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Attempts to fabricate micro injection molding tools and assemble molded micro parts on same EDM machine

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ABSTRACT

An EDM method for manufacturing plastic micro gear pumps is proposed. Micro gates and cavities for mating gears are machined by EDM in both sides of a stainless steel foil, respectively. The foil is then transferred to an injection molding machine, and fixed to a mold to form mating gears by injection molding. The mating gears formed on the foils are then re-positioned on the EDM machine, released from the foil, and placed in a second foil pre-machined by EDM for the pump housing, using an ejector pin fabricated by reshaping the tool electrode used to machine the two foils.

1. Introduction

In recent years, molded parts made of plastic materials are widely utilized in modern devices and optical elements. Among them, demands for micro size molding technology are growing to realize the downsizing of products.

The current research trend of micro injection molding is mainly directed to precision transfer printing technologies which replicate microstructures on the surface of relatively large plastic parts [1], such as micro lens arrays [2] and micro needle arrays [3].

However, little research has been conducted on molding microscale parts individually. Hopmann and Fischer [4] successfully controlled the amount of plastic precisely to mold micro parts. To minimize the waste and degradation of heated polymers, the units for the plasticization and injection were separated. On the other hand, Fujieda et al. [5] proposed a method to mass-produce separated micro parts using an injection molding machine which is widely used to produce parts of centimeter size. With their method, micro cavities and gates are machined on two stainless steel foils of 60 and 40 μm in thickness, respectively. Injection molding of a single micro lens is then carried out by laminating them and inserting them into a mold for molding a thin plate. When the plastic is injected in the cavity for the thin plate, the pressure in the cavity is increased to extrude the plastic from the micro gates into the micro cavities. Therefore, this method has advantages such as not requiring precise measurement of the amount of plastic and enabling large amounts of micro lens to be produced at one time. However, these previous researches did not consider how to handle and assemble the micro parts after injection molding to manufacture functional products. Since the micro parts are small and delicate, their handling and assembly are extremely difficult. Hence, in order to mass-produce micro machines composed of micro plastic parts, it is necessary to develop a system with which fabrication of micro mold inserts, micro injection molding, and micro assembly are continuously performed with minimum manual work.

In a previous research on micro assembly, Langen et al. [6] proposed an assembly method using an electrical discharge machining (EDM) machine as shown in Fig. 1. To assemble a micro pin and metal plate, the pin is first formed by EDM. In this step, taper and neck are also machined at the same time. Then, a hole is machined in the metal using the straight part of the pin as a tool electrode. Next, the tapered pin is press fitted into the hole. Finally, the pin is twisted to break it at the neck, thereby assembling the plate and pin. However, since holes are machined by EDM, all the parts need to be made of electrically conductive materials. Thus, in this research, in order to manufacture micro machines composed of plastic parts, we aim to develop an EDM micro production system which can automate all the processes from tool forming, mold insert fabrication, injection molding, handling, positioning and assembly.

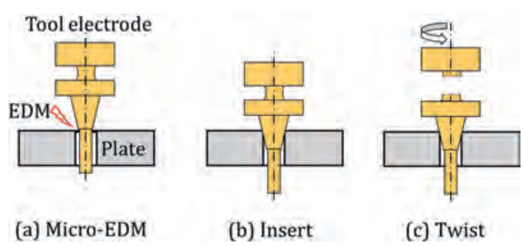

Fig. 1. Fabrication process of pin plate module.

2. Fabricated micro gear pump

For the demonstration test of the developed system, the micro gear pump shown in Fig. 2 was fabricated in the micro channel. The gears are made of plastic (polypropylene), and the micro channel is

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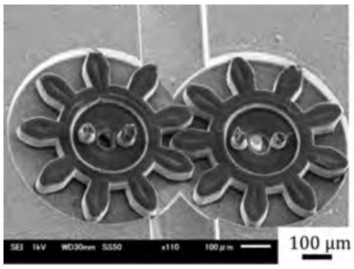

Fig. 2. Fabricated micro gear pump.

made of stainless steel. The right gear is driven by the left gear which is rotated by a shaft inserted into the chamfered hole made at the center of the driving gear.

