Paper ID: IE-38

Investigation of powder and binder mixing mechanism in metal injection molding

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Abstract

In this study, fine aluminium powders were combined with two types of binder systems to produce different sets of feedstock for metal injection molding. Binder system A contained High Density Polyethylene (HDPE), Paraffin Wax (PW) and Stearic Acid (SA) while binder system B consisted of HDPE and SA, without PW. Investigations were performed on analysing the effects obtained among the feedstock on the availability of PW. The feedstock were prepared with different powder loading (58wt.%, 62wt.%, 70wt.%) and binder composition ratio but conducted under similar mixing temperature and mixing time. The mouldability of the feedstock and evolution on interface of the microstructure were investigated. Rheological analysis was carried out to determine the optimum range of binder composition for ideal molding. The morphological changes on the structure of the green (injected) parts and brown (debinded) parts were examined through FeSEM analysis. Result revealed that optimum powder loading of 62wt.%and binder composition ratio of 38wt.%with binder system consisting of HDPE, PW and SA at the ratio of 55:35:10 under the mixing speed of 350rpm and mixing time of 6 hours provided the good performance.

Keywords: *Color strength; dyeing process; dye concentration; FLES.*

1. Introduction

Metal Injection Molding (MIM) is a technique applied to manufacture small metal parts with complicated designs in a high density and high performance mode. As a subset of Powder Injection Molding (PIM), MIM combines the technologies of thermoplastic injection molding and powder metallurgy to produce complex-shapes cost effectively and improved mechanical properties. MIM has four main processing steps as mixing, injection molding, debinding and sintering (Fig. 1).

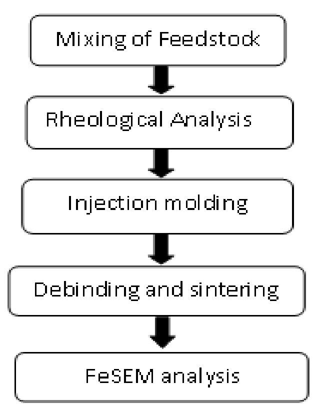

Fig.1 Design experimental setup with the four main processes in MIM.

In order to enable better rheological properties for molding and improved mechanical properties for handling, metal powders are hot mixed with thermoplastics polymers (binder) and some additives. Supati et al.,

[1] has stated that when powder is increased, the viscosity is also increased while with low mixing speed, high viscosity is resulted. Altering mixing temperature has insignificant effects on viscosity. The mixture of metal powder and binders (feedstock) is injection-molded into the required shape and the binder is removed and the powder is sintered to full density incorporating certain shrinkage. Fine (20 μm) powder exhibits higher packing density and produces improved mechanical properties [2]. It is also reported that finer starting powders give lower porosity after the sintering process of MIM [3]. The typical ratio of powder and binder mixing is about 60vol.% powder, 40vol.% binders whereas aluminium mixture constitutes about 86% powder by weight for typical mix ratio [4]. However, very few investigations have been carried out on the effects of composition ratio between aluminium powder and binder. Therefore, a desired aluminium powder mixing and binding strategy are to be developed for the better performance of MIM.

2. Materials and Methods

2.1 Material Properties

Aluminium powder of 99.9% purity, GF290-600-18 with particle size in the range of 0 to 60 micron meter and relative density of 2.7g/cm^3 by the supplier Good Fellow was used in the feedstock preparation. The microstructure of the aluminium powder particles was observed using the Scanning Electron Microscopy (SEM) analysis. Figure 2 shows the morphology of the raw material of powder and binder components used in the mixing.

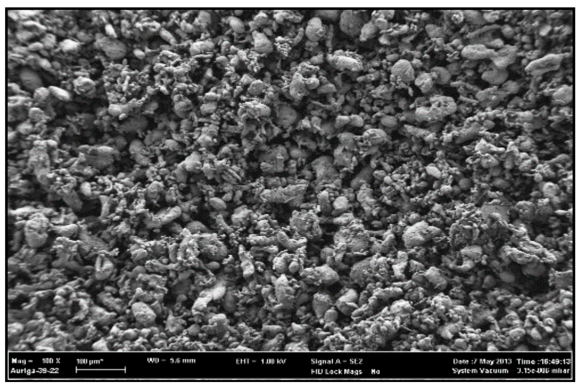

Fig.2 SEM micrographs on the morphology of the aluminium powder.

