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Full Length Research Paper

Injection moulding temperature and powder loading influence to the metal injection moulding (MIM) green compact

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The influence of temperature and powder loading on the Metal Injection Moulding (MIM) green compact is presented. The feedstock used is a mixture of stainless steel (SS316L) powder and a composite binder system consisting of polyethylene glycol (PEG) and polymethyl methacrylate (PMMA). The bi-modal particle size distribution powder has a composition of 30 and 70% by weight of fine and coarse SS316L powder respectively with a powder loading of 64 and 65% by volume. The Battenfeld BA 250 CDC injection-moulding machine was used to produce a MIMA tensile specimen. The as-moulded density was measured using the Archimedes water immersion method according to the MPIF Standard 42. The injection temperature was varied from 120 to 150°C while the injection pressure remains at 350 bars. The three-point bending test was performed using INSTRON 5567 to measure the green strength according to the MPIF Standard 15. Results showed that the bi-modal feedstock with the higher powder loading was more sensitive to temperature and that the injection temperature was less significant to the as-moulded strength and density.

Keywords: Metal injection moulding, bi-modal, particle size distribution, density, green strength, powder loading.

INTRODUCTION

Metal injection moulding (MIM) is expected to be very efficient for manufacturing small and complex metallic components on a large scale. Large amounts of components with excellent mechanical properties and high geometrical accuracy may be obtained by this newly developed technology, at a much lower cost than with traditional techniques (Barriere et al., 2003). The mixture of powder and binder is termed the feedstock. It is expected that each powder particle in the feedstock mixture will be enveloped by a very thin film of binder and in tight contact with its neighbours. Moreover, all the spaces between the powder particles will be filled with binder. The volume fraction of solid powder to the total volume of powder and binder is termed the powder loading. In general, it is expected that MIM feedstock will have a high powder loading. A large excess of binder will

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Abbreviation: MIM, Metal Injection Moulding; **PEG,** polyethylene glycol; **PMMA,** polymethyl methacrylate; **SA,** stearic acid.

Table 1. Chemical composition of ANVAL 316L stainless steel powder.

Elements	wt%
C	0.09
Si	0.32
Mn	0.80
P	0.041
S	0.016
Cr	16.40
Ni	12.40
Mo	2.31

Table 2. Particle size distributions.

	D_{10}	D_{50}	D_{90}	S_W
Coarse	9.563	19.606	40.058	4.159
Fine	5.780	11.225	19.840	4.873

make the binder separate from the powder during moulding, leading to flashing or inhomogeneities in the moulded parts. Further, a large excess of binder leads to compact slumping during debinding, since the particles are not held in place as the binder is removed (German and Bose, 1997). Higher powder loading means smaller compact volume shrinkage and easier dimension tolerance control, which is very important for the mass production of complex and delicate MIM parts. However, too high a powder loading is also unacceptable because it will lead to such high feedstock viscosities that the injection moulding process will fail (Li et al., 2007).

The minimization of the binder fraction means shorter debinding times and smaller shrinkage rates. Some efforts have been made in this direction, noticing that there is a minimum amount of binder to avoid particle contact whilst keeping the viscosity levels adequate for the injection moulding. Another possible improvement is to work on the particle distribution. The use of bi- or tri-modal particle distributions seems to be an adequate alternative for quality improvements allowing a higher powder loading with the same level of viscosity. In addition, the use of multi-modal size distributions helps to eliminate the rheological dilatancy in concentrated suspensions (Resende et al., 2001).

This paper presents an investigation into the influence of moulding temperature and powder loading on the injection moulding of SS316L powder in bi-modal particle size distributions. The binder system used is polyethylene glycol (PEG) and polymethyl methacrylate (PMMA) with Stearic acid (SA) as surfactant. This binder composition has been successfully used to mould a variety of metal (Chuankrerkkul et al., 2008a, b; Omar et al., 2003) and ceramic (Chuankrerkkul and Nilpairach, 2011) powders. Both PEG and PMMA bond to stainless steel, forming a rigid and robust moulding compact with increasing amount of PMMA in the binder composition (Chuankrerkkul et al., 2007). In addition, the water-soluble characteristic of PEG promotes a faster debinding process since PEG has opened more pores within the compact part after the water-leaching process, thereby, enabling capillary force to extract more PMMA binders during thermal debinding (Ibrahim et al., 2011; Jamaludin et al., 2009a, b). This investigation will establish an understanding of the injection moulding process using a bi-modal particle size distribution feedstock with PEG and PMMA as the binder. The investigation began with the rheological properties of the feedstock followed by the observation of moulding defects and the as-moulded flexure strength and percentage of theoretical density at various injection temperatures.