3. EDM micro production system

3.1. Whole system

Fig. 3 shows the flow chart of the whole production system that was developed. First, a tool electrode is machined by EDM (a). Next, the stainless steel foil of 100 μm in thickness is fixed to the positioning jig on the EDM machine, and the cavities are machined by EDM (b) using the tool electrode machined in step (a). The foil is inserted into the mold (c) and injection molding is performed (d). Before the foil with the molded micro gears is detached from the mold and fixed again to the positioning jig on the EDM machine (e), another stainless steel foil, called base foil, is fixed on the same jig and pump cavities are fabricated on it by EDM (f). Finally, molded parts are released from the insert foil and assembled to the base foil using an ejector pin made from the same rod that had been used throughout the whole production process on the developed system, reshaped repeatedly for different purposes (g).

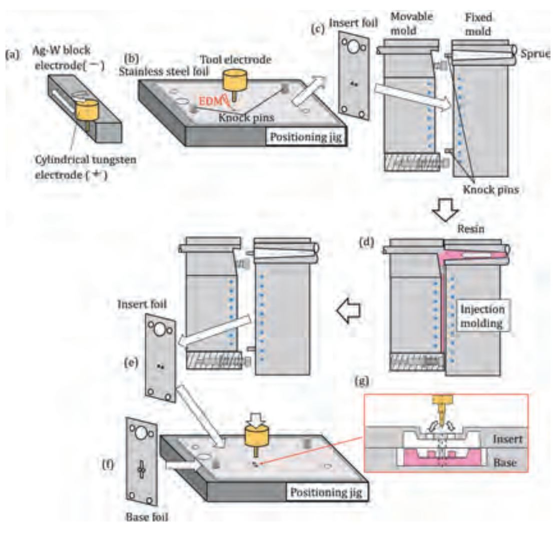

Fig. 3. Flow chart of EDM micro production system.

3.2. Machining of micro cavities

First, as shown in Fig. 3(a), a tungsten cylindrical rod of 500 μm in diameter is machined by EDM using a silver tungsten block electrode to obtain a tool electrode of 48 μm in diameter with the machining conditions shown in Table 1. The EDM machine used in this research was Sodick AE05 with a positioning accuracy of 0.5 nm. In step (b), the stainless steel foil, called insert foil, is positioned on the jig on the EDM machine using two knock pins. The repeatability of positioning the stainless steel foil is within ±2 μm. Table 2 shows the EDM conditions for the cavity machining. By setting the electrostatic capacitance as the stray capacitance, the discharge energy can be minimized to enable fine processing.

Table 1
Machining conditions used for shaping tool electrode.

Power supply voltage (V)	137
Servo reference voltage (V)	120
Capacitance (pF)	2200
Rotation speed of tool electrode (rpm)	3000
Workpiece	Tungsten

Table 2
Machining conditions used for fabricating cavity.

Power supply voltage (V)	137
Servo reference voltage (V)	120
Capacitance (pF)	Stray capacitance
Rotation speed of tool electrode (rpm)	3000
Workpiece	Stainless steel foil (SUS304)

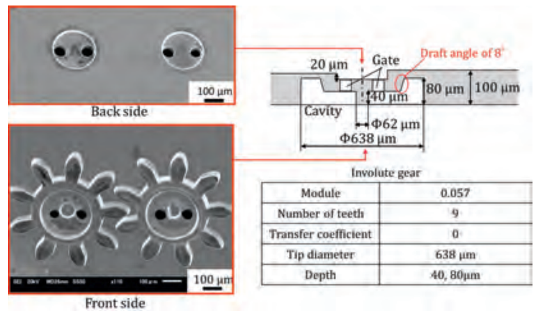

Fig. 4. Cavities of micro gears machined on insert foil.

Fig. 4 shows the cavities of the micro gears machined on the insert foil. It took about nine hours to finish all the machining. The cavities of two gears are machined so that they are meshed with each other. Two gate holes are prepared for each gear to facilitate the filling of the plastic and to release the gear from the insert foil evenly using the ejector pin as described later in Section 3.5. In addition, the periphery of the boss in the cavity has a draft angle of 8° to facilitate the release of the plastic gear after injection molding. Without the draft angle, the release resistance is large due to the shrinkage of the plastic, causing the deformation of gears at step (g) in Fig. 3.

