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Effects of Replacing Binder with Powder Space Holder on Properties of Metal Injection Moulded Foam

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Abstract

Metal foam can be produced using metal injection moulding with powder space holder. In this study, the effects of volume fraction of spacer holder on the foam properties were studied. Spherical poly (methyl methacrylate) (PMMA) particles were used as a space holder material. The 30% volume fraction of stainless steel 316L powder was mixed with varied volume fractions of binder and PMMA. There were five volume fractions of PMMA, namely 30% to 50%, with an increment of 5%. The results showed that the volume fraction of PMMA affected the properties. As the volume fraction of PMMA increased, the number of pores increased as well, but the sintered density and the mechanical properties decreased.

Key words: Metal foam, Metal injection moulding, Powder space holder

Introduction

The interest in metal foam has significantly increased due to their extended applications, which include automotive parts, filters, cushions, insulators and biomedical implants.(2) Currently, there are different manufacturing methods for metal foams. The conventional process is the gas injection method, where gas bubbles are injected into a liquid metal. The liquid metal is transferred using a conveyer belt to solidify. This process is very effective in continuously producing large size foams, but it is difficult to control the process to obtain a uniform structure. Another process is the deposition method, which starts from the ionic state of metal and deposits a polymeric foam preform with open cells. Similar to the deposition method, the investment casting method also uses a polymeric foam preform. In the investment casting method, the polymeric foam preform is dipped into graphite slurry, or is coated with a thin layer by metal vaporisation. Subsequently, the polymeric foam preform is removed by thermal treatment.(1) These two processes can produce a complex shape part which can be fabricated by preforming the polymeric foam. However, both methods are expensive.(4)

Metal injection moulding (MIM) is a manufacturing process combining the traditional powder metallurgy process and plastic injection moulding.(3) It is capable of producing small parts with complex shape on a mass production scale. Hence, MIM using powder space holder (MIM-PSH) has been developed for producing complex metal foam parts.(5) The MIM with powder space holder for producing foam is similar to conventional MIM, as shown in Figure 1. There are four main steps, which are mixing, injection, debinding and sintering. In the first step of mixing, metallic powder, binder and powder space holder are homogeneously blended together. The mixture is then granulated and injected to obtain "green" parts. The green part is heated to remove binder and powder space holder. This step is the debinding step and "brown" parts with the structure of foam are obtained after debinding. Brown parts are then sintered at a high temperature to obtain a metal foam. It is noted that MIM-PSH can produce both open-cell and close-cell foams. Poly (methyl methacrylate) (PMMA) is a common powder space holder.(7,12,13,5,10,9) PMMA can be easily decomposed in the debinding stage, and the metal foam with uniform foam structure can be manufactured by MIM-PSH.(5) In addition, MIM-PSH can be

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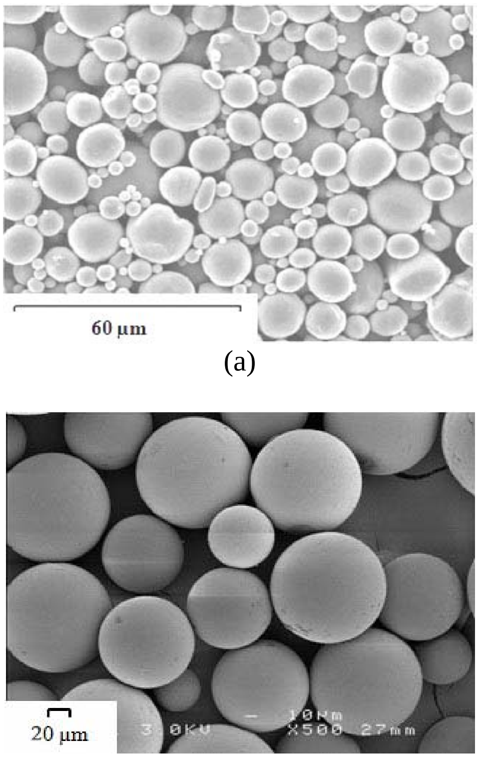
cost-effective for micro-sized, highly complex porous shape with high dimensional accuracy.(12) As a result, PMMA was used in this work as the powder space holder. Nishiyabu, *et al.* (2008) studied the properties of 316L foam produced by MIM with 30 and 60% volume fraction, and 10 and 40 µm average size of PMMA. The effect of powder space holder shape was also studied.(7) Spherical and strip carbamide particles were used as the powder space holder. Previous works only studied two volume fractions of powder spacer. Therefore, this work systematically investigated the effect of volume fraction of PMMA (powder space holder) on the properties of metal foam produced by MIM-PSH.

