Paper

Development of Plastic Injection Molding Using the LIGA Process

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Plastic injection molding was conducted with a mold cavity mounting a precision Ni stamper, which was fabricated by the LIGA process. The used thermoplastic materials were PC (polycarbonate), TPX (polymethylpentene), and POM (polyacetal) in consideration of applications in the optical, medical, and mechatronics fields. To evaluate the high aspect ratio microstructures fabricated by plastic injection molding, the microstructures were measured as to thermoplastic material filling, mold release, flatness, and transferability. In a test pattern having lines and spaces, each material filled the bottom of a stamper having a height of 100 μm and a line width of 20 μm. In a test pattern including posts and gear teeth, materials filled the bottom of a stamper having 300 μm in height. Measured surface roughness of both the stamper and the molded product was several tens of nm, which of a sufficient transferability for practical application using plastic injection molding.

Keywords: *LIGA process, deep X-ray lithography, Ni stamper, plastic injection molding, high aspect ratio, material filling*

1 INTRODUCTION

One of the key technologies for the 21st century will be micro-machining technology. As research and studies in the fields of the microelectronics, mechatronics, medical technology, and biotechnology are promoted, the demands for microparts produced by those technologies will be greatly increased. Focusing on the economical mass production of the microparts, precision plastic injection molding is a promising technique.

In plastic injection molding, high transferring accuracy of less than a micrometer can be achieved. However, mass production technology for molding high aspect ratio microstructures is rarely reported. DVDs are a molded plastic product with a diameter of 120 mm, having high-density pits precisely transferred on their surfaces of the order of submicrons. However, the pits have shallow depths and the aspect ratio is 0.1 or less. Microfrensnel lenses and photoconductive plates of other molded plastic products have saw-tooth patterns of several μm to several tens of μm formed on their surfaces. Those patterns are required to be transferred more precisely than pits on DVDs, so as to have the aspect ratio of approximately 1 (corresponding to several μm to several tens of μm).

To produce a mold having microstructures with a relatively low aspect ratio, the conventional semi-conductor process or photo-fabrication in which ultraviolet rays are used, can be employed. However, there are some limits in producing a mold having high aspect ratio microstructures, using the conventional machining method. In addition, it is difficult to fill a thermoplastic material into the high aspect ratio microstructures, and defect free release of such microstructure molded product from the mold is also difficult.

To make molds including high aspect ratio microstructures, the LIGA (German acronym for Lithographie, Galvaoformung, Abformung) process is attracting attention. [1]

In the LIGA process, high aspect ratio microstructures can be made using deep X-ray lithography, and precision Ni microstructures with an aspect ratio of 100 or more, can be fabricated by electroforming. By performing plastic injection molding with a mold cavity mounting a precision Ni stamper fabricated using the LIGA process, mass production of high-precision microparts having a higher aspect ratio than the conventional parts, can be realized.

Conventional papers about plastic molding using the LIGA process present a molding method where the temperature of the mold is changed for each shot. [2] [3] [4]

To accurately transfer high aspect ratio microstructures using molten thermoplastic material, it is preferable that the molten material is charged into a mold whose temperature is higher than that of the molten material. However, this may bring about losses as to the longer cycle time required to heat the mold.

To release a molded product from a mold without deformation, the molded product needs to be cooled until sufficiently solidified.

Every shot includes the steps of filling the mold with molten material, cooling the mold, releasing a molded product from the mold, and raising the temperature of the mold to the preset temperature again for the next shot. However, it takes a long time to again raise the mold temperature to the preset temperature for every shot, impairing the paramount advantage of injection molding, that is, the value of mass production.

A compact disk (CD) with accurate microstructures is produced by a conventional method where the mold is set at or below the no flow temperature. Its shot cycle (the total time taken for completing a CD) is only 3 seconds or so.

One paper recommends the cavitiy should be as thin as possible to reduce the heating/cooling time, but this adds constraints as to the molded product shape.

The thermal degradation of thermoplastic material is also a problem. With injection molding, when filling is completed in a single shot, at least the material to be used for the next shot will have already been heated and molten in the cylinder.

As the time to reach the predetermined temperature of the mold becomes longer, the molten built up in the cylinder is apt to entail degradation, decomposition, gas and other problems due to its heating.

It might be suggested that the temperature of the heater in the cylinder is lowered, however, the flowing property of the molten material is not stable if there is a temperature difference for every shot. If molding is not performed in sequence, the value measured for every shot is not stable and it is difficult to minimize the difference.