3.3. Injection molding

Fig. 5(a) and (b) shows the schematic diagram of the mold used in this research and molded product, respectively. This mold was originally developed by Ogawa et al. [7] to produce thin light guide plates with a length of 50 mm, width of 40 mm, and thickness of 0.35 mm. The mold is made by diffusion bonding of laminated tool steel plates. For this reason, coolant channels are arranged at a depth of 2 mm from the molding surface, enabling the control of the mold surface temperature so that it is more or less constant and uniform over the entire surface. Taking advantage of the uniformity of the mold temperature, Fujieda et al. [5] performed micro injection molding by using the space originally made for the light guide plate as a sheet runner from which molten plastic is introduced to micro gates distributed over the insert foil attached on the mold. As a result, they were able to produce a considerable number of micro parts at one time on the large area. Since this method did not require precise measurement of the amount of injected plastic, micro injection molding could be performed using

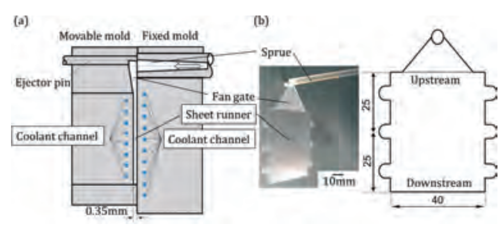

Fig. 5. Mold and molded plastic plate.

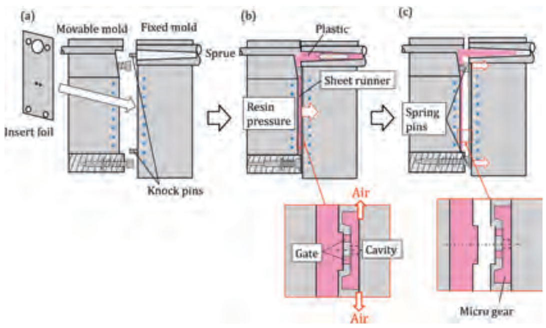

Fig. 6. Micro injection molding process.

Table 3
Injection molding conditions.

Plastic	Polypropylene
Temperature of coolant circulating in molds (°C)	120
Volume injection speed of cylinder 18 mm in diameter (mm^3/s)	1.34×10^5
Plastic temperature in heating area (°C)	290
Holding pressure (MPa)	210
Pressure held time (s)	3
Cooling time (s)	10
Injected plastic volume (mm^3)	3815

Fig. 7. Cavity of micro gears filled with plastic after injection molding.

a normal injection molding machine under the molding conditions usually used in mass production of industrial products.

During injection molding, the insert foil is placed on the fixed side of the mold as shown in Fig. 6(a). The foil is positioned by the knock pins. Next, injection molding is performed as shown in Fig. 6(b) with the conditions shown in Table 3. High temperature and pressure are set for filling the cavities of the micro gears with plastic. The conditions are determined based on the basic experiments in which Fujieda et al. [5] formed cylindrical micro parts with a diameter of 200 µm and a height of 60 µm over the entire surface of the sheet runner. First, the sheet runner is filled with plastic. At this time, the stainless steel foil is pressed onto the fixed mold by the plastic pressure. When the sheet runner is sufficiently filled with plastic, the pressure inside the mold rose and the plastic flows into the cavity through the gates, and the micro parts are molded.

Fujieda et al. [5] also demonstrated that the air vent structure that allows air to escape through the interface between the foil and mold enables easy filling of micro cavities with plastic. Finally, as shown in Fig. 6(c), the sheet runner remains on the movable side when the mold is opened. Since the insert foil is pressed on the fixed side by the spring pins, tensile stress is generated at the gates and the micro parts are separated from the sheet runner. Fig. 7 shows the cavities filled with plastic after injection molding. Regarding the durability of the micro cavities, it was confirmed that the shape of the micro cavities was not deformed after performing thirty injection molding cycles.

3.4. Machining of base foil

As shown in Fig. 8, the pump cavity where the micro gears are assembled is machined on another stainless steel foil by EDM. This cavity needs to be positioned precisely in order to realize the assembly in the next step.

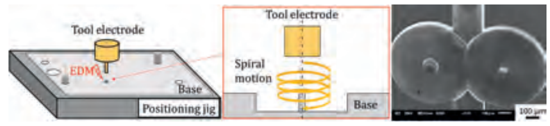

Fig. 8. Base foil where pump cavity was machined by EDM.

For this purpose, machining the base foil with the same EDM machine, tool electrode, and positioning jig as those used for machining the gear cavities is a critical requirement. In addition, in order to obtain a flat bottom surface, the cavity is machined layer by layer using a spiral tool path. The machining conditions are the same as those shown in Table 2. It took about two hours to finish all the machining.

