Abstract
This paper describes a new method of molding micro parts using a mold which was manufactured by layering metallic foils and plates. Coolant channels are circulated uniformly under the mold surface, at a depth sufficiently close to the surface. Hence, the mold temperature can be kept uniform over the large area of inserts of both the movable and fixed die plates. Two stainless steel foils in which micro-gates and cavities are machined by electrical discharge machining, respectively, are layered on the insert of fixed die plate. The space between the insert of movable die plate and the stainless foils, called sheet runner, is first filled with resin due to injection. Thereafter, the micro-cavities are filled with resin through the micro-gates due to the pressure rise in the sheet runner. The air vent effect due to the layered structure helps the resin to fill the cavity smoothly. The process conditions under which polypropylene micro disk of 200μm in diameter and 60μm in thickness can be formed uniformly over the sheet runner area of 40mm by 50mm were obtained changing the injected resin volume, resin temperature, and gate size. Besides, micro lens 200μm in diameter and 50μm in thickness were formed using molds manufactured by electrical discharge machining and electrolyte jet machining.

Key words: Micro parts, Injection molding, Layered structure mold, Electrical discharge machining, Electrolyte jet machining

1. Introduction

Demand of micro parts is rising in recent years in order to realize downsizing of parts and improve the performances of industrial products. The leading method which can mass-produce familiar and general plastics with low cost is injection molding method. There are many reports in which micro structures were formed on large surface areas to obtain various tribological characteristics (Fischer et al., 2014, Unal et al., 2014) and to manufacture an array of microneedles (Lacan et al., 2011). However, there are few papers which deal with injection molding of micro parts separated each other. For instance, micro gears were manufactured using a mold machined by wire electrical discharge machining (WEDM) (Matsuura, 2002). Micro disks were fabricated using a mold machined by etching (Ito, 2008). However, there are still many problems such as injecting minute precise volume of resin with high accuracy, molding parts in large quantity at once, and releasing micro parts from the mold surface. To solve these problems a special mold structure should be devised and process conditions to manufacture micro parts in large quantity at the same time should be investigated in details.

In this study, nine micro-gates and micro-cavities were machined separately in two stainless steel foils by micro electrical discharge machining (EDM) and electrolyte jet machining (EJM) (Kawanaka et al., 2014). Since each foil was positioned accurately on the table of micro EDM and EJM machines using two dowel pins, every gate was fabricated coaxial to the center of each cavity. Then, the layered stainless steel foils were installed on the fixed side insert whose surface temperature was controlled constant and uniform using channels of coolant circulated near the surface of insert. Molding experiments were performed to find the process conditions with which micro parts can be formed uniformly over a large area at once.
2. Principle of micro injection molding using layered structure mold

2.1 Structures

In this study, a mold which was manufactured by layering metallic plates (Ogawa et al., 2006, Ushiguchi et al., 2007) was used to provide a space of flow path of resin as shown in Fig. 1. This mold was originally made to produce light wave guide plates of 40 × 50 mm² with a thickness of 0.35mm or less. Inside the fixed side and movable side inserts, coolant channels with cross section of 2mm×2mm were circulated with an interval of 4mm at a depth 2mm under the mold surface. This structure was realized by diffusion bonding of layering plates (Nakagawa et al., 1985, Sato et al., 2004). Over the upper surface of the second plate from the top, the channel was fabricated by milling prior to diffusion bonding to the top plate. Since the distance between the mold surface and the coolant channels is close compared to conventional molds, temperature response is high. Consequently, the mold temperature over the large area can be controlled to be uniform at high temperature (Ushiguchi et al., 2007). Hence, flowability and replicability of the resin could be increased, and high flatness could be achieved due to decreased residual stress in the molded thin sheet of 0.35mm in thickness as shown in Fig. 2. In this study, the cavity to mold the part in Fig. 2 was used as the sheet runner from which resin is introduced into micro-cavities. The surface of the fixed side insert was ground by 100μm in depth from the die plate surface to make a space for two stainless steel (SUS304) foils of 40μm and 60μm in thickness, respectively. Micro-gates were machined in the 40μm foil, and micro-cavities were machined in the other foil. As shown in Fig. 3, the two foils were positioned on the fixed side insert using two dowel pins of Ø5mm in diameter, thereby the center of micro-gates and micro-cavities coincided precisely each other.