This paper reports an injection molding method where the temperatures of the mold and the material are unchanged. This method enables plastic molding using the LIGA process where the microstructures to be manufactured have a high aspect ratio and taper-less portions, which are unfavorable for injection molding, and with a shot cycle time without the loss of mass production, by optimizing parameters related to molding.

With injection molding, the moldability greatly depends on the material characteristics.

In this paper, the materials for evaluation were selected from the viewpoint of practical use. They were PC having characteristics required for optical use, TPX having chemical resistance as required for medical use, and POM having favorable sliding and anti-creep features, both required for mechatronics uses (e.g. gears). The paper also shows how the molding conditions for each material were picked out.

2 TEST PATTERNS

In plastic injection molding, grain or pellet-sized material is melted and mixed in the heating cylinder of an injection molding machine. The melt is injected into a mold cavity, with pressure applied. After the mold is cooled and the melt solidified, the mold is opened. Thus, a part having the shape of the mold cavity transferred onto the part, can be obtained.

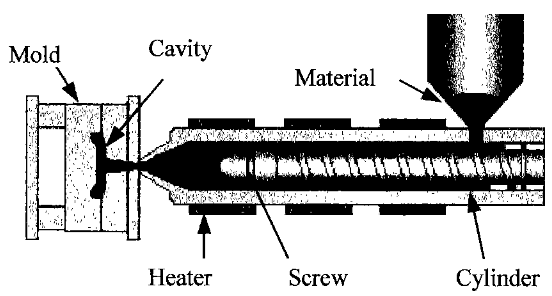

Fig. 1 Conceptual illustration for injection molding

Plastic injection molding is applied to a wide range of products in the various fields, due to its low-cost mass production, as well as the freedom of choice of materials and the high degree of flexibility in design of shapes, according to applications.

For the experiments, two types of test patterns were designed and plastic injection molding was conducted using those patterns.

The first pattern (pattern a) was designed to have ten sets of lines and spaces with the line and space widths of 10 μm to 100 μm in increments of 10 μm. The length of the lines was determined as 8 mm in consideration of various applications to devices in the future. The target height was determined as 200 μm, so that the aspect ratio with respect to the minimum line width became 20.

The second pattern (pattern b) was designed so as to include a total of 220 oval posts with 70 μm width and 200 μm length, aligned in two rows, 110 gear teeth aligned in one row, and some ribs. The target height for pattern b was determined as 300 μm.

The size of the molded product including patterns a and b was 22 mm x 15 mm.

3 ABRICATION OF PMMA RESIST MICROSTRUCTURES

For pattern a, a 100 μm-thick and a 200 μm-thick PMMA resist were deposited on a substrate of a 4-inch Si wafer with a 0.1 μm-thick Ni/Cr conductive layer.

For pattern b, a 200 μm-thick and a 300 μm-thick PMMA resist were deposited on the same substrate.

The X-ray mask (manufactured by Optonics Seimitsu) was composed of a 3 μm-thick Au X-ray absorber, a 40 μm-thick polyimide (PI) membrane, and a 1 mm-thick stainless steel frame. One of the most significant characteristics of the X-ray mask is that it had a disk-shaped membrane with a diameter of 4 inches. Using the above-structured resists and X-ray mask, X-ray lithography was conducted with the synchrotron radiation (SR) source at Ritsumeikan University. The area irradiated by the SR source in the experiment was 20 mm x 30 mm per chip.

The developer used was a GG developer warmed to 38°C.

The GG developer is a mixed solution made by the following four chemical agents. Its mixture ratio is shown in Table 1.

Table 1 Mixture ratio of GG developer

Chemical agent	Vol%
2-(2-butoxyethoxy) ethanol	60
Morpholine	20
2-aminoethanol	5
Pure water	15

Fig. 2 shows an SEM photograph of a PMMA resist microstructure of pattern b.

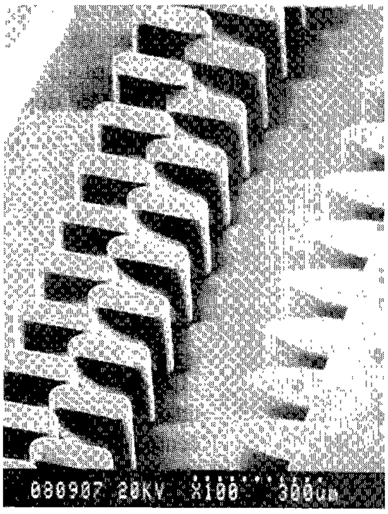

Fig. 2 PMMA structure of pattern b

4 FABRICATION OF Ni STAMPER BY ELECTROFORMING

Using the PMMA resist microstructures, electroforming was conducted in a bath containing an electrolyte of mainly nickel sulfamate, to produce Ni microstructures. Table 2 shows the compositions and conditions of the electrolytic bath.

