Development and Application of Rapid Injection Molds Using Aluminum-Filled Epoxy Resins for Metal Injection Molding

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Research Article

Keywords: Rapid tooling, Metal injection molding, Die life, Manufacturing time, Manufacturing cost

Posted Date: April 14th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-404975/v1>

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Abstract

Metal injection molding (MIM) is a near net-shape manufacturing process combining conventional plastic injection molding and powder metallurgy. Two kinds of injections molds for MIM were developed using conventional mold steel and aluminum (Al)-filled epoxy resins in this study. The characteristics of the mold made by rapid tooling technology (RTT) were evaluated and compared to that fabricated conventional machining method through MIM process. It was found that the service life of the injection mold fabricated by Al-filled epoxy resins is about 1300 molding cycles. The saving in manufacturing cost of an injection mold made by Al-filled epoxy resins is about 30.4% compared to that fabricated conventional mold steel. The saving in manufacturing time of an injection mold made by RT technology is about 30.3% compared to that fabricated conventional machining method.

1. Introduction

Metal injection molding (MIM) is a near-net shape manufacturing approach for fabricating metal components with excellent mechanical properties [1, 2]. In addition, the powder injection molding (PIM) offers a unique solution for the mass production of precision parts with excellent mechanical properties. The advantages of MIM involve high production rate, good mechanical properties, good dimensional control, and good shape complexity. The disadvantages include high sintering temperature, part size limitation, and product with residual pores. The powders used for MIM or PIM involve zirconia [3], 316 L stainless steel [4, 5], tungsten carbide [6, 7], titanium [8, 9], copper, chrome steel, and nickel. In general, the MIM process consists of four distinct steps, i.e. mixing, injection molding, debinding, and sintering. Firstly, the metallic powders were mixed with binders to form a feedstock. The feedstock was then injected to cavity for manufacturing green parts using MIM machine. The binder of green parts can be removed by the de-binding process to form brown parts. Finally, brown parts were sintered at a high temperature and in a high vacuum atmosphere to form final parts. Some studies regarding the MIM process have been carried out. Safarian et al. [10] investigated the effects of sintering parameters, such as dwell time, sintering temperature, and heating rate on diffusion bonding of 316L stainless steel in inserted metal injection molding. It was found that the sintering temperature is the most important parameter compared to the dwelling time and heating rate on diffusion bonding of 316L stainless steel. Sahli et al. [11] developed a numerical model based on elastic–viscoplastic constitutive equations for calculating macroscopic deformation and structural evolution during sintering of complex micro-gear compacts. Hayat et al. [12] developed water-soluble PEG/PMMA binder systems for μ -MIM. It was found that the developed binder systems are more suitable for μ -MIM process that has an inherently higher cooling rate. Imgrund et al. [13] proposed two-component metal injection molding for manufacturing of multi-functional micro parts. It was found that intact material interfaces of less than $500\text{ }\mu\text{m} \times 500\text{ }\mu\text{m}$ can be obtained by careful selection and tailoring of metal powders, injection molding and co-sintering parameters. Oh et al. [14] investigated the nano powder effects on both of solvent and thermal debinding processes. The results showed that the immersing time requiring in the solvent was increased by the nano powder and the amount of the residual binder. Kate et al. [15] investigated the influence of

feedstock properties on the injection molding of aluminum nitride. It was found that the estimated feedstock properties as input parameters in mold-filling simulations that could be extended for a variety of material systems and geometries early in the design phase. Lamarre et al. [16] developed a new injection concept for increasing the moldability of powder-binder mixtures in the low-pressure powder injection molding. Zhang et al. [17] used three metallic powders with different compositions, particle shapes and particle sizes for producing micro-structured parts using injection molding process. The results showed that the micro-structured parts can be obtained using the process chain of injection, debinding and sintering with metallic powders. Zhang et al. [18] produced the M2 tool steel components with microstructures using PIM process. Nayak et al. [19] developed powders to fabricate stainless steel parts using PIM process. García et al. [20] fabricated steel matrix composites reinforced with different amounts of vanadium carbide (VC) using MIM process and investigated the effects of adding VC on dry sliding wear behavior using both pin-on-disk and ball-on-flat tests. Dehghan-Manshadi et al. [21] reviewed recent developments in MIM of titanium and its alloys as well as the outstanding challenges with a special focus on MIM of hydride-dehydride titanium powder. Thavanayagam et al. [22] investigated the effect of binder composition, powder loading, de-binding time and temperature on the debinding rate for removing polyethylene glycol-polyvinyl butyral with water, and porosity and microstructure of molded parts. Two materials have been proposed for fabricating mold inserts for MIM process, including silicone [23] and hardened steel [24]. However, these methods have disadvantages, including complex manufacturing processes, long processing time, and high production cost. Inductively-coupled plasma etching requires high production cost due to the complex manufacturing processes and long processing time. In addition, conventional milling machine has limitations on the minimum size of the microstructures in mold insert. To solve these drawbacks, a cost-effective method for fabricating an injection mold for MIM process was demonstrated using rapid tooling technology (RTT) [25–30]. In this study, injection molding simulation software Modlex3D was employed to determine the initial process parameter settings for MIM. The Al-filled epoxy resins were used to fabricate injection mold using RTT and applied to MIM. The characteristics of the injection mold fabricated by RTT were evaluated and compared to that fabricated conventional machining method through MIM process. The changes in surface roughness of the mold surface after MIM were continuously recorded to evaluate the longevity of the injection molds fabricated. The difference between mold life, production cost and production time was investigated.