In this study, nine sets of micro-gate and micro-cavity were machined at the locations: (a) to (i), shown in Fig. 4. (a), (b) and (c) are located in the upstream, (d), (e) and (f) are in the middle, and (g), (h) and (i) are in the downstream area. As shown in Fig. 5, resin injected from the nozzle of the injection molding machine (FANUC ROBOSHOT S-2000iB) passes through the sprue bush and fan gate, and fills the space of the sheet runner at first. The flow of resin in the leading edge, when the surface temperature of the inserts is low, is called fountain flow because resin blows out through the gap between the solidified layers growing on the surfaces of both inserts. In the case that the resin temperature is sufficiently high however, the resin may not be solidified until the resin enters the micro-gate and fills the micro-cavity. As the resin pressure is elevated suddenly after the whole space of sheet runner is filled with resin, resin is pushed into the micro-gates and fills the micro cavities. Since two stainless steel foils are layered without bonding with each other or with the fixed side insert, air can be vented out easily, thereby micro-cavities can be filled with resin without a difficulty. When the die is opened, the sheet runner is pulled out with the movable die because of the hook shape of the ejector pin shown in Fig. 5. On the other hand, the layered foils are set on the fixed side insert by screws. Therefore, molded micro parts can be separated automatically at the micro-gates from the sheet runner. After that, the two metal foils are released from the fixed side insert and delaminated each other. At this time, since micro-cavities have a taper of 5° widening toward the fixed side insert, micro parts are remained in the foil of 60μm in thickness without being pulled out to the movable side. This method has the following four advantages. First, use of special machines for micro injection molding is not necessary because there is no need to inject minute volume of resin with high accuracy. Second, design of molded parts can be changed easily by changing the metallic foil in which micro-cavities are fabricated. Third, air can be vented out easily and micro-cavities can be filled with resin easily due to the air vent effect resulting from the layered structure. Forth, micro parts in large quantity can be molded at once on the sheet runner area.

![Fig. 1 Mold inserts manufactured by diffusion bonding steel plates with coolant channels](image-url)
2.2 Making molds using micro EDM

Micro-gates and micro-cavities were machined using a micro EDM machine (Sodick AE-05), which has an ability to machine micro-rods with a diameter smaller than 2 μm at a minimum. Machining setup is shown in Fig. 6. At first, a cylindrical tungsten rod 500 μm in diameter was machined by EDM to obtain tool electrodes of 28.5 and 194 μm in diameter using a copper-tungsten block electrode of 14 mm × 16 mm × 50 mm with a polarity that the copper-tungsten block was negative. The diameters of the tool electrodes machined were measured on the machine using an optical microscope installed on the EDM machine. Next, the cylindrical tool electrodes of 28.5 and 194 μm in diameter were used to drill micro-gates and micro-cavities, respectively, on the stainless steel foils using the machining conditions shown in Table 1. In the drilling processes, the polarity of the tool electrode was negative. Two dowel pins of Ø5 mm in diameter were set to the jig to obtain a high positioning accuracy of the foils, thereby centers of micro-gates and micro-cavities coincided precisely with each other even though the two foils were machined separately. Straight micro-gates were machined using the tool electrode of 28.5 μm in diameter without a spiral motion of the tool electrode, while micro-cavities were machined using the spiral tool path shown in Fig. 7 because the side surface has a taper angle of 5° as mentioned in Section 2.1. Tapered micro-gates which are described later were also machined using the spiral path. The machining time for the micro-gate and cavity was 202 s and 75 s, respectively.
3. Influence of molding conditions on formability of micro parts

3.1 Air vent effect of layered structure

To investigate the air vent effect of the layered structure, the filling ability of resin in a micro cavity was compared between the two structures shown in Fig. 8. Fig. 8(a) shows a micro cavity made in a monolithic stainless steel foil, and Fig. 8(b) shows a layered structure cavity. Under the injection molding conditions shown in Table 2, the 3D shape of the micro protrusion formed over the sheet runner was measured using a laser confocal microscope as shown in Fig. 9. Resin temperature was 220°C. Fig. 10 shows the filling ratio which is defined as the volume of resin extruded in the cavity to the total volume of the cavity. The ratio was significantly higher with the layered structure than the monolithic one. Thus, the air vent effect of the layered structure was verified.
3.2 Process windows for filling of sheet runner

Table 3 shows the injection molding conditions to obtain the process windows for filling the cavity of the sheet runner. Short shot and burr were generated purposely by changing the resin temperature and injected resin volume to investigate the relation between the filling conditions of the sheet runner and the formability of micro parts shown in Fig. 5. Fig. 11 shows the area filling ratio of sheet runner which was defined as the area which is filled with resin divided by the whole area of sheet runner. Area filling ratio of sheet runner less than 1 means short shot. Area ratio of burr which is defined as the area of burr around the sheet runner divided by the area of sheet runner is shown in Fig. 12. In the cases that injected resin volume was less than 2554 mm$^3$, short shot always occurred regardless of the resin temperature. When the injected resin volume was larger than 3308 mm$^3$, short shot never occurred regardless of the resin temperature. When the injected resin volume was between them, short shot happened more easily at lower resin temperature. In the cases that injected resin volume was larger than 3500 mm$^3$ burr was generated at any temperatures except for the lowest temperature of 190°C. The process windows can be summarized as shown in Fig. 13.