Table 2 Compositions and Conditions of Electrolytic Bath

Electrolyte	Nickel sulfamate: 350 g/l Boric acid: 30 g/l Pit inhibitor: 5 ml/l
Bath temperature	38°C
pH	4.0
Cathode current density	1 – 3 A/dm^2
Anode	S nickel

At the commencement of electroforming, the current was applied with the cathode current density of 1 A/dm^2, for approximately 24 hours. Then, the current density was gradually raised to 3 A/dm^2. The bath temperature of 38°C is relatively low for that containing nickel sulfamate. However, this temperature was set so as to become close to that of the developer, to prevent the PMMA microstructures from thermal deformation.

High aspect ratio microstructures having beam patterns, such as pattern a, are susceptible to damage during the wetting processes, for example, the developing and cleaning processes, due to the flow or the surface tension of the solvent. To prevent microstructures from being damaged during the wetting processes, conditions for the developing and cleaning processes were optimized. As a result, Ni microstructures were stably fabricated. Figs. 3 and 4 show SEM photographs of a precision Ni stamper (for pattern a) produced by electroforming after the PMMA resist microstructures were fabricated. Ni microstructures with a minimum line width of 10 μm, height of 200 μm, and length of 8 mm, were formed without deformations or damages.

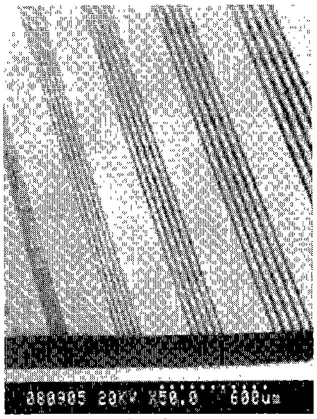

Fig. 3 Ni microstructure of pattern a

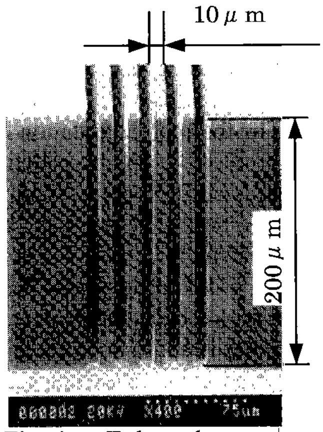

Fig. 4 Enlarged view of Fig. 3

5 PLASTIC INJECTION MOLDING

5-1 Flowing Properties of Molding Materials

To properly fill material into high aspect ratio microstructures, the mechanism of the reduction in the viscosity of the melt was examined from a rheological point of view.

When the melt is injected at a higher injection speed than a normal setting to augment the flow of the melt, the viscosity of the melt is reduced due to shear heating caused by the frictional resistance when the melt flows through a channel. It is said that the temperature during the shear flow increases in proportion to the square of the flow speed [5].

The viscosity of the melt is reduced depending on the shear rate of the melt, as the flow speed is high. Thermoplastics have linear giant molecules, and are subjected to the reduction of viscosity, due to alignments of molecular chains and disentanglements of the molecular chains [6]. The flowing property of thermoplastics is not classified as Newtonian fluids due to their molecular structures, but classified as non-Newtonian fluids. The apparent viscosity η is expressed by the following formula when the shear rate is relatively high [5] [6].

$$\eta = \tau/\gamma = m\gamma^{n-1}$$

where

η:	apparent viscosity (Pa·s)
τ:	shear stress (Pa)
γ:	shear rate (s^{-1})
m:	consistency index
n:	power law index $n < 1$

The apparent viscosity of the melt decreases as the shear rate increases.

5-2 Test Equipment

An injection molding machine having an internal pressure waveform controlling system, was used in the experiments, since variations in the injection molding controls influence the material filling into the microstructures. Under the control of this system, the waveform of the internal pressures when the melt is injected and filled to seal the gate, becomes identical for every shot, with the pressures of the melt detected and fed back to the controlling system.

The mold has a structure such that the stamper and a sensor that detects the pressures of the melt, can be mounted.

In general, a mold has 10 – 20 μm vents (slits) to smoothly expel the residual air or gas generated by the material which is filled in the cavity. However, the air or gas in the cavity is not expelled smoothly from the vents because of compression resistance during material filling. As a result, it is expected that the material can not be filled into microstructures. Therefore, a vacuum pump was used to reduce pressures inside the cavity.