A binder system consisted of three different polymers was prepared. High Density Polyethylene (HDPE), Paraffin Wax (PW) and additives of Stearic Acid (SA) were mixed together at a constant composition ratio of 55%, 35% and 10% respectively. Few characteristics of the binder components used are shown in Table 1. Mixing experiments were conducted in a Retsch Planetary Ball Mill PM 100. 50ml grinding jar was clamped eccentrically on the sun wheel with the amount of feedstock restricted to less than two third of the jar volume. The extremely high centrifugal forces of Planetary Ball Mills create very high pulverization energy. The interplay between the frictional and impact forces produces an effective degree of mixing and homogenizing of the metal powder and binder system.Six feedstock formulations with the powder loading range between 58 wt. % and 70 wt. % were prepared. Identifications for each feedstock was labelled as listed in Table 2. Constant mixing speed of 350 rpm and mixing time of 6 hours were applied. Two types of binder systems were prepared for mixing. Binder System A consisted of all three binder components of PW, HDPE and SA while Binder System B consisted of only two components which are the HDPE and SA, without PW.

Table 1 Characteristics of binder components used.

Binder Component	Supplier	Melting Temperature (°C)
Paraffin Wax (PW)	Leica	57
High Density Polyethylene (HDPE)	Good Fellow	130
Stearic Acid (SA)	Aldrich	72

Table 2 Identification for various powder and binder composition

	Powder Loading (wt.%)	HDPE (wt.%)	PW (wt.%)	SA (wt.%)	Label
Binder System A	58.0	23.10	14.70	4.20	A58
	62.0	20.90	13.30	3.80	A62
	70.0	16.50	10.50	3.00	A70
Binder System B	58.0	35.00	-	7.00	B58
	62.0	32.00	-	6.00	B62
	70.0	25.00	-	5.00	B70

2.2. Rheological Analysis

After each mixing experiment, the feedstock viscosity was measured using a Physica MCR 301 Rheometer. A measuring plate with diameter of 15mm was used. Thermal equilibrium was achieved after charging the barrel for 10 minutes. Each feedstock was loaded onto the pre-heated barrel at 90°C. By increasing the speed of piston, shear rates were varied within the range of 100 to 10000 s^{-1}. Shear stress was obtained by measuring the pressure drop across the die length.The injection molding of feedstock was carried out using the in-house prototype injection molding machine. Five sets of molds were used to form different geometrical shapes, including the tensile mold and mold with various gear sizes. The injection pressure was set to be 7 bar and the injection temperature were varied within the range of 80 to 100°C. The specimen produced is shown in Fig. 3.Solvent debinding of the green part was done by immersing the specimen in hexane at 50°C for 5 hours. Subsequently, thermal debinding was carried out in a vacuum furnace at 250-500°C for 30 to 90 minutes. The parts were sintered under vacuum phase at 580-640°C for 30-120 minutes.

Fig.3 Tensile specimen produced with dimension 64mm x 10mm x 3mm.

3. Result and discussion

3.1 Rheological Properties

Flow and viscosity curves were dictated the flow ability of feedstock under various shear rates.The zero shear viscosity at low shear rates is a vital material property and is directly proportional to the average molar mass. Empirical studies have revealed that for the range of shear rates in the gates and the mold is within 100 to 1000s^{-1}, feedstock with flow viscosity less than 1000 Pa.s is mouldable [5]. Different flow curves of the various powder binder compositions were combined and compared for each binder system respectively (Fig. 4). From the flow curves it was observed that the viscosity is inversely proportional to the shear rate. It is reported that the range of parameters in which the feedstock exhibits pseudoplastic flow is desired [3]. Pseudoplastic flow where the viscosity decreases with increasing shear rate can help to reduce the required temperature and pressure for successful molding. Pseudoplastic flow or shear thinning behaviour is vital to ease mold filling, reduce jetting and assisting in shape retaining. It is best suited for injection molding process due to its viscosity of the mixture decreases when approaching the nozzle and when the mold is filled the viscosity increases [7-8].

As shown in Fig.4, the viscosity of feedstock obtained is relatively low and thus is expected to be injected. Sample A70 which contained 70% of aluminium powder loading has higher viscosity when compared to Sample A62 and A58. It is reported that torque of the mixture decreases when the composition of PW increases indicating viscosity reduces [12]. Behaving as Newtonian fluid, viscosity of paraffin wax remains constant as shear rate increases. Meanwhile, the viscosity of polyethylene which displays pseudoplastic behaviour decreases as the shear rate increases. For feedstock with Case B, higher range of viscosity was found with the similar range of shear rate. It can be observed that the maximum and minimum viscosities obtained are not varied too much from each other. The range of minimum viscosity falls in between 14 Pa.s and 30 Pa.s whereas the maximum viscosity range is 330 Pa.s to 360 Pa.s. Compared to the maximum allowable viscosity for molding of 1000 Pa.s, all the samples are suitable to be molded.