![Image of Fig. 11 Area filling ratio of sheet runner]

![Image of Table 2 Injection molding conditions used to verify air vent effect.]

Table 2 Injection molding conditions used to verify air vent effect.

<table>
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<tr>
<th>Resin</th>
<th>Polyoxymethylene; POM</th>
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<td>Temperature of coolant circulating in inserts [°C]</td>
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<td>Holding pressure [MPa]</td>
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<td>Pressure held time [s]</td>
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<tr>
<td>Cooling time [s]</td>
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</table>

![Image of Fig. 12 Area ratio of burr]

![Image of Table 3 Injection Molding conditions]

Table 3 Injection Molding conditions

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<th>Polypropylene: PP</th>
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<tr>
<td>Cooling time [s]</td>
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</table>
3.3 Influence of resin temperature on micro molding ability

Number of micro parts successfully formed in the upstream area: (a), (b), (c), middle area: (d), (e), (f), and downstream area: (g), (h), (i) is shown in Fig. 14. Fig. 15 shows an example of micro parts formed at the locations from (a) to (i). Dots in Fig. 14 indicate the micro part was successfully formed like the parts formed at (a), (b), and (c) in Fig. 15. It was judged that the forming was successful when the micro cavity was completely filled with the resin, as a result the edges of both the front and reverse sides of the micro disk were formed sharp. The injected resin volume was kept constant at 3817mm³ while the resin temperature was changed. It was found in Section 3.2 that burr was generated around the sheet runner at all resin temperatures when the resin volume was 3817mm³. However, no micro parts were successfully formed when the resin temperature was below 270°C. On the other hand, micro parts were successfully formed at all the positions when the resin temperature was 280°C or higher. Besides, it can be seen from Fig. 15 that, filling was started from the upstream area at the low resin temperature. This is because pressure at the upstream area was significantly higher than the middle and downstream areas due to the high flow resistance of resin at the low temperature. Even though the micro injection tool developed in the present work holds the air vent effect, if the resin in the micro-gate or in the micro-cavity near the gate is solidified during injection, the micro-cavity cannot be fully filled with the resin.

![Fig. 14 Relation between number of micro parts successfully formed and resin temperature (Injected resin volume of 3817mm³)](image1)

![Fig.15 SEM image of micro parts (270°C, 3817mm³)](image2)

3.4 Influence of injected resin volume on micro molding ability

It is thought that formability can be increased by increasing injected resin volume, because the pressure applied to the micro gate will increase with increasing the resin volume. Fig. 16 shows change in the number of micro parts successfully formed at each position with increasing the injected resin volume. The resin temperature was set at highest of 290°C. It was found in Section 3.2 that the injected resin volume less than 2799mm³ caused short shot, and that the injected resin volume larger than 3562mm³ resulted in burr generation. Thus, it is found that micro parts were not formed successfully at any positions when short shot occurred even if the resin temperature was highest and fluidity of resin was sufficiently high. On the other hand, micro parts were formed successfully at all positions when the injected resin volume was sufficiently large to generate burr. Fig. 17 shows SEM images of micro parts formed when the injected resin volume was 2799mm³. It is found that filling was started from the downstream area when the resin temperature was high. The reason is considered as the following. When the temperature of resin is high, the pressure difference between the upstream and downstream areas is small whereas the solidified layer in the upstream is much thicker compared to the downstream, which prevents resin from entering into the micro-cavities. Although cavities (a) and (c) are positioned in the upstream area, they were filled with resin successfully. This is because the resin reached the corners last in the sheet runner. The process windows for total number of micro parts formed successfully are shown in Fig. 18.
4. Influence of structure of micro-gates