5-3 Tests

In the optical, medical, and mechatronics fields, applications using plastic microparts are greatly anticipated. Three types of materials, PC, TPX, and POM meeting the required characteristics in each field, were selected for evaluation.

To achieve the proper material filling into high aspect ratio microstructures, molding factors such as the injection speed, internal pressures, and temperatures, were assigned using an experimental design (Taguchi method) [8] to narrow down to the optimum molding conditions. Plastic products molded under the extracted experimental conditions, were evaluated with respect to the material filling, transferability, flatness, and mold release.

Material filling: To avoid a section of a molded product to be observed, from being deformed or damaged due to cutting, molded products as test pieces were coated with a commercially available epoxy resin in liquid form and which was solidified. After the molded products with the solidified epoxy resin were cut and polished to form the section, the heights of lines and posts were measured and the shapes were observed under a microscope.

Mold release: Scratches and damaged shapes of patterns were observed under an electron microscope .

Flatness: Using a shape measuring instrument, the flatness of the molded products was measured at the rear side of the patterns.

Transferability: Surface roughness of the molded products was measured at their vertical surfaces in the vertical and lateral directions, using an atomic force microscope (AFM).

5-4 Experimental Results and Discussion

(1) Material filling

Pattern a:

All the above-three materials were able to fill the bottom of the stamper having the height of 100 μm and the line width of 20 μm.

It was comparatively easy to form the stamper having a line width of 20 μm, but was not easy to form a stamper having the line width of 10 μm. Therefore, the development of technology for the prevention of deformation and damage of the stamper was made in parallel with the molding evaluation. As a result, as shown in Fig. 4, a stamper having a line width of 10 μm could finally be formed. However, with injection molding, the stamper was damaged when it was released from the mold, and a pattern with a line width of 10 μm could not be formed.

Fig. 5 is a sectional view of the molded product of TPX having a line width of 20 μm.

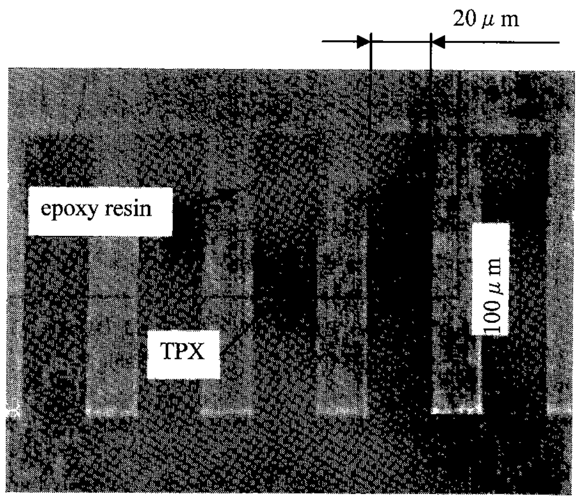

Fig. 5 Sectional view of pattern a having a line width of 20 μm

Pattern b:

As to the product molded using POM, the incomplete filling of a rib having a total length of 4.2 mm was measured. Material filling depends on the molding conditions. The molding conditions include a case where the material is apt to fill the core layer at the center more than the skin layer near the surface of the mold, and another case where there is no significant difference as to filling between the core layer and the skin layer. If only the maximum length the material fills the center is measured, the variation between measurements becomes very large. Therefore, for measurement purposes, the point where the material fills less than half the mold width (as shown in Fig. 6) is regarded as the measuring point for incomplete filling.

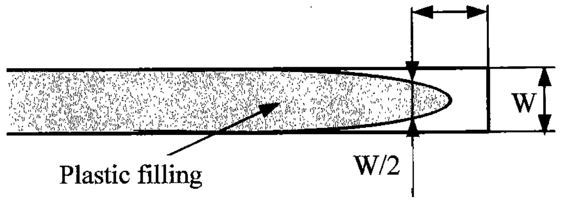

Fig. 6 Definition of incomplete filling length

The results of the filling analysis are given in Table 3 and Fig. 7.

