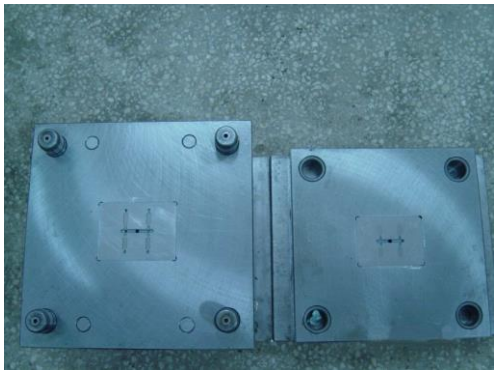

Fig. 5. Injection mold for the designed microlens array.

The Polymethylmethacrylate (PMMA) material, CM-205, made by Chimei Chemicals, was selected for the injection molding. Single factor injection molding experiments of the microlens arrays were performed on a Haitian® HTF86X1/J1 injection molding machine, which can supply 183MPa maximum injection pressure. The five main processing parameters are the melt temperature, the mold temperature, the injection time, the packing pressure and the packing time. Fig. 6 shows the injection-molded microlens arrays with its runner system. Table 1 lists the processing conditions used in this study. When one processing parameter was investigated and varied, the other processing parameters were kept at the default values. The default values are as follows: a melt temperature of 235 °C, a mold temperature of 70 °C, an injection time of 0.4s, a packing pressure of 75% maximum injection pressure, and a packing time of 2.4s. To make sure that the injection molding machine was running in a stable state, sampling will start from the fifth injection molded parts after the adjustment of the processing parameter, five specimens will be collected under every group of processing parameter. The micro columns array (including the overflow well) will be carefully separated with the runner system by a knife at the end of gate. The weight of injection-molded microlens array were measured by a Mettler Toldeo® AB135-S accuracy balance (accuracy 0.01/0.1mg), the average value of every 5 specimens in the same group will be took as the weight of the injection molded micro columns array. The digital image of microlenses was captured by a Rational® VMS-1510A digital video-meter.

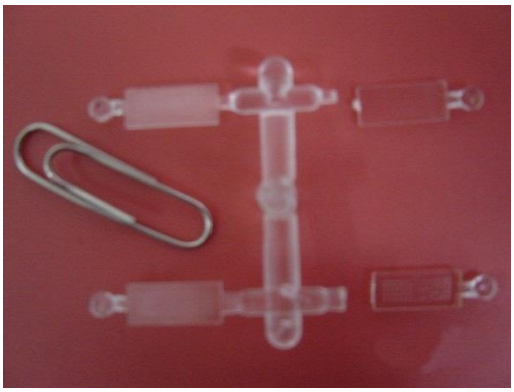

Fig. 6. Injection-molded microlens array with its runner system.

Table 1. Processing conditions used in this study.

Processing Conditions	**Set no.**				
Factors under investigation	Melt temp. (°C)	Mold temp. (°C)	Injection time (s)	Packing press. (%)	Packing time (s)
Melt temperature (°C)	230, 235, 240, 245, 255, 260	235	235	235	235
Mold temperature (°C)	70	50, 60, 70, 75, 80, 85, 90	70	70	70
Injection time (s)	0.4	0.4	0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6	0.4	0.4
Packing pressure (%)	95	95	95	75, 80, 85, 90, 95, 100, 105	95
Packing time (s)	2.4	2.4	2.4	2.4	0.4, 0.8, 1.2, 1.6, 2.0, 2.4, 2.8

4. 3D numerical simulation

The Moldflow Plastics Insight (MPI®) v.6.2 commercial software package was used to carry out the numerical simulations. It is one of the commonly used commercial packages, specifically aimed towards injection molding simulation. The simulation model of microlens array is shown in Fig. 9, whose gate and overflow well were pre-modeled as one part of the simulation structures. The overflow well was designed for the ejection of molded product. The mesh of the simulation model was done in the software package Hypermesh and then imported to Moldflow, which passed the mesh quality check including mesh match percentage in Moldflow. The mesh had 338751 tetrahedral elements and 67490 nodes. There are six element layers across the base plate thickness and five element layers across the height direction of the micro columns.