MATERIALS AND METHODS

The metal powder used is the ANVAL 316L, stainless steel, gas atomised, powder with a pycnometer density of 7.93 g/cm^3. The chemical composition of the metal powder is shown in Table 1. The PEG, supplied by Fisher Scientific, and PMMA, supplied by Alfa Aesar, has densities of 1.2963 and 1.1919 g/cm^3, respectively. A binder system based on 73% weight of PEG and 25% weight of PMMA is prepared. In order to improve the mouldability of the binder system, 2% weight of SA of density 0.847 g/cm^3, supplied by KIC Chemicals, Inc., was added as lubricant.

The distribution of the particle size is shown in Table 2. The feedstock is abbreviated as B1_64 and B1_65 to indicate the SS316L volume fraction of 64 and 65%, respectively. The SS316L powder was mixed with binders in the sigma blade mixer for 95 min

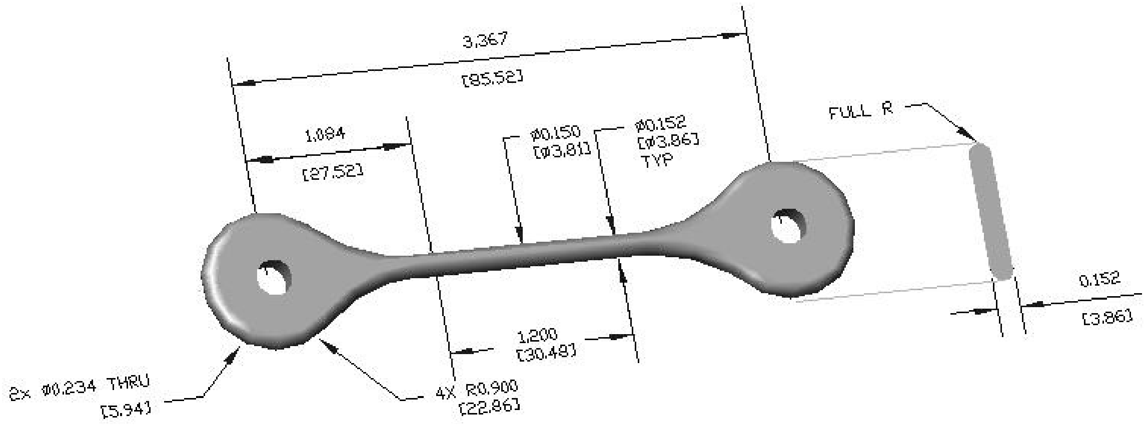


Figure 1. Injection molded specimen.

at 70°C. After mixing, the paste was removed from the mixer and fed into the strong crusher for granulation.

A Shimadzu 500-D capillary rheometer was used to study the rheological characteristics of the feedstocks. The MIMA tensile specimen, as shown in Figure 1, was injection moulded with the Battenfeld BA 250 CDC injection-moulding machine. In order to evaluate the temperature influence, the injection pressure was maintained at 350 bars while the injection temperature was varied at 10° intervals between 120 and 150°C, inclusive.

RESULTS AND DISCUSSION

Rheological properties

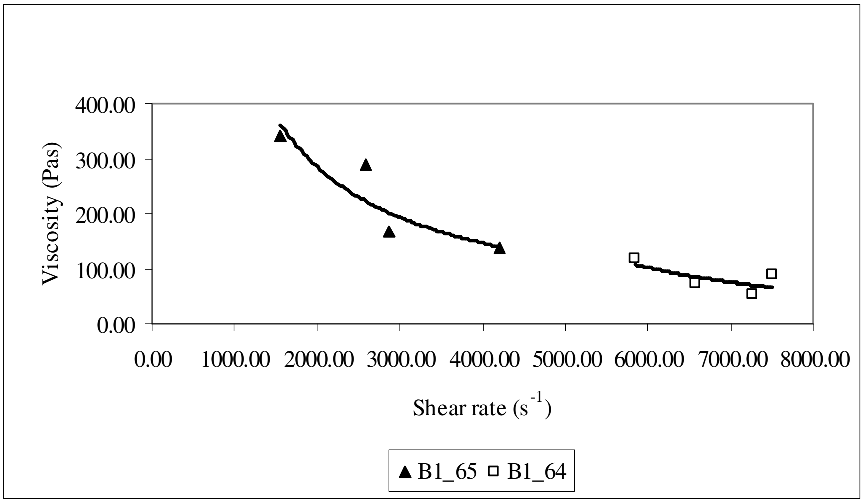
In the MIM process, the feedstock rheological properties are the key features that influence the steady flow and the uniform filling into the mould cavity. The evaluation of the feedstock rheological properties is based on its viscosity, shear and temperature sensitivity (Khakbiz et al., 2005). Figure 2 shows the apparent viscosity as a function of the shear rate for B1_64 and B1_65 at injection temperatures of 120, 130 and 140°C, respectively. The apparent viscosity decreased as the shear rate and temperature increased.