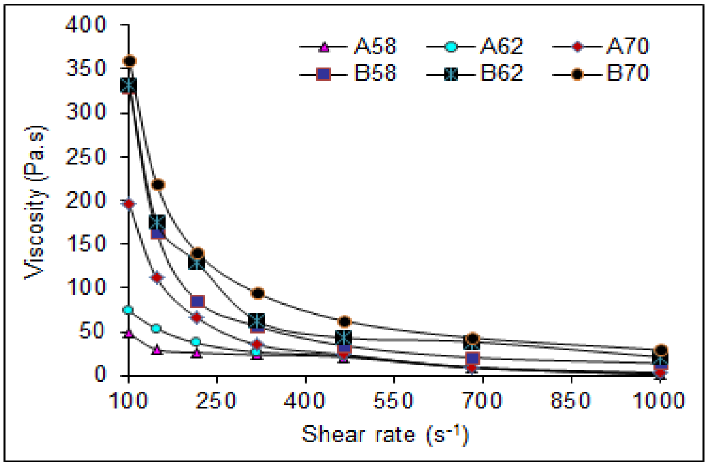

Fig. 4 Flow curve for feedstock with different mixing combinations.

3.2 Powder loading

Pseudoplastic fluid which exhibits shear-thinning properties is correlated by the Power Law as followed,

$$\tau = k\left(\dot{\gamma}\right)^{n} \qquad (1)$$

whereτ is the shear stress, $\dot{\gamma}$ is the shear rate, k the fluid consistency coefficient and n is the flow behaviour index or flow exponent (<1). It is noted that low value of flow behaviour index, n indicates rapid changes between feedstock viscosity and shear rate. However, a rapid decrease in feedstock viscosity with increasing shear rate during moulding is desirable.After completing the rheological testing, the data of the shear stress for each different feedstock formulation was collected and the log τ - log $\dot{\gamma}$ graphs for all six feedstocks have been plotted as shown in Fig. 5.

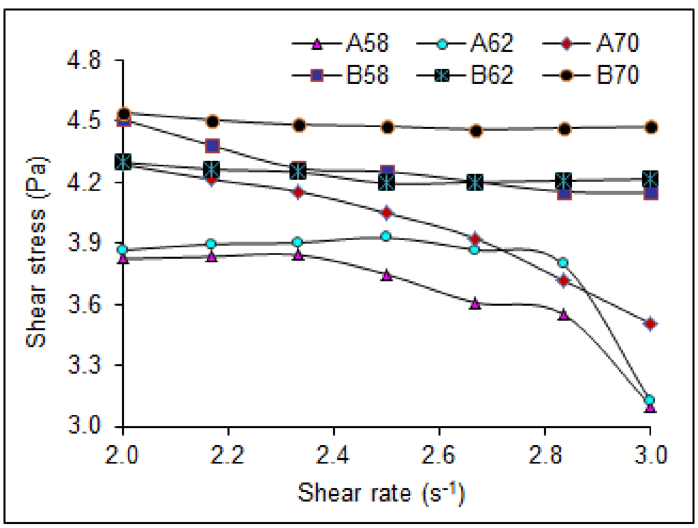

Fig. 5 Relations of shear stress and shear rate for feedstock.

Fig. 5 shows that all the six feedstocks are maintaining basically the pseudo-plastic flow characteristics. In general, it is observed that all the mixing formulations were pseudo-plastic but, the flow exponent values are different. Flow exponent values, *n* were obtained as 0.0796, 0.0801, 0.0899, 0.106, 0.108, and 0.115, respectively for different mixing conditions. It is also noticed that the flow exponent has started to increase with the increase of powder loading from 58 to 62% for both binder systems, achieving the lowest value of 0.0801 and 0.108, respectively. On the other hand, the flow exponent has started to decrease with the increase of shear rate for both of cases. Higher powder loading is preferred to ensure higher shear sensitivity of feedstock in order to produce complicated parts. Hence, the lower flow exponent for 62% powder loading has enabled it to be an optimum powder–binder composition for MIM feedstock. This is to achieve fast powder re-packing and binder molecule orientation during molding. Shear thinning of the samples feedstock with increasing shear rate was mainly due to the powder particle ordering and the binder molecule orientation with flow [5]. Furthermore, the SEM photograph of the feedstock for Case A with powder loading corresponding to 62% is shown in Fig. 6. It is observed that the particles are uniformly dispersed in the matrix and are enveloped by the binder. Thus, the resulting homogeneity is properly revealed for the selected feedstock formulation A62.

3.3 Injection Molding

Feedstock A58, A62, B58 and B62 were successfully molded. However, there were failures during injection molding for samples A70 and B70 with maximum flow viscosity of 196Pa.s and 361Pa.s respectively as shown in Fig. 8. These samples were tested to be with the viscosity flow of less than 1000 Pa.s, which were expected to be mouldable. Although the injection temperature has been set above 130°C which was over the melting point of the binder HDPE, the feedstock was still could not be injected due to the relatively high viscosity flow of the feedstock.