Table 3 Experimental conditions

	Factor	Unit	1	2	3
A	Cyl. temp.	℃	190	210	230
B	Mold temp.	℃	80	90	100
C	Injection speed	mm/sec	100	300	600
D	Injection pres.	MPa	40	70	100

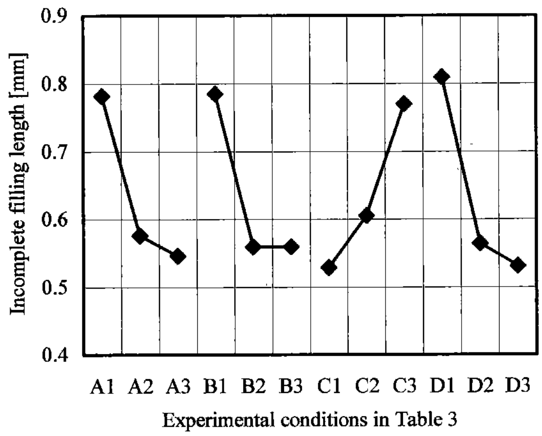

Fig. 7 Factor and Effect diagram

The results indicate that if any of the values of molten material temperature, the mold temperature, and the injection pressure are higher, they significantly contribute to the filling of the stamper. It has been shown that the faster the injection speed, the less the molten material is prone to fill the stamper. This is because the air in the cavity is not discharged. However, when the injection speed becomes too slow, the filling of the stamper becomes incomplete. The injection speed and the injection pressure were linked in further detail based on the above results. Fig. 8 shows the relationship between the injection speed and the injection pressure as a result of the detailed linkage. The mold temperature and the molten material temperature were set to level 3 which is thought as the upper limit in terms of the material characteristics. As to the molten material temperature, the filling was incomplete under level 1, which was set as one of general molding conditions for POM. Although the higher molten material temperature can contribute to the filling, if the temperature is excessively raised, the molten material may generate lots of gas thereby hampering the filling. Therefore, the setting of the material temperature was carefully treated.

As is apparent in Fig. 8, the slower injection speed and the lower injection pressure lead to incomplete material filling. At the injection speed of 100 mm/sec or more, the material was unable to fill the stamper as the speed increased, as with the result of L9. [8] The molding conditions to minimize the incomplete filling length were an injection speed of 60 mm/sec, and an injection pressure of 130 Mpa. At that time, the incomplete filling length of the rib having a total length of 4.2 mm was 82 μm. The rib is longer than the post or the gear which has a length of 200 μm, and the gas accumulated at the bottom is less prone to escape. Therefore, it was more difficult to fill the rib than the post or gear.

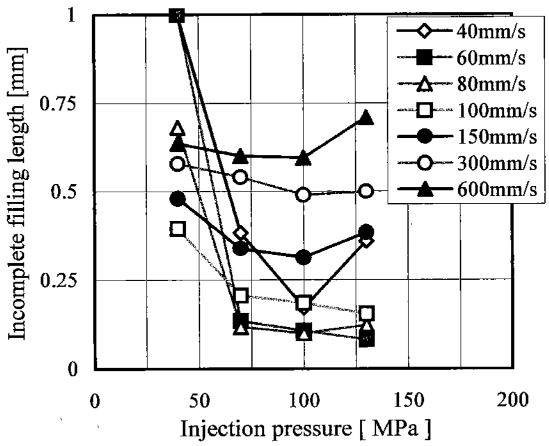

Fig. 8 Relevance between injection speed, injection pressure, length of unfilled portion

Similarly, molding conditions for TPX and PC were narrowed. Fig. 9 is a sectional view of molded posts of TPX.