As shown in Figure 2, B1_64 exhibits a higher shear rate and lower viscosity than B1_65. Moreover, Table 3 shows that, the activation energy, E for B1_65 is higher than B1_64. A high activation energy indicates that the feedstock is highly sensitive to temperature fluctuations during injection moulding, and there is a possibility of the melt freezing quickly in the mould (Jamaludin et al., 2008; Yimin et al., 1999). The sensitivity to the temperature (activation energy) and pressure (flow behaviour index) demonstrates the feedstock's robustness and stability during the injection moulding process.

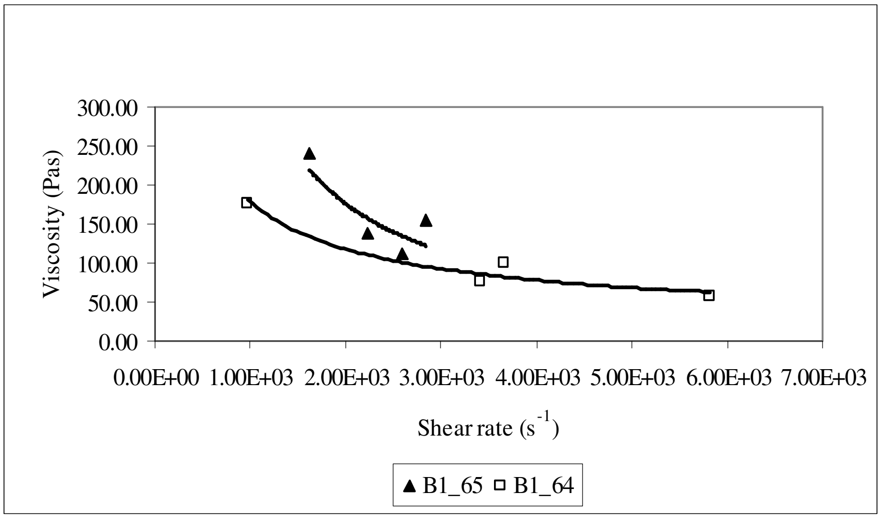
In Table 3, the flow behaviour index (n) shows the pseudo-plastic behaviour of the feedstocks. The flow behaviour index indicates the feedstock's sensitivity to the shear stress while the flow activation energy indicates its sensitivity to temperature. Both feedstocks show the typical shear thinning effect known for polymers, namely, with increasing shear rate, the apparent viscosity decreases. Similarly, the smaller the flow behaviour index (n), the higher the shear sensitivity and the greater the pseudo-plastic behaviour of the feedstock. Some moulding defects, such as jetting, are associated with low values of the flow behaviour index (Yang et al., 2002). Further, the mouldability index shows that B1_64 has better mouldability than B1_65. This is due to less inter-particle friction in the B1_64 feedstock. Better mouldability is expected for feedstocks with a lower powder loading, but it is proportional to the shrinkage in the final product. Table 3 shows that both B1_64 and B1_65 have their best mouldability index at 130°C.

An investigation reported by Resende et al. (2001) into the bi-modal mixture of iron spherical powder (1 and 7 µm) discovered that lower flow behaviour index values were obtained with the same powder loading when compared to the mono-modal distribution. The powder loading influence on the flow behaviour index is lower in bi-modal distributions. Further, in the same investigation, they found that the mono-modal distribution has its flow behaviour index increased as the powder loading increases and vice versa for the bi-modal distributions. These findings agree with the results shown in Table 3, especially for 130°C.