Figure 1. Schematic representation of metal injection moulding using powder space holder technique.

Materials and Experimental Procedures

In this work, the water–atomised stainless steel 316L powder (PF-20F) provided by Atmix Co. Ltd., Japan, was used. The powder has the average size of 10.5 µm. PMMA was supplied by Sunjin Chemical Co. Ltd., Korea. PMMA was used as the powder space holder in this work and had a particle size of 84.7 µm. Figure 2 shows the scanning electron microscopy (SEM) images of the 316L powder and PMMA particle. The 316L powder is rounded, while the PMMA particle is spherical. The binder in this experiment comprised of three components: paraffin wax as a plasticiser, high density polyethylene (HDPE) as a backbone polymer and stearic acid as a surfactant. The binder reduces the viscosity of the feedstock and facilitates injection moulding. The backbone polymer provides the essential strength of the green parts. The surfactant strengthens the adhesion between binder and powder and weakens the agglomeration of the powder.(6)



(a)

(b)

Figure 2. SEM micrographs of (a) 316L powder and (b) PMMA particle.

Stainless steel 316L powder, PMMA and a HDPE-based binder were mixed together in five batches with different volume fractions, as shown in Table 1. The solid loading of metal powder was kept constant at 30% volume fraction. The volume fraction of PMMA and binder were correspondingly varied with the constant combined volume fraction of 70%. The volume fraction of PMMA was increased from 30% to 50% with an increment of 5%, while the volume fraction of binder was decreased from 40% to 20% with an increment of 5%. Thus, the experiment was designed to replace the binder with more PMMA, while the solid loading of metal powder was constant. The mixing was carried out in a 1-liter Yamamura DSI-5MHB-E kneader. The mixing time was 30 minutes and the mixing temperature was varied between 130°C and 138°C.

This mixture was injected into tensile-test specimen shape using a 50-ton Niigata MS50S-V injection moulding machine. The tensile-test specimen has a rectangular cross-section with the width of 6.0 mm and the thickness of 3.5 mm. The total length of the tensile-test specimen is 100 mm, while the gauge length is 38.5 mm according to the Metal Powder Industries Federation MPIF standard 10. The injection temperature was varied between 133°C and 140°C. The injection pressure, speed and time were 50MPa, 20 mm.s^{-1} and 6 s. The mould temperature was kept constant at 23°C. Green parts were thermally debound at 450°C for 1 hour in air using a Fine SHKS-2H debinding furnace to remove binder and PMMA powder space holder. Debound parts were sintered at 1100 °C for 2 hours in an argon atmosphere using a Shimsadzu VHL20/20/23 sintering furnace. The densities of the green and sintered parts were measured. The samples were cut, mounted, grinded with silica papers and polished with diamond solution for the observation of microstructures using the optical microscopy. Hardness in HR15W scale (MPIF standard 43) and tensile tests (MPIF standard 10) were tested and reported.

Table 1. Fraction by volume of each component: PMMA, binder and metal powder.

Volume fraction of PMMA (% vol)	Volume fraction of binder (% vol)	Volume fraction of metal powder (% vol)
30	40	30
35	35	30
40	30	30
45	25	30
50	20	30

Results and Discussion

Processing Parameters

Most processing parameters for mixing and injection moulding were kept constant, apart from the mixing and injection temperatures, which were varied with the volume fraction of PMMA. Figure 3 shows the variation of mixing and injection temperatures. The mixing and injection temperatures increased as the volume fraction of PMMA increased and the volume fraction of binder decreased. It is recognised that the result for the 50% volume fraction of PMMA cannot be shown because it was not possible to inject the feedstock with 50% PMMA. From Table 1, a feedstock with 50% volume fraction of PMMA contained 30% by volume of metal powder and 20% by volume of binder. This means that during injection, there was only 20% liquid phase during injection (binder) and 80% solid phase during injection (PMMA and metal powder). This resulted in the high viscosity of feedstock. Furthermore, it was not possible to inject this feedstock with 50% volume fraction of PMMA, regardless of the injection condition. As the volume fraction of PMMA increased, the viscosity of feedstock was higher and it was more difficult for the feedstock to flow. As a result, the higher mixing and injection temperatures were required to increase flow ability.(11)