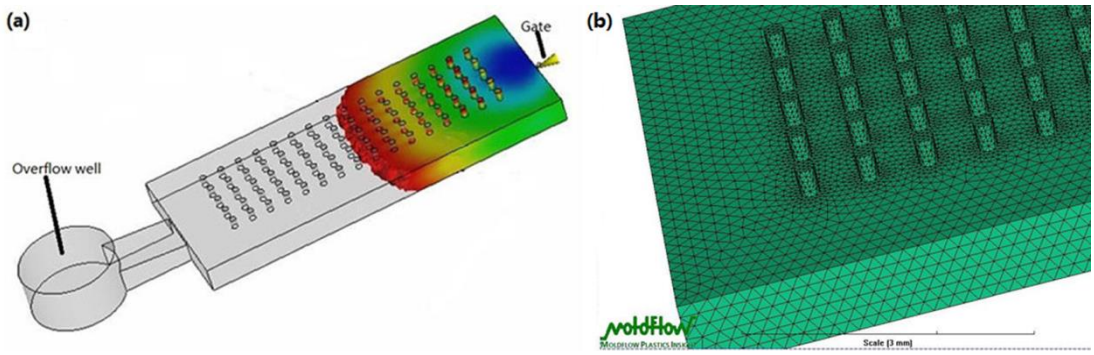

Fig. 7. 3D geometrical simulation model in MPI® software. (a). Overall model. (b). Detailed meshes.

5. Results and discussion

Fig. 8 presents the effects of processing parameters on the part weight of injection-molded microlens arrays from both the experimental and simulation results. It is found that the data of part weight from the experiments and the simulations are of the same order of magnitude. The values of part weight from the experiments increased with increase of the melt temperature, increased with increase of the mold temperature. The melt exhibits a lower viscosity, a less pressure loss and a smaller temperature gradient with a higher melt temperature or a higher mold temperature during the filling stage. This brings a better filling into the micro structures and thus larger part weight of the molded product. The data from the simulation results shows an opposite trend, where the values decreased with increase of the melt temperature and decreased with increase of the mold temperature.

From Fig. 8(c), the part weight increased and then decreased with increase of the injection time. The values from the experiments are around 1.38% higher than the values from the simulation. It reached its peak value at the injection time of 0.8s from the experimental results, while it reached its peak value at the injection time of 1.2s from the simulation results. The peak value reflects the time with better filling of the micro structures. The values of part weight from the experiments and the simulations represent the similar increasing trends with increase of the packing pressure, shown in Fig. 8(d). A larger packing pressure is useful in making the material in the cavity denser. The values from the experiments are around 2.13% higher than the values from the simulation. From Fig. 8(e), the values of the part weight from both the experiments and the simulations rapidly increased then slightly varied with increase of the packing time. The experimental values are about 1.22% higher than the values from the simulation. The part weight reached its peak value at the packing time of 0.8s from the experimental results, while it reached its peak value at the packing time of 1.2s from the simulation results. The gate is frozen and the melt cannot be filled into the cavity any more when the part weight reached its peak value. The part weight is then almost fixed at its peak value.