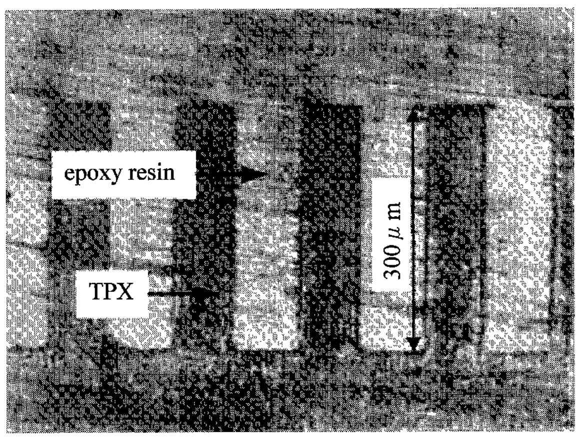

Fig. 9 Sectional view of posts molded under optimum conditions

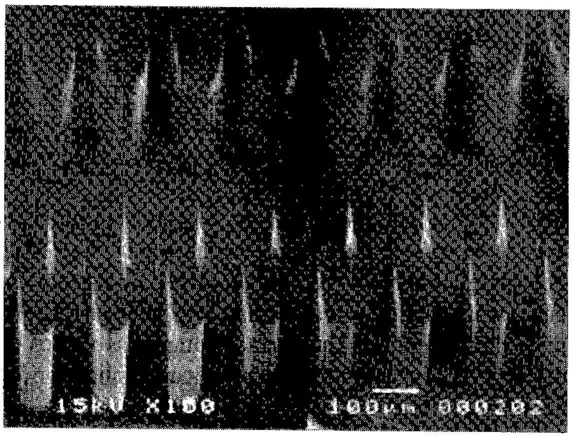

Fig.10 SEM photograph of the molded product in pattern b

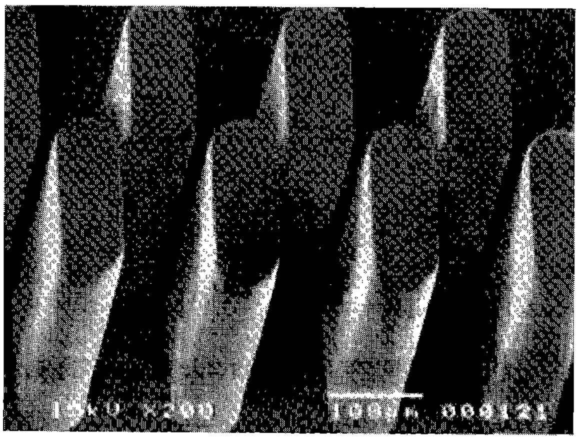

Fig. 11 SEM photograph of posts in pattern b

A sharp edge is formed on the top of each post of the molded product. This indicates that the material was able to fill the bottom of the stamper. Figs. 10 and 11 show SEM photographs of the mold product of TPX.

(2) Mold release

Stampers fabricated using the LIGA process tend not to have tapered portions, due to the vertical emission angle of X-rays, so that release of the molded product from the stamper mounted in the mold cavity, becomes difficult. Therefore, deformation on molded product was a worry, with the resistance during mold release increased, for the above reasons. However, the molded products were separated from the mold without any problems. When the molded products having pattern a were observed under an electron microscope, they were not deformed or scratched.

Due to the structure of pattern b having more protruded portions than pattern a, the mold release resistance increases, and the molded products having pattern b are more susceptible to deformation during mold release. When the injection pressure and speed were too low for the production of the molded products having pattern b, the pressure of the melt was not sufficiently applied to the posts, resulting in cracks in the roots of the posts during mold release and the deformation of bottom surfaces. When the injection pressure and speed were too high for the production of the molded products having pattern b, the posts were pulled up when separated from the mold, resulting in deformed products. However, these problems were solved by optimizing the molding conditions. Consequently, molded products that were observed under the electron microscope, did not have scratches or deformations.

(3) Flatness

As all injection-molded parts shrink without exception, there is a difference in size between the mold and the product.

Given that it is possible to completely fill the mold, the accuracy of the product shape may be obtained not by bringing the dimension of the mold close to that of the product but instead shrinking the product to as close to a similar shape of the mold as possible. Typical factors that the product deviates from the similar figure include unevenness of shrinkage due to the difference of thickness and deformation during mold release. During this evaluation, the roots of the posts are most susceptible to uneven shrinkage. When the shrinkage in such a part is different from that in another part, warpage may occur on the surface where a pattern is formed.

In the case of such a part where material filling is difficult, mold release is not easy. As a result, warpage may occur on the surface.

As shown in Fig. 12, warpage of a patterned part of a product was measured on the reverse side with reference to a line connecting both ends which are beyond the patterned part and where needles are placed.

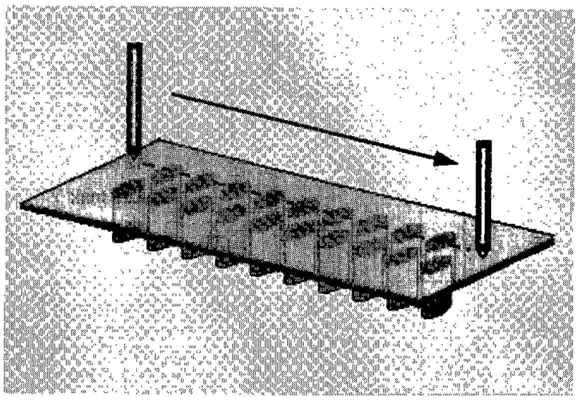

Fig. 12 Measurement of flatness

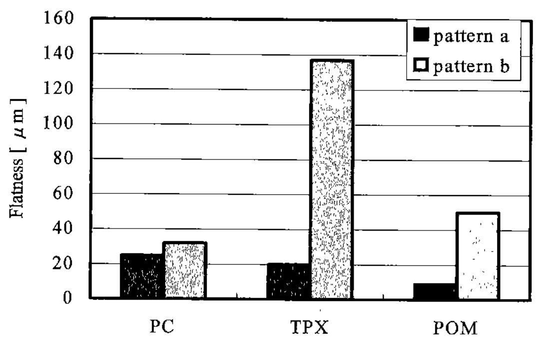

Fig. 13 Flatness of molded products

Fig. 13 shows the measurement results.

