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Advanced Micromanufacturing for Ultra Precision Part by Soft Lithography and Nano Powder Injection Molding

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***Abstract*—**Recently, the advanced technologies that offer high precision product, relative easy, economical process and also rapid production are needed to realize the high demand of ultra precision micro part. In our research, micromanufacturing based on soft lithography and nanopowder injection molding was investigated. The silicone metal pattern with ultra thick and high aspect ratio succeeds to fabricate Polydimethylsiloxane (PDMS) micro mold. The process followed by nanopowder injection molding (PIM) by a simple vacuum hot press. The 17-4ph nanopowder with diameter of 100 nm, succeed to be injected and it forms green sample microbearing with thickness, microchannel and aspect ratio is 700µm, 60µm and 12, respectively. Sintering process was done in 1200 C for 2 hours and heating rate 0.83^{o}C/min. Since low powder load (45% PL) was applied to achieve green sample fabrication, ~15% shrinkage happen in the 86% relative density. Several improvements should be done to produce high accuracy and full density sintered part.

***Keywords*—**Micromanufacturing, Nano PIM, PDMS micro mould.

I. Introduction

MICRO manufacturing process nowadays is one of interesting subject that investigated worldwide since the demand and needs of very small devices are increase day by day. Some methods to make micro and high accuracy component are already introduced by some researchers to find the best and optimum process, such as using laser cutting, 3D microstereolithography, micro CNC, microinjection molding, micro-electro-mechanical system (MEMS) etc. Some methods are constrained by its very high cost and time consuming [1-2]. The powder injection molding (PIM), a variant of powder metallurgy (PM), has been developed in recent years. An alternative process to fabricate micro component with low cost equipment and micro mold material were demonstrated in this work. The injection molding machine and metal micro mold are unnecessary in this process, since PDMS as the micro mold and simple vacuum hot press as the injector were applied.

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II. Material and Experimental Method

The 17-4ph nanopowder with an average diameter of 100 nm and spherical shape were selected in this experiment to produce the feedstock. The multiple components binder system was utilized in this experiment which consists waxes, ethylene vinyl acetate (EVA) and polypropylene [3]. The nanopowder and binder system were mixed in a *Brabender plastograph* mixer for 1 hour at 170 °C. The feedstock with 40, 45 and 50 % powder loading feedstocks were prepared.

In our research, the Nickel metal pattern was used with microbearing shape, from POSTECH research institute, South Korea. The pattern was chosen as the alternative master pattern because its tremendous performance for strength, accuracy and high thickness (up to ~ 700 µm). It’s also represent complex structure of micro part since the existence of micro channel with width 60 µm and some micro holes with diameter 300 µm. After that, the pattern was transferred into PDMS silicone mold with 10% curing agent and curing process was done in the vacuum drying furnace for 4 hours.

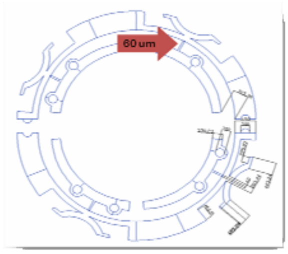

Fig. 1 Micro bearing pattern (60 um in micro channel)

PDMS silicone mold it’s very well known material in soft lithography process because its excellent behavior to transfer the 2 dimensional with high accuracy and can sustain its shape in the thermal PIM working temperatures. It’s also has good strength in the term of compaction or stretching force so using PDMS in PIM process can be great choice to provide green samples with high accuracy and complex structures.

Next, the feedstocks were injected into micro cavities with several injection temperatures and under vacuum (-100.8 KPa). The vacuum hot press was designed and made for that purpose. Before the molding process, the feedstocks were prepared in flake shape with 1 mm thickness.

Sintering was done in 1200^{0}C for 2 hours with 0.83^{o}C/min. Before the sintering, wax decomposition, debinding and pre sintering were done in 300 C for 2 hours; 550 C for 2 hours; and 900 C for 2 hours; respectively. The presintering is needed to reduce the oxide that exist and cover the nanopowder. The sintering process was done in the alumina tube furnace and in the ultra high purity Hidrogen with very slow heating rate, 0.83 C/min.