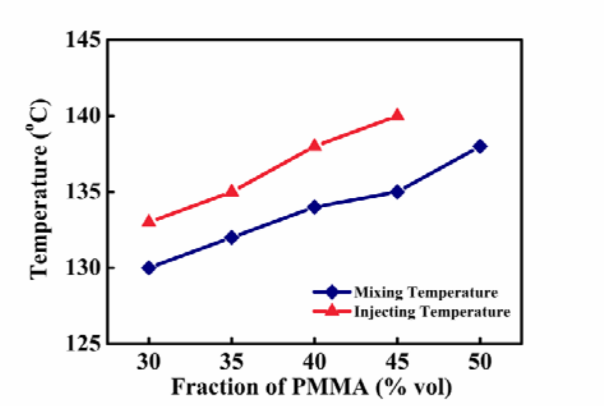


Figure 3. Mixing and injection temperatures as a function of the volume fraction of PMMA.

Density and Microstructure

Figure 4 shows the green and sintered densities as a function of volume fraction of PMMA. The sintered density is higher than the green density for all percentages of PMMA showing consolidation during sintering. The samples had a similar green density because the volume fraction of metal powder was kept constant. The average green density of all specimens was 3.05 g.cm^{-3}. The sintered density of 3.58 g.cm^{-3} was observed in the 30% PMMA volume fraction, which is the highest sintered density. On the other hand, the sintered specimen with 45% PMMA volume fraction had the lowest sintered density of 3.49 g.cm^{-3}. In addition, the sintered density decreased with increasing volume fraction of PMMA, although the green density was similar and the solid loading was kept constant. It is noticed that there are two basic shrinkage mechanisms in the sintering of MIM with PSH, which are (1) the shrinkage due to the consolidation of powder and (2) the shrinkage due to the cellular structure.(9) Since the solid loading and the sintering pattern were kept constant, the shrinkage due to the consolidation of powder should be similar. The difference is the shrinkage due to the cellular structure. As more PMMA was added, there were more spaces after the removal of PMMA. Therefore, more shrinkage was expected as the volume fraction of PMMA increased. This resulted in a smaller volume of sintered specimens with similar mass due to the constant solid loading. Hence, the density decreased as the amount of PMMA was increased.

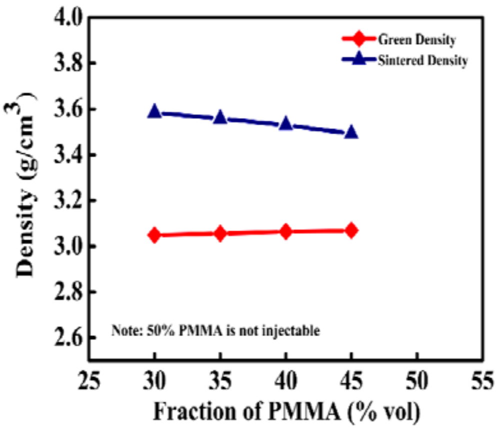
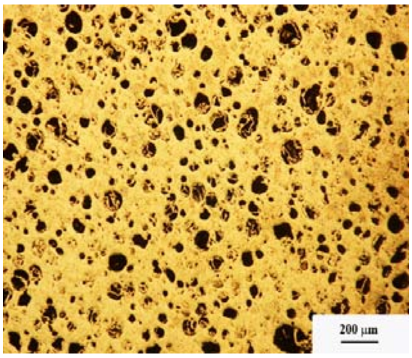
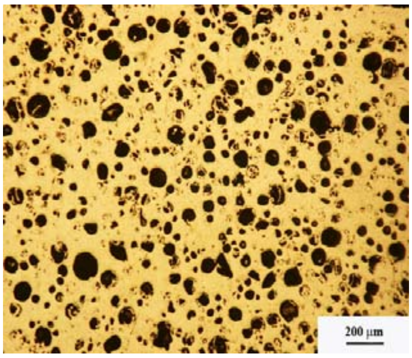


Figure 4. Green and sintered densities as a function of the volume fraction of PMMA.

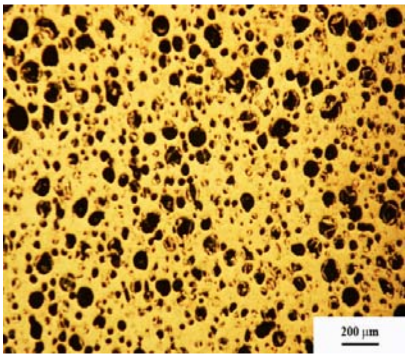
The microstructures of the sintered 316L stainless steel specimens with four different volume fractions of PMMA are shown in Figure 5. The number of pores depended on the PMMA contents. For all microstructures, the pores were introduced by the burnout of PMMA. All pores of this kind retained the spherical shape of powder space holder and distributed homogeneously in the 316L stainless steel matrix. The number of pores increased with the increased addition of PMMA. The microstructure of 45% PMMA volume fraction exhibited a large number of pores distributed thoroughly inside the specimen as shown in Figure 5 (d). There were more pores distributed in the microstructure of 45% PMMA volume fraction than in the other volume fractions.