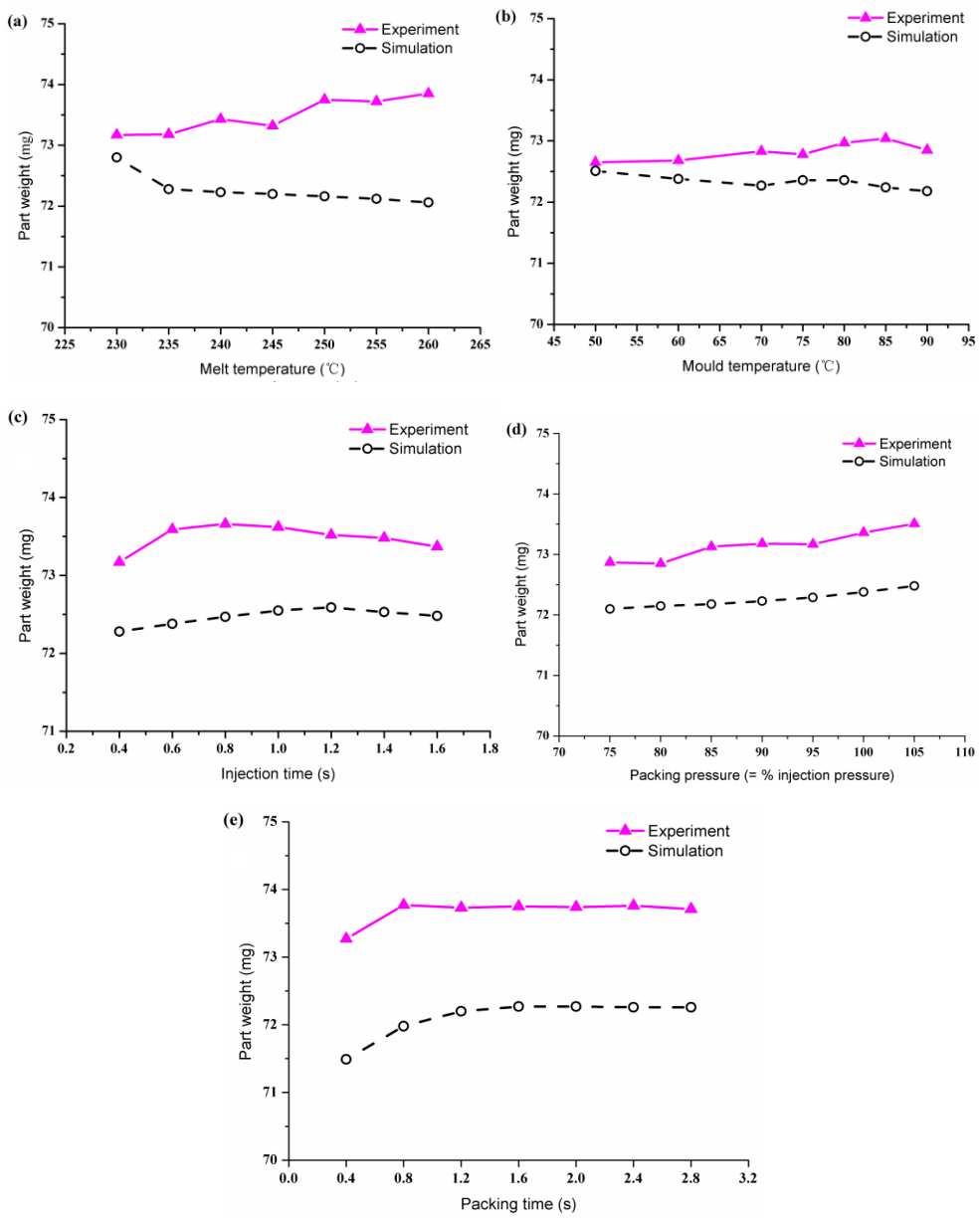

Fig. 8. Effects of processing parameters on the part weight of injection-molded microlens arrays from both the experimental and the simulation results.

The differences between the numerical simulation and the experimental results may stem both from the experimental errors and the possible limitations involved in the commercial packages. For the experimental aspects, the accuracy may be affected by the measuring method, the precision of instrument, the separation between the part and the gate, and the ambient environment. For the commercial packages, some possible limitations have been clearly pointed out by Weng et al. (2010). Firstly, the rheological data used in the current packages are obtained from macroscopic experiments. These macroscopic data would not be suitable for molding microscale flows. Furthermore, the simulation tool uses the no-slip boundary. While De Gennes (1985) states that a polymer melt will exhibit a non-zero tangential velocity at a melt-smooth metal interface, in contrast to the commonly imposed no-slip condition. This would bring substantial discrepancy to the simulation results. Thirdly, another complicated boundary factor in the simulation is the surface tension.