III. Result and Discussion

A. Micromold

The PDMS micro mold succeeds to be fabricated from silicone metal master pattern. As seen in the Fig. 2, The PDMS can transfer the silicone metal pattern into micro mold with low deviation. It's also suitable when the injection process was done. From the Fig. 3, PDMS mold expansion can keep its dimension when it was injected in the several temperatures with low deviation. In this process some challenges were recognized in the fabrication of PDMS micro mold:

a. Much care must be completed when remove the PDMS from the high aspect ratio pattern. The existence of empty space on the bottom area of pattern should be assured. The small empty area can promote small crack in the PDMS mold or even can break the nickel metal pattern when demolding the PDMS from its pattern was done.
b. The PDMS pattern can be used for many times depends on the injection temperature and planarization process. After using for several times, the PDMS can still keep its shape and dimension. The bending can be happened if the high pressure and high temperature applied in the some part of area. This challenge can be answered by using cool flat steel over the PDMS during cooling process.
c. Some patterns can't be removed from PDMS mould when the pattern is not vertically flat or not strongly stick with the substrates.

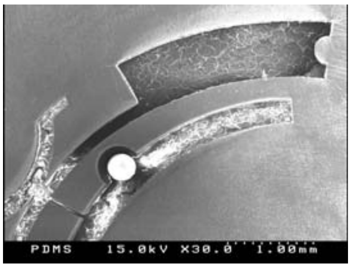

Fig. 2 PDMS mold

B. Injection Molding Result

Injection processes were done in special vacuum hot press equipment. The deviation of sample during injection can be seen in Fig. 4. From this graph, it can be inferred that with the higher temperature, the deviation can be decreased slightly. Since wax binder were used and start to decompose in 200^0C, 190^0C was choosen as the optimum injection temperature. The injection processes were done in 190^0C for 2 minutes. Small air can be trapped during the process (cold shut). It's very potential happen while there's no mold riser part in the PDMS that can reduce air trapped and turbulence during the injection process. We found that this air trapped can be happen if the vacuum process were not good (smaller than –100 KPa) or the insufficient feedstock amount that will be injected. If the feedstock is not enough, the air trapped can be happened and the mold can't be filled completely. The rapid cooling is also avoided since the feedstock is very easy to shrink during the cooling process.

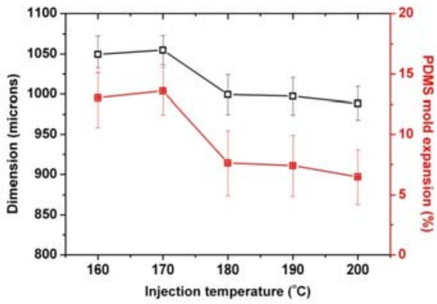

Fig. 3 Effect Injection temperature on green part dimension

The demolding process was done manually. The simple semi-manual demolding machine is still developed in this research while much care should be attained to prevent the crack of green sample. To minimilize the crack and decrease the friction between the green sample and the PDMS mold, some lubricant should be furnished in the micro mold before injection process.

C. Green Sample

The green sample with low deviation (see Table I), and completely demolded from PDMS mold succeed to be achieved in this experiment. These green densities can be seen in Fig. 4 and Fig. 5 for detail appearance.

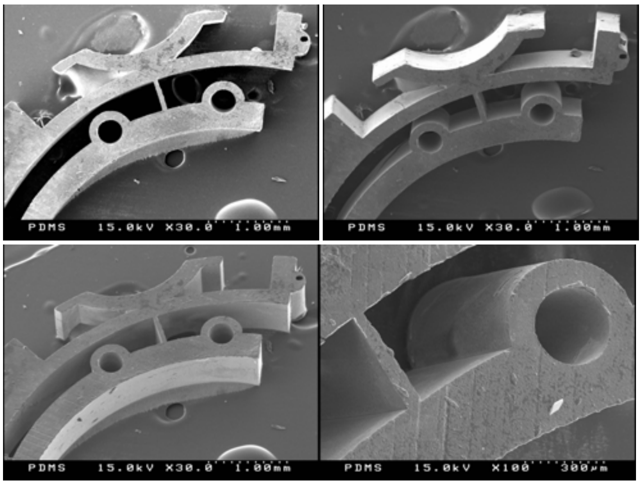

Fig. 4 Green Samples

From three kinds of feedstock that prepared, high powder load with high viscosity reduced the micromold filling when the injection process was applied. It's found, that completely filling can be achieved with 45 % PL feedstock.