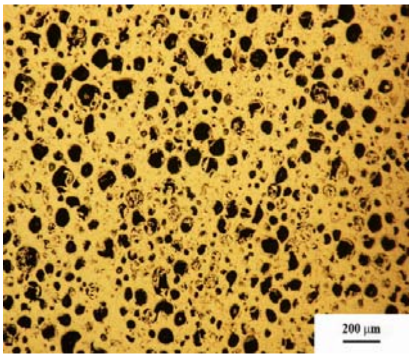
(a) 30% vol PMMA



(b) 35% vol PMMA



(c) 40% vol PMMA



(d) 45% vol PMMA

Figure 5. Optical microstructure of sintered parts cross section as a function of the volume fraction of PMMA.

Mechanical Properties

Sintered metal foam was subjected to hardness and tensile tests. The hardness of metal foam specimens was tested using Rockwell W (HR15W). The hardness of sintered parts varied with the volume fraction of PMMA, as shown in Figure 6. As a result, the volume fraction of PMMA increased from 30% to 45%; consequently, the hardness decreased from 32-21 HR15W. An error is also displayed. The error increased as the volume fraction of PMMA increased. It is perceived that the 45% volume fraction of PMMA had the largest error; this volume fraction also contained a large number of pores. The microstructures of the specimens showed that the number of pores increased with increasing volume fraction of PMMA. Therefore, the hardness values decreased as the number of pores in the specimens increased.

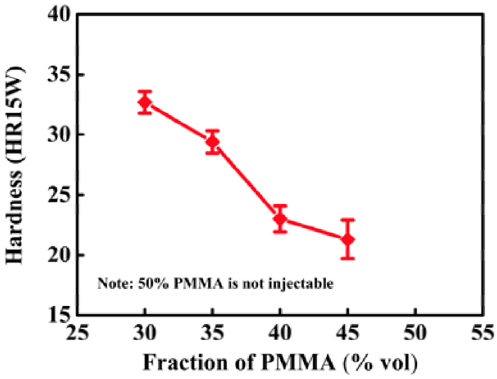


Figure 6. Hardness of sintered parts as a function of the volume fraction of PMMA.

Figure 7 shows the tensile strength and the elongation of sintered parts as a function of the volume fraction of PMMA. The tensile strength and elongation were dependent on the volume fraction of PMMA. As the volume fraction of PMMA increased, both tensile strength and elongation decreased. The 30% volume fraction of PMMA had the highest tensile strength of 125 MPa with 14% of elongation. The lowest values were obtained for the 45% volume fraction of the PMMA, which had the lowest tensile strength of 97 MPa, and the elongation of 10%. The results are similar to the hardness results. The mechanical properties decreased with an increase in porosity, or the volume fraction of PMMA increased.

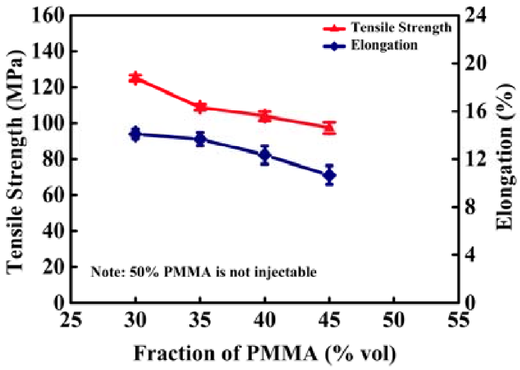


Figure 7. Tensile strength and elongation of sintered parts as a function of the volume fraction of PMMA**.**

Conclusions

Stainless steel 316L foams can be produced by applying a powder space holder method to a metal injection moulding process. The material used for space holding is a spherical PMMA particle. Five different volume fractions of PMMA were varied to replace the binder and the volume fraction of metal powder was kept constant. The experimental results show that the sintered density was higher than the corresponding green density. The sintered density decreased when the volume fraction of PMMA increased. The microstructure showed that the number of pores depended on the fraction of PMMA. The pores of spherical shape were homogeneously dispersed in the 316L stainless steel matrix. The number of pores increased with increasing volume fraction of PMMA. Tensile strength, elongation and hardness decreased as the volume fraction of PMMA increased.

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