4.1 Influence of shape of micro-gates

Formability of micro parts may be changed according to the shape of micro-gates. Influence of the shape of the micro-gates on the formability of micro parts was investigated using three types of gates: (A) convergent gate, (B) straight gate, and (C) divergent gate, as shown in Fig. 19. The dimension of narrowest aperture of each micro-gate was kept the same as 30μm in diameter. The tapered micro-gates were machined with the cylindrical tool electrode of Ø28.5μm in diameter using the spiral tool path as described in Section 2.2. The machining conditions except for machining time were set the same as in Table 1. Fig. 20 shows the inner surface of the straight gate machined by EDM. Since the same pulse conditions were used, the roughness of the inner surfaces of all the gates was the same. The roughness of the side surface of the cylindrical cavity was greater than that of the gate, because the discharge energy was larger. The surfaces of the stainless steel foils were used as received, and their surface roughness was 0.5μm Rz. The machining time for the convergent gate and divergent gate was 322s and 331s, respectively. Molding conditions were the same as in Table 3. The results in Fig. 21 show the influence of the shape of micro-gate on the number of micro parts successfully formed in the stainless steel foil among the nine micro parts generated by a single injection. With the convergent gate, micro-cavities were difficult to be filled compared with the straight gate. This is because resin can easily enter into the micro-gate while the sheet runner is still being filled with resin because the inlet diameter is large. In this situation, the resin in the convergent gate is solidified and clogs the gate because of the taper. Hence, no more resin can enter the gate even if the resin pressure is elevated when the sheet runner is completely filled with resin. With the divergent gate in contrast, micro-cavities were more easily filled compared to the straight gate. Even when short shot happened in the sheet runner, all the micro-cavities were fully filled at the resin temperature of 290°C. This is because the micro-gates were not clogged by the solidified resin in the divergent gate. However, the flaw left on the micro part is large compared with the other gate shapes because the outlet diameter of the micro gate is 60μm.
4.2 Influence of diameter of micro-gates

Micro-gates are not part of the final product, and therefore should be as small as possible from aspects of design and functionality. With the conditions shown in Table 1, micro-gates of diameters Ø20μm, Ø25μm and Ø30μm were machined by micro EDM. The electrodes used for micro-gates of diameters Ø20μm and Ø25μm were cylinders of diameters Ø19μm and Ø25μm, respectively. The time required for machining was 191s and 197s respectively. Fig. 23 shows the influence of the gate diameter on the number of micro parts successfully molded using the micro-cavities in Fig.5 under the molding conditions shown in Table 3. It was found that the formability drops as the gate diameter becomes smaller. When the gate was smaller than Ø25μm, micro-products could not be formed.
5. Manufacturing mold for injection molding of micro lens by micro EDM

The micro mold products made in Section 4 were all limited to 2-dimesional shapes. Hence, attempts to make 3-dimensional shapes were made. In this research, micro-lens shown in Fig. 24 were made using the layered structure mold shown in Fig. 25. The molding conditions were set at resin temperature 290 °C and injected resin volume 2799 mm³ which creates burrs on the edges of the sheet runner, and fills the micro-cavities easily. Other conditions were the same to Table 3. Straight gates in the shape were used for micro-gates for simplification. Micro-gates of diameter Ø40μm were used as the micro-products could not be formed when the micro-gate was Ø30μm. This is because the location of the micro-gate was off-centered from the axis of the micro-lens as the micro-gate should not be located on the lens surface, and because the thickness of the flange was 30μm, thinner than the micro disk formed in the previous sections. Micro-gates and micro-cavities were manufactured by the process shown in Fig. 26. First, a stainless steel foil of thickness 60μm was set on a micro EDM machine, and a cylindrical cavity shown in Fig. 26(A) was machined by a tool electrode of Ø116μm in diameter using an orbital tool trajectory. Next, the lens cavity was roughly machined as shown in Fig. 26(B) and (C) using electrodes of diameter Ø67μm and Ø37μm, respectively. Third, lens cavity as shown in Fig. 26(D) was precisely machined by spiral machining with an electrode of diameter Ø14μm. The electrode moved along the same pass twice for precise machining. After manufacturing the micro-cavity, the stainless steel foil was replaced by another stainless steel foil of 40μm in thickness, on which a micro-gate as shown in Fig. 26(E) was drilled with the electrode of Ø37μm in diameter. The process of finish machining of the lens cavity was performed using a low discharge energy with the power supply voltage of 30V. Other processes were performed using a higher energy with the power supply voltage of 54V. Other conditions of micro EDM were the same as Table 1. The mold and molded micro lens are shown in Fig. 27. The shape of the micro lens was almost the same with the manufactured micro mold. To assess the micro lens mold from the viewpoint of replication of discharge craters, the surface topographies of both the mold and molded parts were observed in details as shown in Fig. 28. The power supply voltage of the RC discharge circuit was 54V for cylindrical cavity higher than 30V for lens cavity. Therefore, the diameter of craters at the cylindrical cavity and those at the lens cavity were 4μm and 2μm, respectively as shown in Fig. 28. Craters were replicated to molded micro lens in both cases. This result shows that application of mold surface machined by EDM to optical components such as lens is difficult due to large surface roughness.
6. Electrochemical machining of mold for injection molding of micro lens