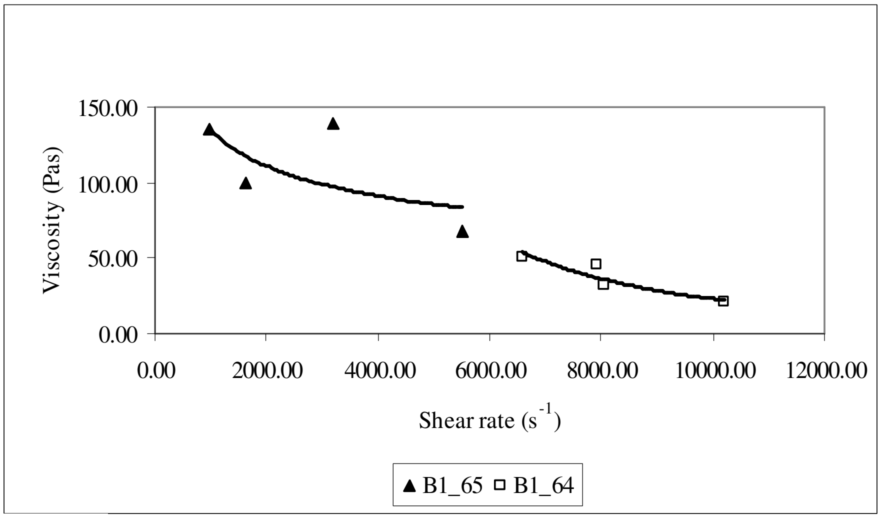
Moreover, the investigation of 17-4PH stainless steel powder in mono-modal distributions at various powder loadings done by Li et al. (2007) found that the shear sensitivity of the feedstock at powder loading 60 to 68% by volume was increased when injection moulded at 135°C, but the opposite was the case at 72% by volume powder loading. The shear thinning of MIM feedstock with the increase in shear rate results from the ordering of the powder particles and the orientation of the binder molecules with the direction of flow. On the other hand,



120°C



130°C



140°C

Figure 2. Apparent viscosity as function of shear rate.

Table 3. Rheological properties.

Flow activation energy, E (kJ/mole)	B1_64 (36.54)		B1_65 (159.90)	
T	Flow behavior index, n	Moldability index, α	Flow behavior index, n	Moldability index, α
120	-0.949	156	0.043	90
130	0.4058	761	-0.0411	149
140	-1.055	171	0.7166	109

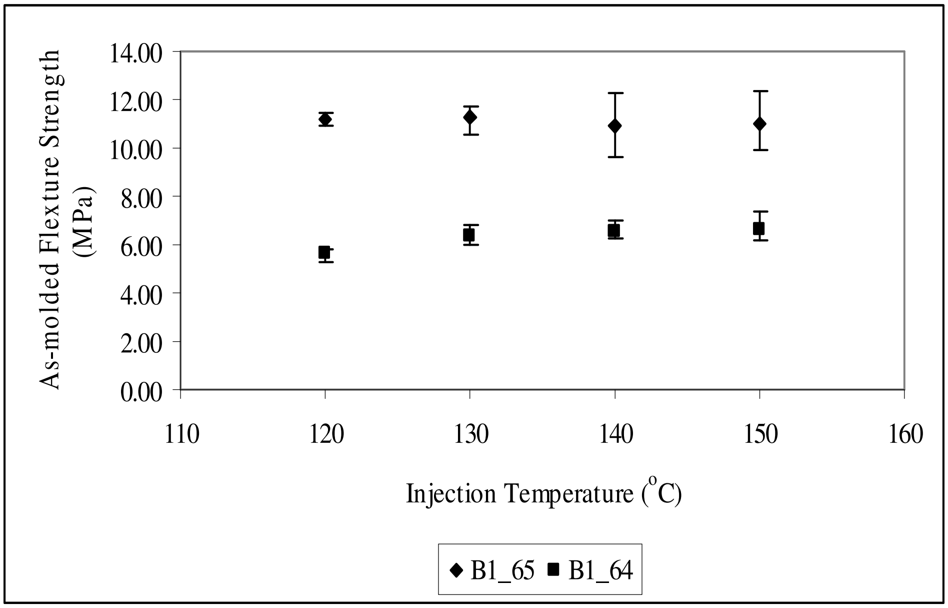


Figure 3. As-molded flexure strength.

the activation energy was increased at 72% by volume. This indicates that the feedstock was more sensitive to the temperature and less sensitive to shear stress at 72% by volume and vice versa for powder loadings less than 68% by volume. Moreover, the results in Table 3 show that the feedstock temperature sensitivity was increased at a powder loading of 65% by volume, and the shear sensitivity at same powder loading (130℃) was also increased, however, it was decreased at 130℃.

Typically, during the flow of highly filled materials, after overcoming the yield point and the low shear rates, particles start to order themselves in the flow direction to allow inter-particle motion resulting in a higher maximum packing fraction and lower viscosity. Pressure suppresses this effect resulting in higher viscosity. At high shear rates, the volume increases because particles cannot form layers and slide over each other. The rheological dilatancy might be connected to the increase in powder loading in the binder suspension, as discussed by Haunsnerova et al. (2006).