2. Experimental Details

A manufacturing process for fabricating an injection mold for MIM process was developed. Figure 1 shows the process layouts for fabricating an ultra-large injection mold with complex geometric conformal cooling channels. An intermediary mold which is complementary in shape to the injection mold was fabricated by both liquid silicone rubber (KE-1310ST, Shin Etsu Inc.). The Al-filled epoxy resins (TE 375, Jasdi Chemicals Inc.) was used to make an injection mold through the intermediary mold. A vacuum machine (F-600, Feiling) was used to eliminate air bubbles from the resulting mixture. The fabricated injection mold was then cured using a convection oven (DH400, Deng Yag Inc.) for obtaining the required

mechanical properties. Finally, the fabricated injection mold was machined to the dimensions needed. In order to compare the performance of the injection molds fabricated by Al-filled epoxy resins, STAVAX-electro slag remelting (ESR) stainless mold steel (ASSAB Inc.) was also used to fabricate an injection mold. An injection machine (α -S100iA, FANUC Inc.) was used to form green parts. In this study, two-plate mold with a direct gate was used in this study because it is the easiest injection mold structure. In addition, two cavities in one mold base were used in this study because the performance of two different mold inserts can be evaluated under the same injection process parameters. Table 1 shows the MIM process parameters. The master model and injection mold were designed by using Pro/ENGINEER software. The dimensions of the master model were 15 mm in length, 15 mm in width, and 2 mm in thickness. The feedstock is the mixture of metal powder and binder for injection molding. The quality of feedstock is depended on the type of metal powder and binder because the agglomeration, debinding, particle packing, and dimensional correctness were affected by the type of binder employed. In this study, the metal matrix composite contains Fe and Ni powers. The polypropylene and paraffin wax in a proportion of 50:50 were mixed as binder in this study. The metal powders (60 vol. %) and binder (40 vol. %) were warmed at 100°C and then mixed in a mixer at 150°C for 2 h. The average particle sizes of the metal powders were examined by field emission scanning electron microscopy (SEM) (JEC3000-FC, JEOL Inc.). The solvent (n-Heptane) de-binding process was used to remove the binder from the green parts. The solvent debinding time was about 6 h using a de-wax furnace (MIM-500D, Yu-He Inc.). The sintered products can be obtained from green parts using a vacuum sintering furnace (VM-600, Mei-Yang Inc.). The sintering temperature was about 1300°C with a heating rate of 5–10°C /min under nitrogen purged atmosphere. The sintering time was about 24 h in the vacuum environment. In order to minimize the defects caused by the nature of injection molding process, Moldex 3D simulation software was used in this study because it provides the quality control tool for evaluating molding conditions. The service life of the two kinds of injection molds were carried out using an MIM injection machine. The centre-line average surface roughness (Ra) value was used to evaluate the changes in the surface roughness of the two kinds of injection molds. The measuring range is 250 μm $\times$ 250 μm . The WLI (7502, Chroma Inc.) was used to measure the surface roughness of the mold surface after MIM. The changes in surface roughness of the fabricated injection mold were investigated and compared to the injection mold fabricated by conventional mold steel. The micro-Vickers hardness of specimens was measured under the load of 2.9 N with 15 s using a micro-Vickers hardness tester (HM-112, Mitutoyo Akashi Inc.). Typical defects in the sintered parts such as porosity, cavities, inclusions and cracks were examined via an X-ray computed tomography (CT) scan (Tom tomoscope 200 – 190 3D CNC Werth Messtechnik GmbH Inc.).