3.5. Assembly

First, as shown in Fig. 9, the base foil with the pump cavity machined and the insert foil attached with micro gears after injection molding are laminated and placed back onto the positioning jig on the EDM machine.

Next, as shown in Fig. 10, the micro gears are released from the insert foil by punching the gates of the micro gears using the ejector pin prepared by reshaping the tool electrode used for the previous step of machining the pump cavity. The four gates, two for each gear, are punched evenly, so that both gears are released at the same time in parallel to the base foil surface. As a result, assembly with the base foil was performed successfully. In this method, machining and assembly are performed on the same EDM machine. For this reason, the same machine coordinates can be used commonly for all the processes: tool electrode forming, insert foil and base foil machining, and assembly. In addition, since the cavities for micro gear pairs are made at a meshed position during the cavity machining step, assembly without interference between gears can be realized.

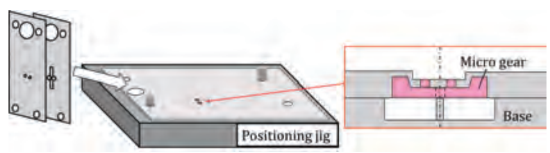

Fig. 9. Positioning on EDM machine.

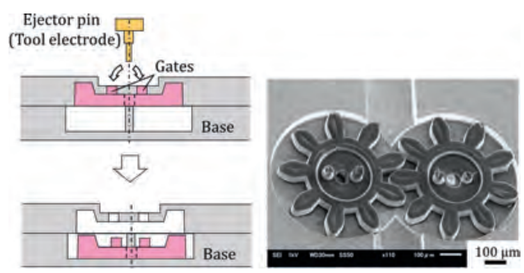

Fig. 10. Assembly of micro gears.

3.6. Wear and reshaping of tool electrodes

In this research, in order to ensure reliable positioning of tool electrodes and ejector pin relative to the foils, all the tool electrodes and the ejector pin were formed for the use of each step from a single rod which was consistently held by the chuck of the EDM machine. Hence, before the rod is reshaped for the next step, the tip of the rod was removed by EDM using the silver tungsten block electrode, as shown in Fig. 11. Fig. 12 shows the length worn by EDM in each step and the removal length by reshaping of the rod tip. In total, the rod was shortened by 3.45 mm in length. This allows all steps to be performed without replacing the rod.

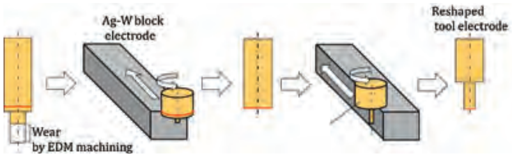

Fig. 11. Reshaping of rod.

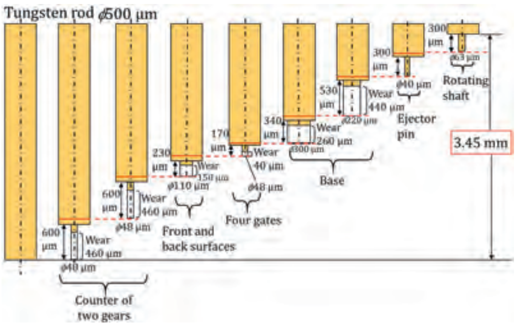

Fig. 12. Wear and removal length of rod.

4. Operation test

The rotating shaft is also formed by EDM from the same rod and inserted into the driving gear using the rotating z-axis of the EDM machine. It was found that the micro gears can be driven by the rotation axis of the EDM machine as shown in Fig. 13. One side of the rotating shaft is cut flat to fit the chamfered hole made at the center of the driving gear shown in Fig. 2.

Finally, as shown in Fig. 14, the pump cavity is sealed with a Teflon film of 12 μm in thickness and the film is pressed by an acrylic plate of 1 mm in thickness against the base foil. Then the pump cavity and the straight micro channel are filled with water. Thus, we investigated whether water can flow by operating the micro gear pump, and the flow rate of water was found to be significantly low. The reason for this may be that the gap between the gear and the pump cavity has become larger than expected due to shrinkage of the plastic as shown in Fig. 15. Polypropylene usually shrinks by 2–5% in length. In this case, the tip diameter of the injection molded micro gear was 608 μm, while the tip

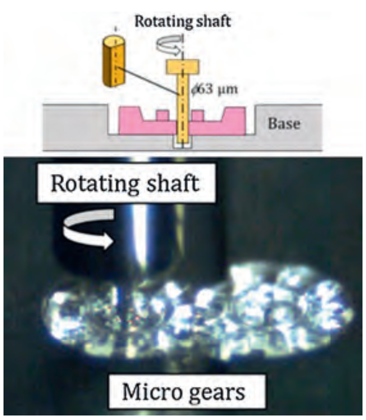

Fig. 13. Rotation of driving gear using rotation axis of EDM machine.