The measurement result indicated that molded products having pattern b were not as flat as those having pattern a. It was predicted that the molded products having pattern b incurred a greater residual strain caused by the molding shrinkage due to their shapes having much more protruded portions than pattern a and also due to residual stresses applied during mold release.

As to the measurement result indicating that the flatness of TPX for pattern b was greater than that of other materials, it was predicted that the rigidity of TPX at high temperatures was lower than that of the others, so that deformation during mold release was likely to occur.

(4) Transferability

The side surfaces of the stamper and molded product were measured as shown in Fig. 14.

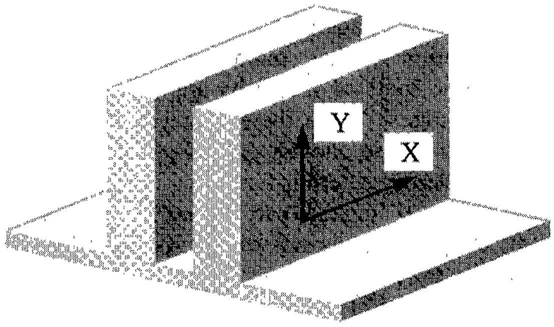

Fig. 14 Measurement directions using AFM

The surface roughness of the stamper and the molded product were measured at their side surfaces. Fig. 15 shows the measurement results.

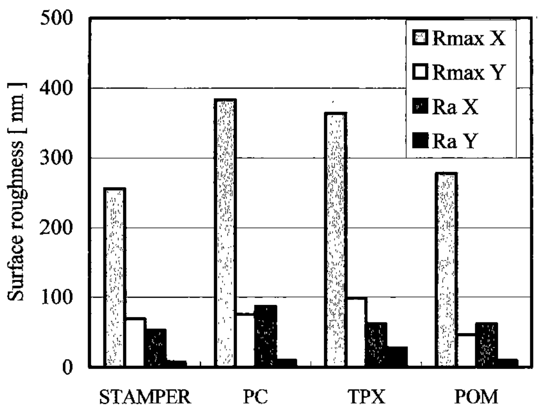

Fig. 15 Surface roughness of stamper and molded products

Surface roughness measured in the X direction depends on the configuration of the sidewall of the Au X-ray absorber in the X-ray mask. That measured in the Y direction depends on the accuracy of the X-ray lithography process. Values of surface roughness measured in the X direction were greater than those measured in the Y direction in every material. As the transferability is compared between a mold and a molded product, the molded product generally has poorer transferability, since very fine protruded and recessed patterns are more difficult to be transferred onto the molded product. In view of the poorer transferability of the molded product, the surface roughness of the product seemed to be smoother than the surface roughness of the mold. However, when the surfaces of the stamper and the molded product were measured by an atomic force microscope (AFM), the surface roughness value of the molded product of every material was slightly greater than the surface roughness value of the stamper. The surface roughness values of all materials will be sufficient for practical application using plastic injection molding.

Figs. 16, 17, 18, and 19 show the surface profiles of the Ni stamper, and the molded products of PC, TPX, and POM, respectively.