Table 1
MIM process parameters

Parameters	Value
Injection time (s)	0.108
Injection pressure (MPa)	70
Injection speed (mm/s)	80
Packing pressure (MPa)	50
Packing time (s)	1
Molding temperature (°C)	160
Mold temperature (°C)	20

3. Results And Discussion

The metal injection molding simulation software Moldex 3D can be resolved and predicted the metal injection molding problems in the mold design stage. In this study, an injection mold with two cavities was designed for MIM process, as shown in Figure 2. Figure 3 shows the simulation result of filling process. The filling time of the molded part is approximately 0.108 s. Figure 4 shows the simulation result of maximum injection pressure. The maximum injection pressure is approximately 59.72 MPa. In general, the powder concentration distribution is usually unsteady. Figure 5 shows the simulation result of the powder concentration distribution. As can be seen, black-line marks were observed near the gate due to low powder concentration. Figure 6 shows the simulation result of volume shrinkage. The shrinkage of molded part is uniform and the volume shrinkage is approximately 2.36 % [31]. Figure 7 shows the simulation result of the warpage. As can be seen, the molded part was deformed inward and the total displacement of the warpage is approximately 0.034 mm.

Figure 8 shows the morphology of the Fe powder. Figure 9 shows the morphology of the Ni powder. Figure 10 show the results of the short shot test. As can be seen, the whole filling processes of the green part were similar to the simulation results [32]. Figure 11 shows the injection molds fabricated by rapid tooling and STAVAX steel. Figure 12 shows a green part was ejected during MIM process. Figure 13 shows the green parts fabricated by STAVAX steel and Al-filled epoxy rapid tooling via MIM process. The length, width and thickness of the molded part are 15 mm, 15 mm and 2 mm, respectively. In order to make the green parts easily release from the mold inserts ,the draft angle of the molded part was designed as 5°. This result shows that the green part of Fe₂Ni can be successfully fabricated by an injection mold fabricated by Al-filled epoxy rapid tooling.

In order to evaluate the longevity of injection molds made by STAVAX stainless steel [33] and Al-filled epoxy resins, the MIM process was carried out with feedstock of Fe₂Ni. Figure 14 shows the average surface roughness of mold surface as a function of injection molding cycles. Figure 15 shows the

average surface roughness of the injection mold fabricated by STAVAX stainless steel after 1 to 2500 injection molding cycles. As can be seen, the average surface roughness of mold fabricated by STAVAX stainless steel after 1, 500, 900, 1300, 1600, 2500, and 2700 molding cycles were 148 nm, 168 nm, 156 nm, 160 nm, 147 nm, 212 nm, and 143 nm, respectively. Figure 16 shows the average surface roughness of the injection mold fabricated by Al-filled epoxy resins after 1 to 2500 injection molding cycles. The average surface roughness of the injection mold fabricated by Al-filled epoxy resins after 1, 500, 900, 1300, 1600, 2500, and 2700 molding cycles were 174 nm, 161 nm, 175 nm, 158 nm, 219 nm, 227 nm, and 220 nm, respectively. The results clearly show that the changes in the average surface roughness of the injection mold fabricated by Al-filled epoxy resins before 1300 molding cycles is very close to that of the injection mold fabricated by STAVAX stainless steel. However, the average surface roughness of the injection mold fabricated by Al-filled epoxy resins increased with increasing the injection mold cycles after 1300 molding cycles.

To understand the dimensional accuracy of the green parts molded by mold steel and injection molding tool, a series of experiments was performed [34]. Figure 17 shows the dimension of the green part as a function of injection molding cycles. As can be seen, the dimension of the green part increased abruptly after 1300 injection molding cycles, while the changes in the dimension of the green part were stabilized after injection molding cycles of 2,000. The dimension of the green part fabricated by the mold made of STAVAX stainless steel after 1, 500, 900, 1300, 1600, 2500, and 2700 molding cycles was 14.6 mm, 14.57 mm, 14.58 mm, 14.66 mm, 14.65 mm, 14.66 mm, and 14.66 mm, respectively. The increase in the dimension of the green part was about 0.06 mm due to the wear of the mold surface after MIM process. The dimension of the green part fabricated by the mold made of Al-filled epoxy resins after 1, 500, 900, 1300, 1600, 2500, and 2700 molding cycles was 14.64 mm, 14.64 mm, 14.64 mm, 14.67 mm, 14.68 mm, 14.7 mm, and 14.7 mm, respectively. The increase in the dimension of the green part was also about 0.06 mm due to the wear on the mold surface after MIM process [35]. According to the changes in both dimension and surface roughness, it was found that the longevity of the injection mold fabricated by Al-filled epoxy resins are about 1300 molding cycles.