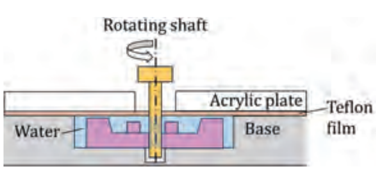

Fig. 14. Micro gear pump.

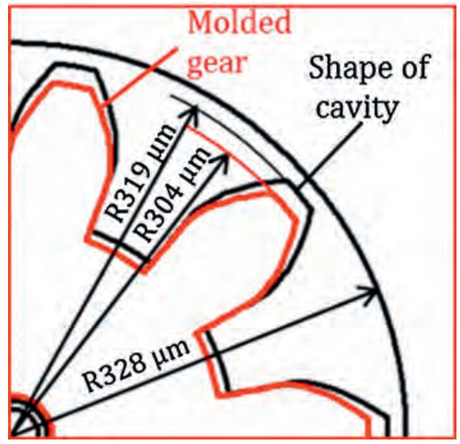

Fig. 15. Shrinkage of micro gear.

diameter of the gear cavity made in the insert foil was 638 μm, indicating that the shrinkage of the gear was 4.8% in diameter. These results suggest that even microscale products should be designed considering the shrinkage of plastic.

5. Conclusions

In this research, we proposed a micro production system to machine micro molding inserts and assemble injection molded plastic parts using an EDM machine. As a result, the following conclusions were obtained.

- Since micro cavities were fabricated in a replaceable foil put on the commonly used mold, mass production of micro parts with higher flexibility became possible. Furthermore, micro cavities were easily filled with plastic due to the air vent effect.
- Since positioning was performed automatically using the same machine coordinates for all the steps, micro gear pumps of submillimeter size were fabricated successfully without the need for the manual positioning, handling, or assembly of micro tools and parts.
- The total fabrication time of the micro gear pump was 16 h, and the depletion of the rod from which all the tool electrodes, ejector pin and rotating shaft were formed was 3.45 mm.

We also succeeded in driving the micro gear pair by inserting a rotating shaft which was formed by reshaping the tool electrode into the center hole of the micro gear. Although the flow rate of the micro gear pump produced was insignificant, it is possible to apply this system to the fabrication of various micro machines made of plastics.

References

[1] Lucchetta G, Sorgato M, Carmignato S, Savio E (2014) Investigating the Technological Limits of Micro-Injection Molding in Replicating High Aspect Ratio Micro-Structured Surfaces. *CIRP Annals – Manufacturing Technology* 63(1):521–524.

[2] Kirchberg S, Chen L, Xie L, Ziegmann G, Jiang B, Rickens K, Riemer O (2012) Replication of Precise Polymeric Microlens Arrays Combining Ultra-Precision Diamond Ball-End Milling and Micro Injection Molding. *Microsystem Technologies* 18(4):459–465.

[3] Shan G, Zhongjun Q, Zhuang M, Yujun Y (2012) Development of High Efficiency Infrared-Heating-Assisted Micro-Injection Molding for Fabricating Micro-Needle Array. *Microsystem Technologies* 18(1–4):459–465.

[4] Hopmann Ch, Fischer T (2015) New Plasticising Process for Increased Precision and Reduced Residence Times in Injection Moulding of Micro Parts. *CIRP Journal of Manufacturing Science and Technology* 9:51–56.

[5] Fujieda R, Katoh S, Kunieda M (2017) Research on Injection Molding of Micro Parts Using Layered Structure Mold. *Journal of Advanced Mechanical Design Systems and Manufacturing* 11(1):1–12.

[6] Langen HH, Masuzawa T, Fujino M (1995) Modular Method for Microparts Machining and Assembly with Self-Alignment. *Annals of the CIRP* 44(1):173–176.

[7] Ogawa Y, Fukuhara K, Kunieda M, Yamazaki T, Yamazaki H (2006) Research on Injection Molding by Temperature Control Using Laminated Mold. *SPR Meetings JSPE* 571–572. (In Japanese).