Properties of the as-moulded specimens

After the green compact had been ejected from the mould cavity, the green strength of each compact was tested with the three-point bending test using INSTRON 5567 based on the MPIF Standard 15. The density was measured using the Archimedes water immersion method according to the MPIF Standard 42. The results are shown in Figures 3 and 4, respectively.

Figure 3 revealed that the flexure strength of the as-moulded part at high powder loading (B1_65) was higher than the one with low powder loading (B1_64). This is due to the interlocking between powder particles, which firmly attaches the powder particles within the matrix. However, the injection temperature does not have any significant effect on the as-moulded strength. Although, the flexure strength increases when the powder loading increases, the mouldability of higher powder loading feedstock becomes more difficult due to the higher resistance caused by inter-particle friction. The

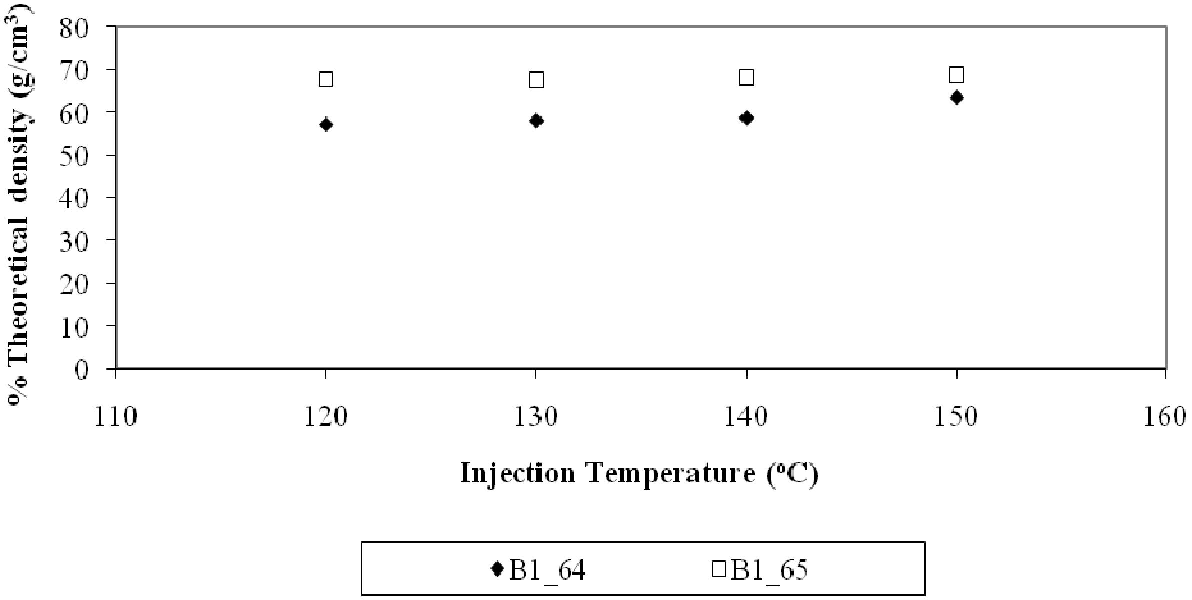


Figure 4. As-molded density.

Table 4. Remarks for injection molding of B1_65.

T	Remarks
120	In complete filling. Only the upstream and middle part filled
130	In complete filling. Only the upstream and middle part filled
140	Complete part produced with weld line at the down stream
150	Complete part produced with weld line at the down stream

mouldability of this feedstock has been improved by Omar (1999) by adding more stearic acid in the binder composition but a longer time is needed to solidify the green compact before it is ready for ejection.

Furthermore, due to the higher volume fraction of B1_65, Figure 4 shows that it has a better as-moulded density than B1_64. The investigation indicates that the injection temperature does not have any significant effect on the as-moulded flexure strength of either feedstock.

However, the rheological properties of the feedstock at various injection temperatures still have great significance for the success of the moulding process. Table 4 shows that B1_65 was unable to completely fill the mould cavity at 120 and 130°C compared to B1_64, which was able to be injection moulded at an injection temperature as low as 120°C.

The success of the injection moulding process also depends on the rheological properties shown in Table 3. The activation energy (E) of B1_65 is considered high (159.90kJ/mole) compared to 36.54 kJ/mole for B1_64. Consequently, B1_65 freezes prematurely in the mould cavity before it reaches the downstream point in the cavity, especially at low injection temperatures.

Conclusions

The successful injection moulding of MIM feedstock depends on the rheological properties of the feedstock.

A bi-modal powder distribution feedstock at higher powder loading is more sensitive to temperature than to the powder loading.

The flexure strength and density of the as-moulded part from the bi-modal powder distribution feedstock is proportional to the powder loading.

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