In order to validate the method of using the part weight to evaluate the replication accuracy of molded microlens arrays, the digital images of microlenses with different injection times are captured and shown in Fig. 9. The microlenses are found to be filled better and possess a larger part weight with the injection time between 0.8s and 1.0s. This finding is also well reflected by the effect of injection time on the part weight, shown in Fig. 8(c). It is concluded that the effects of processing parameters on the part weight are similar to the effects on the replication

accuracy of micro parts. This similarity can thus be utilized to evaluate the replication accuracy in a simple and practicable way.

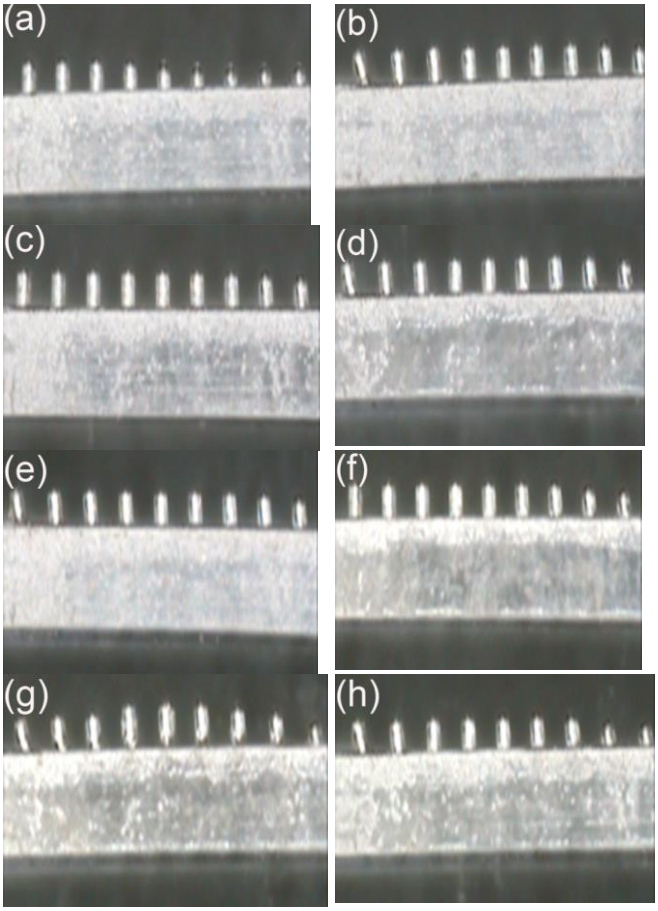

Fig. 9. Digital images of microlenses with different injection times.(a). t=0.4s, W=73.15mg. (b). t=0.6s, W=73.58mg. (c). t=0.8s, W=73.72mg. (d). t=1.0s, W=73.62mg. (e). t=1.2s, W=73.55mg. (f). t=1.4s, W=73.46mg. (g). t=1.6s, W=73.32mg. (h). t=1.8s, W=73.30mg.

6. Conclusions

In this paper, a weight analysis aimed for the replication accuracy improvement has been proposed. The effects of processing parameters on the part weight have been investigated by both numerical simulation and experimental methods. It is found that the data of part weight from the experiments and the simulations are of the same order of magnitude. From the experimental results, the values of part weight increased with increase of the melt temperature, increased with increase of the mold temperature, increased and then decreased with increase of the injection time. The value increased with increase of the packing pressure, rapidly increased then slightly varied with increase of the packing time. It reached its peak value at the injection time of 0.8s, or at the packing time of 0.8s. However, there is a little discrepancy between the experimental and the simulation results which could arise both from experimental errors and the possible limitations of the simulation software. With the help of digital video-meter, it is finally validated that the effects of processing parameters on the part weight are similar to the effects on the replication accuracy of micro parts. This similarity can thus be utilized to evaluate the replication accuracy in a simple and practicable way. A better understanding of the replication accuracy can help us improve the product quality, reduce the cost and optimizing the processing parameters.

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