To understand the difference in hardness [36] between black-line area and general area in the sintered part, a series of experiments was performed. Figure 18 shows the micro-Vickers hardness of black-line area and general area in the sintered part. The average micro-Vickers hardness of the black-line area is about 162.9 HV, while the average micro-Vickers hardness of the general area is only about 149.6 HV. As can be seen, the average micro-Vickers hardness of the black-line is higher than those of the general area. This is because the metal powder near the sprue has a higher density than general area due to high injection pressure during MIM.

The final part made with Fe₂Ni powders can be applied to the rotating shaft. Figure 19 shows the results of green part and sintered part. The shrinkage of length, width, and thickness of the final part is about 22%. In order to evaluate the advantages of an injection mold fabricated by RT technology, both production costs and manufacturing time of an injection mold fabricated by two different methods were investigated. Figure 20 shows the X-ray analysis of the green part and sintered product. The results

clearly show that no any defects were found in the green part. However, some defects were found in the sintered products. This is because the defects cannot be fully verified due to polymer materials existed in the green part will affect the inspection results. Therefore, the quality assurance operations of the MIM products still depend on final sintered products. Figure 21 shows the black-line position in the simulation result, green part, and sintered part. It should be noted that the black-line position in both simulation result and green part is in the vicinity of the gate. In addition, the position of black-line position predicted by simulation software is very close to the position of the green parts. This means Moldex 3D simulation solution can effectively predict the position of black-line in the new MIM product development stage. Figure 22 shows the volumetric shrinkage in simulation result and green part. It is interesting to note that there is obvious volumetric shrinkage in the vicinity of the gate. In addition, the volumetric shrinkage position predicted by simulation software is very close to the sintered part.

Figure 23 shows the production cost of the molds fabricated by conventional method and RT technology. The total production cost of an injection mold fabricated by conventional method is about NT\$ 13,550. The total production cost includes the mold material cost of NT\$ 600, micro-hole machining cost of NT\$ 150, wire-cut machining cost of NT\$ 900, computer numerical control (CNC) machining cost of NT\$ 3,600, precision milling cost of NT\$ 300, and mirror finish machining cost of NT\$ 8,000. The total production cost of an injection mold fabricated by RT technology is only about NT\$ 9,430. The total production cost involves the mold material cost of NT\$ 1830, the labor cost of NT\$ 4,000, CNC machining cost of NT\$ 3,240, and precision drilling cost of NT\$ 360. Thus, the saving in production cost of an injection mold made by Al-filled epoxy resins is about 30.4% compared to that fabricated conventional mold steel. Figure 24 shows the manufacturing time of the molds fabricated by conventional method and RT technology. The total manufacturing time of an injection mold fabricated by conventional method is about 76 h. The total manufacturing time include mold material preparation time of 60 h, micro-hole machining time of 0.5 h, wire-cut machining time of 1.5 h, CNC machining time of 5 h, precision milling time of 1 h, and mirror finish machining time of 8 h. The total manufacturing time of an injection mold fabricated by RT technology is only 53 h. The total manufacturing time includes mold manufacturing time of 48 h, CNC machining time [37, 38] of 4.5 h, and precision drilling time [39] of 0.5. Thus, the saving in manufacturing time of an injection mold made by RT technology is about 30.3% compared to that fabricated conventional machining method. These results obtained are very practical and economical for making large-sized molds [40] for MIM process and offer potential for many applications in the MIM industry. However, inherent limitations of injection molding tool fabricated with Al-filled epoxy resins are their low mechanical properties and heat transfer capability compared to STAVAX stainless steel [41]. These limitations can further be improved by adding copper powders [42,43], molybdenum disulfide [44-47], zirconia ceramics [48,49], or silicon nitride ceramics [50-53] particles in the mixture. These issues are currently being investigated and the results will be presented in a later study.