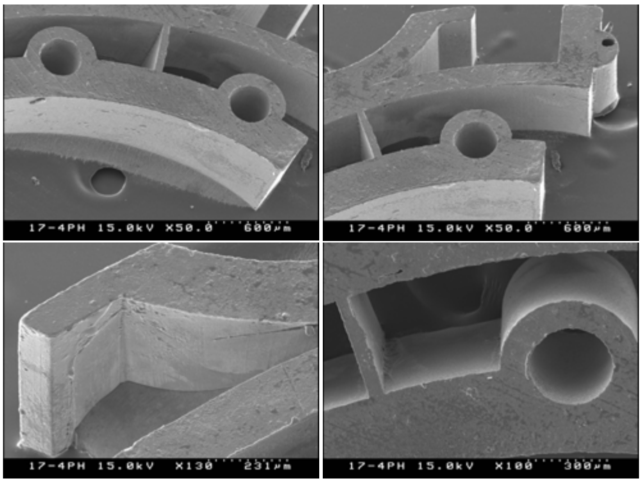

Fig. 5 Green samples in details

From the Fig. 5, the detail structure can be seen clearly which the feedstocks can completely fill the micromold. The ultimate achievement can be seen in the 60µm microchannel with 700 µm in thickness. It can be seen that there's no any air trapped or defect in the green sample and it infers that the feedstocks, the injection process and the micromold great enough to be an alternative to produce the micropart.

From this research, the factors that affecting to the tolerance greenparts can be devided by: mold strength, modability, constant stress, vacuum condition, demolding and pressing speed.

a. Mold strength is needed to obtain desired shape and high dimension tolerance. PDMS strength can be enhanced by modifying curing agent percentages.
b. Moldability is depending on the ability of feedstock to fill the cavity. Due to the binder material is thermoplastic polymer; viscosity of the feedstock is reduced with increasing temperature.
c. Demolding process to obtain green part is the critical process. The small part is susceptible with damage during this process. PDMS mold prior easily demolding due to flexible properties.
d. Another factor influence the dimension accuracy is constant stress during molding process. This condition influenced by pressing, pressing speed, and the feedstock thickness.

D. *Sintered Part*

The crack can be happened in the sintered part. Several causes can be the reasons of crack. One of them is the micro crack during demolding process (from green sample). It's believed, even micro crack can be an initial crack that cause crack in sintered part. During the sintering, the micro crack will propagate and break the sintered part. One solution to reduce the crack is use the slow heating rate in the sintering process. With this method, the crack propagation will be decreased significantly. The main solution, the crack formation during the demolding process must be avoided. A semi-manual demolding machine is needed to overcome this problem. The sintered part can be seen below:

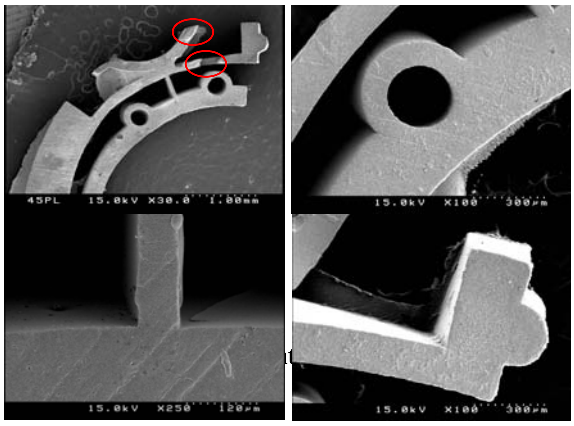

Fig. 6 sintered samples

TABLE I
TOLERANCE OF MICROBEARING PART

Position	Pattern dimension	PDMS Mold	Green Part	Sintered Part
1	60	60.63 ± 1.01	61.13 ± 0.97	55.43 ± 3.11
2	330	333.50 ± 1.06	340.13 ± 1.31	294.61 ± 3.84
3	300	309.08 ± 0.94	310.08 ± 5.06	271.36 ± 2.78
4	100	102.90 ± 0.91	110.97 ± 2.76	100.98 ± 3.09

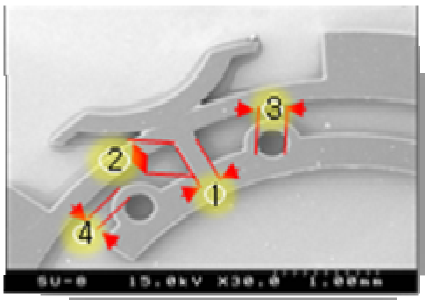

Fig. 7 Point of Check

From the Table I, it can be infered that the PDMS and nano powder injection powder process can be alternative to fabricate micro part with low deviation. This process still needs more development to increase the mechanical properties since the final relative only 84% and shrinkage up to 15%.

IV. CONCLUSION

The 700 um silicone metal pattern succeed to form PDMS micro mold. The experiment succeed to show that the 17-4PH feedstocks can be injected into PDMS micro mold without any air trap and can fill the 60 μm micro channel fully. The green sample succeeds to be demolded from PDMS micro mold. Some cracks happened in sintering part, some causes stil l in progress to be solved so the high density, high accuracy an d good part in mechanical properties can be produced.

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