Fig.8 Incomplete molding of feedstock A70.

3.4 Debinding and Sintering

Significant sample size reduction and colour change on the debound brown parts were observed. The volume shrinkage and weight loss after the process of solvent debinding were mainly caused by the elimination of PW component. The microstructure of the brown parts was examined through SEM analysis as shown in Fig. 9. It was shown in the fractograph that, a layer of wax formed material was covering the surface of the part before debinding (Fig. 9a). After debinding (Fig. 9b), the layer of wax has been removed, hence the mixture of other remaining components were exposed.

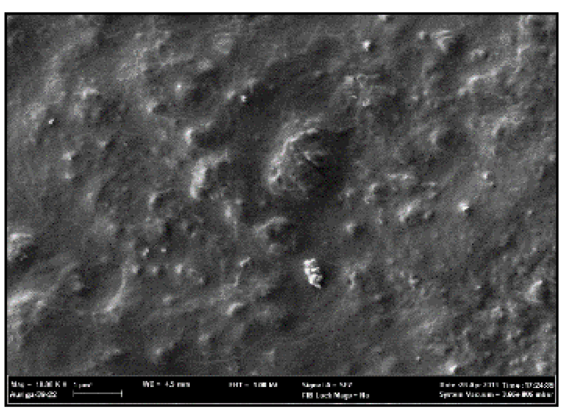

Fig.9a Comparison on the surface microstructure before debinding

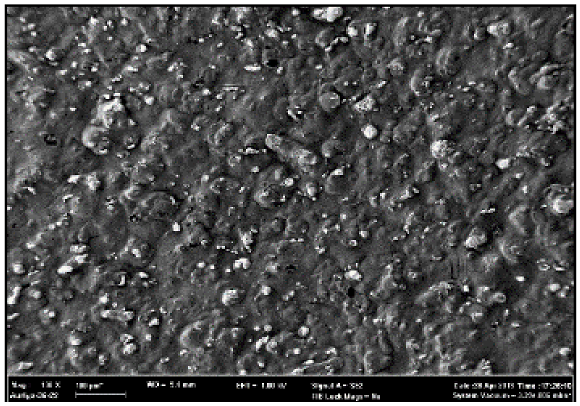

Fig.9b Comparison on the surface microstructure after debinding

4. Conclusions

The critical feedstock combination for better performance in MIM is found to be of 62wt% powder loading and binder composition of 38wt% with binder system A consisting of 20.9wt% HDPE, 13.3wt% PW and 3.8wt% SA at the ratio of 55:35:10 under the mixing speed of 350 rpm and mixing time of 6 hours. This is mainly due to its better rheological properties of maximum viscosity of 73.8Pa.s and relatively low flow behaviour index of 0.0801.

5. Acknowledgements

The authors would like to thank the University of Malaya for their financial support under UM.TNC2/RC/AET/261/1/1/RP020-2012B grant.

References

[1] Supati, R., Loh, N. H., Khor, K. A., & Tor, S. B. (2000). Mixing and characterization of feedstock for powder injection molding. *Materials Letters* (46), 109–114.

[2] Arakida, Y., & Miura, R. (1991). Powder injection molding as a metal forming process – effects of powder morphology, size and size distribution. *Key Engineering Materials 53-55*, 377-382.

[3] Zlatkov, B. S., Griesmayer, E., Loibl, H., Aleksić, O. S., Danninger, H., Gierl, C. (2008). Recent advances in PIM technology I. *Science of Sintering, 40*, 79-88.

[4] German, R. M. (2011). *Metal injection molding: A comprehensive MIM design guide.* USA: Metal Powder Industries Federation.

[5] Li, Y., Li L., & Khalil, K. A. (2007). Effect of powder loading on metal injection molding stainless steels. *Journal of Materials Processing Technology* (183), 432-439.

[6] German, R. M., & Bose, A. (1997). *Injection molding of metals and ceramics* (pp. 14-20). USA: Metal Powder Industries Federation.

[7] Gołombek, K., Matula, G., Mikuła J., &Dobrzański, L. A. (2011). Influence of binder composition on the properties of feedstock for cemented carbides. *Archives of Materials Science and Engineering, 51*(2), 116-124.

[8] Liu, Z.Y., Loh, N. H., Tor, S. B., &Khor, K. A. (2003).Characterization of powder injection molding feedstock. *Materials Characterization, 49*, 313–320.

[9] Thomas-Vielma, P., Cervera, A., Levenfeld, B., &Várez, A. (2008). Production of alumina parts by powder injection molding with a binder system based on high density polyethylene. *Journal of the European Ceramic Society*, *28*(4), 763-771.