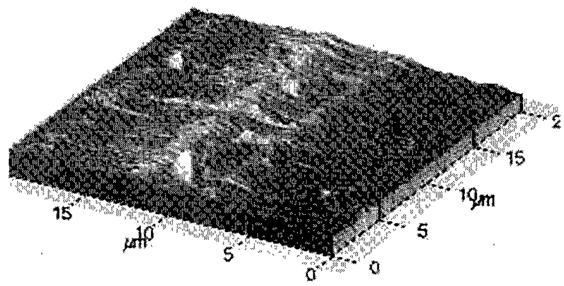

Fig. 16 Ni stamper surface profile measured by AFM

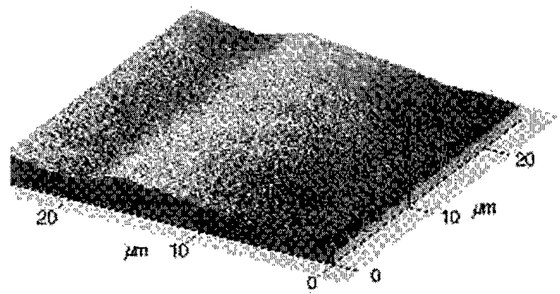

Fig. 17 PC surface profile measured by AFM

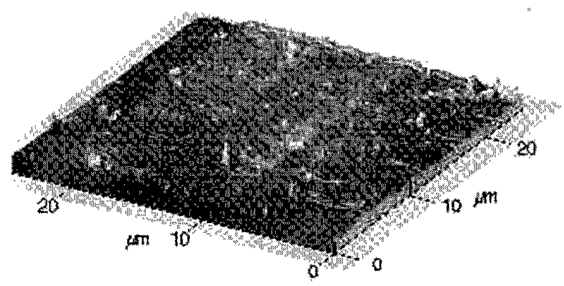

Fig. 18 TPX surface profile measured by AFM

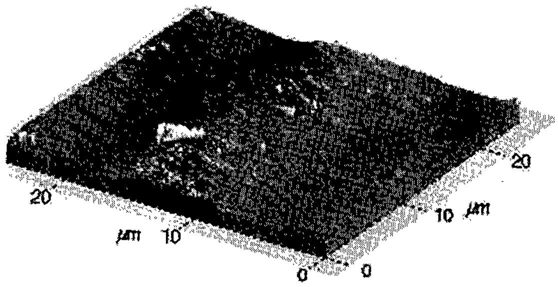

Fig. 19 POM surface profile measured by AFM

Horizontal dents were observed more on POM than PC or TPX. The crystalline material of POM starts solidifying and shrinking at its melting point as a boundary. When the injection speed is low, the non-uniform solidification and shrinkage of the material may occur. This may cause creased patterns on the surfaces. However, it was not deemed that those dents on the POM came from the creased patterns caused by the non-uniform solidification and shrinkage, in view of the small size of the dents. If the dents were caused during mold release, the dents would continuously appear in the Y direction. However, the dents did not continuously appear in the Y direction. Therefore, the dents will be caused due to characteristics particular to POM. Transferability varies according to the molding conditions, such as characteristic and flowing property of the material, mold temperature, and pressure maintained. For crystalline thermoplastic materials like POM, degree of crystallization on molded product surfaces varies according to the mold temperature. Therefore, molded products without the dents on their surfaces may be possible by narrowing down the molding conditions.

6 CONCLUSION

Plastic injection molding was conducted with a mold cavity mounting a precision Ni stamper, which was fabricated by the LIGA process. Evaluated materials were PC, TPX and POM in consideration of applications in the optical, medical, and mechatronics fields. Molding conditions were narrowed down using experimental design (the Taguchi method) to achieve the primary object of proper material filling into high aspect ratio microstructures. The products fabricated by plastic injection molding under the extracted conditions, were evaluated with respect to material filling, mold release, flatness, and transferability.

Results

(1) Material filling:

Pattern a: Each material filled the bottom of the stamper having a height of 100 μm, a line width of 20 μm and a length of 8 mm.

Pattern b: As to PC, an unfilled part with a radius of 10 μm max. was found on an edge on the upper surface of the pattern.
TPX filled the bottom of the stamper with posts with a height of 300 μm.
As to POM, an unfilled part with a radius of 15 μm max. was found on the upper surface of the pattern.

(2) Mold release:

By narrowing down the molding conditions, even a mold that does not to have tapered portions could be released.

(3) Flatness:

Pattern a: Preferable flatness was obtained in the order of PC, TPX, and POM. As to PC (max.) , the flatness was within 30 μm.

Pattern b: Preferable flatness was obtained in the order of TPX, POM, and PC. The flatness was 140 μm for TPX and 30 μm for PC.

(4) Transferability:

Ra X resulting from the shape of the sidewall of the Au X-ray absorber, was 53 nm for the stamper and 87 nm for PC (max.).
Ra Y resulting from the accuracy of the X-ray lithography process, was 8 nm for the stamper and 28 nm for TPX (max.).

These results suggest that production of high aspect ratio microparts by plastic injection molding will be feasible.

We will further investigate the minimum size that can be molded, mold endurance and the like for the mass production of microparts by plastic injection molding.

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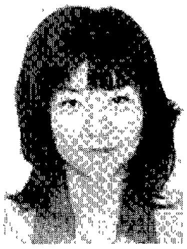

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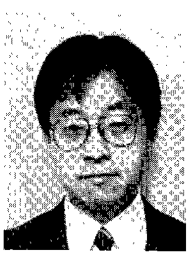

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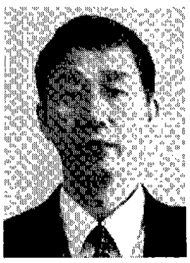

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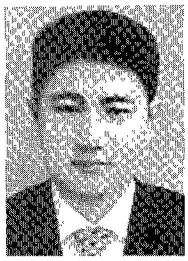

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