In Section 5, it was found that craters of the micro EDM surface were replicated to molded micro lens. Hence, manufacturing processes for lens cavity with lower surface roughness are necessary. For this purpose, electrolyte jet machining (EJM) (Kawanaka et al., 2014) shown in Fig. 29 was used. EJM is a method which selectively machines the area directly below the nozzle by emitting a jet stream of electrolyte, while applying voltage between the nozzle and the workpiece. EJM has the advantage of mirror machining by controlling current density. Therefore, EJM is more suitable than micro EDM in the case of machining molds for injection molding of micro lens. The structure of the mold is shown in Fig. 30. The structure is the same as Fig. 25 except for the diameters of the micro-gate and micro-lens which were 50μm and 129μm, respectively. Since the diameter of the micro-lens was larger than that in Fig. 25, micro-products could not be formed when the micro-gate was Ø40μm. Therefore, the micro-gate was set as Ø50μm in this experiment.
Following is the manufacturing process. First, the lens cavity with a mirror-like surface as shown in Fig. 31 was machined by EJM using a cylindrical nozzle of inner diameter of Ø100μm on a stainless steel foil of 60μm in thickness using an EJM machine. EJM machining conditions are shown in Table 4. Although the current density inside of the jet is not constant, the current used for machining divided by the inner area of the nozzle was defined as the current density for simplification. Although the surface was mirror-like near the center where the current density was high, corrosion pits were generated in the periphery of the cavity. Hence, micro EDM was used to fabricate the cylindrical cavity of 200μm in diameter and 50μm in depth as shown in Fig. 30, thereby eliminating the corrosion pits in the periphery under the conditions shown in Table 1. Results of injection molding using the same conditions to Table 3 are shown in Fig. 32. Micro lens with the same shape as the micro-mold could be formed. Furthermore, since the surface of the lens cavity was mirror-like, the surface of the molded lens was smoother than that shown in Fig. 28. However, as the shape of the lens cavity is determined by the current density distribution in the electrolyte jet, as shown in Fig. 29, arbitrary shapes cannot be obtained with the stationary jet. Hence, machining by scanning the jet with a diameter smaller than the diameter of the lens is necessary to obtain precise shapes of micro lens.

Table 4 Electrolyte jet machining conditions

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Fig. 29 Principle of electrolyte jet machining (EJM)

Fig. 30 Structure of micro lens mold manufactured by EJM

Fig. 31 Lens cavity manufactured by EJM

Fig. 32 Micro lens mold manufactured by EJM and molded micro lens
7. Conclusions

In this study, a mold for micro injection molding which can be used for mass production of polypropylene micro parts 200 μm in diameter and 50 to 60 μm in thickness was produced by layering stainless steel foils in which micro-gates and cavities were machined by EDM and EJM. The molding conditions under which the micro parts can be formed in large numbers uniformly over a sheet runner were investigated. The followings are the conclusions.

1. Process windows with regard to the injected resin volume and resin temperature for molding micro parts uniformly were obtained. High resin temperature and large injected resin volume which can avoid short shot and even generate burr of the sheet runner are required to form micro parts successfully. At low resin temperature, micro-cavities are filled with resin from the upstream area, while at high resin temperature, cavities are filled from the downstream area.

2. The micro cavity was filled with resin more easily using the layered structure mold than the monolithic structure mold due to the air vent effect.

3. The shape of micro-gate affects the formability of micro parts. Micro-cavities can be more easily filled by resin using divergent micro-gates. In the cases that the diameter of micro-gates on the micro parts side is the same, formability is best with straight gates. When the gate diameter was larger than Ø25μm, micro-products of 200μm in diameter and 60μm in thickness were successfully formed.

4. Craters were replicated to molded micro lens in both cases of high and low power supply voltages when the mold was manufactured by EDM. Therefore, molds for application to optical components, such as lens are difficult to obtain when machined by only EDM.

5. The surface roughness of the lens cavity machined by EJM was better than that machined by micro EDM. However, the shape of the lens cavity is determined by the current density distribution of EJM. Hence, machining by scanning the electrolyte jet with a diameter smaller than the diameter of the lens is necessary to obtain precise shapes.

Acknowledgement

This research was performed using the micro EDM machine AE-05 offered by Sodick Co., Ltd.

References