4. Conclusions

MIM is a near-net shaping approach for producing metallic parts with high intricate shape and good mechanical properties. Developing a cost-effective method for fabricating an injection mold is one of the

key problems needed to be resolved in the development of a new metal part. A new metal part can be fabricated by an injection mold fabricated by conventional mold steel. However, it is not an effective way for a new metallic part in the research and development stages due to high production cost and high risk. The metallic components with high density can be fabricated MIM process integrating powder metallurgy and plastic injection molding. The main conclusions from the experimental work in this study are as follows

1. The findings of this study are very practical and provide the greatest application potential in the research and development stage of a new metal part.
2. The saving in manufacturing time of an injection mold made by RT technology is about 30.3% compared to that fabricated conventional machining method.
3. The saving in production cost of an injection mold by Al-filled epoxy resins is about 30.4% compared to that fabricated conventional mold steel.
4. The longevity of the injection mold fabricated by Al-filled epoxy resins is about 1300 molding cycles.

Declarations

- Funding:
This study received financial support by the Ministry of Science and Technology of Taiwan under contract nos. MOST 109-2637-E-131-004, MOST 107-2221-E-131-018, MOST 106-2221-E-131-010, MOST 106-2221-E-131-011, and MOST 105-2221-E-131-012.
- Conflicts of interest/Competing interests :Not applicable
- Availability of data and material Data and materials are available
- Code availability Not applicable
- Authors' contributions
Arthur 1 Wrote the paper/ Conceived and designed the analysis/ Performed the analysis
Arthur 2/3 Collected the data/Contributed data or analysis tools
- Ethics approvalNot applicable
- Consent to participate I am agreeing to participate
- Consent for publication I am agreeing to publish this work

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Figures

Figure 1

Process layouts for fabricating an ultra-large injection mold tooling with complex geometric conformal cooling channels

Figure 2

Schematic illustration of an injection mold with two cavities

Figure 3

Simulation result of filling process

Figure 4

Simulation result of maximum injection pressure

Figure 5

Simulation result of powder concentration distribution

Figure 6

Simulation result of volume shrinkage

Figure 7

Simulation result of the warpage

Figure 8

Morphology of the Fe powder

Figure 9

Morphology of the Ni powder

Figure 10

Results of the short shot test

Figure 11

A green part was ejected during MIM process

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In order to evaluate the longevity of injection molds made by STAVAX stainless steel [33] and Al-filled epoxy resins, the MIM process was carried out with feedstock of Fe2Ni. Figure 14 shows the average surface roughness of mold surface as a function of injection molding cycles. Figure 15 shows the average surface roughness of the injection mold fabricated by STAVAX stainless steel after 1 to 2500 injection molding cycles. As can be seen, the average surface roughness of mold fabricated by STAVAX stainless steel after 1, 500, 900, 1300, 1600, 2500, and 2700 molding cycles were 148 nm, 168 nm, 156 nm, 160 nm, 147 nm, 212 nm, and 143 nm, respectively. Figure 16 shows the average surface roughness of the injection mold fabricated by Al-filled epoxy resins after 1 to 2500 injection molding cycles. The average surface roughness of the injection mold fabricated by Al-filled epoxy resins after 1, 500, 900, 1300, 1600, 2500, and 2700 molding cycles were 174 nm, 161 nm, 175 nm, 158 nm, 219 nm, 227 nm, and 220 nm, respectively. The results clearly show that the changes in the average surface roughness of the injection mold fabricated by Al-filled epoxy resins before 1300 molding cycles is very close to that of the injection mold fabricated by STAVAX stainless steel. However, the average surface roughness of the injection mold fabricated by Al-filled epoxy resins increased with increasing the injection mold cycles after 1300 molding cycles.

Figure 14

Average surface roughness of mold surface as a function of injection molding cycles

Figure 15

Average surface roughness of the injection mold fabricated by STAVAX stainless steel after injection molding cycles of (a) 1, (b) 500, (c) 900, (d) 1300, (e) 1600, and (f) 2500

Figure 16

Average surface roughness of the injection mold fabricated by Al-filled epoxy resins after injection molding cycles of (a) 1, (b) 500, (c) 900, (d) 1300, (e) 1600, and (f) 2500

Figure 17

Dimension of the green part as a function of injection molding cycles

Figure 18

Micro-Vickers hardness of black-line area and general area in the sintered part

Figure 19

Results of green part and sintered product

Figure 20

X-ray analysis of the green part and sintered product

Figure 21

Black-line position in (a) simulation result, (b) green part, and (c) sintered part

Figure 22

Volumetric shrinkage in (a) simulation result and (b) green part

Figure 23

Production cost of the molds fabricated by conventional method and RT technology

Figure 24

Manufacturing time of the molds fabricated by conventional method and RT technology