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# INFLUENCE OF TEMPERATURE TO THE INJECTION MOLDING OF BIMODAL POWDER MIXTURES

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## ABSTRACT

*Investigation on the influence of temperature to the injection of Metal Injection Molding (MIM) feedstock prepared with bimodal powder mixture is presented. Feedstocks used were a mixture of 19.606 and 11.225 $\mu$m stainless steel powder with composition of 30 and 70 % volume respectively mixed with PMMA/PEG and stearic acid as a binder in sigma blade mixer. Tensile specimen according to MIMA standard was injection molded with Battenfeld BA 250 CDC injection-molding machine and the as-molded density was measured with Archimedes water immersion method according to the MPIF Standard 42. The injection temperature was varied from 120 to 140 $^{o}$C while the injection pressure remains at 350 bars. The three-point bend test was performed using INSTRON 5567 to measure the green strength according to the MPIF Standard 15. Results found that an injection temperature 140 $^{o}$C is able to produce an acceptable compact. Also a compact with bimodal powder containing 30 % of fine powder distribution has an acceptable density and strength when injection molded at 140 $^{o}$C.*

**Keywords:** *Metal injection molding, bimodal powder distribution, packing density, as-molded strength.*

## INTRODUCTION

Metal Injection molding is a combination of four sequential technological processes – mixing, injection molding, debinding and sintering. Intensive mixing of the metal powder and the binder makes the feedstock homogenous. In the next phase, a green part is produced when a mixture of metal powder and binder has been injection molded by a injection molding machine.

The palletized mixture of powder and binder used in injection molding is termed as feedstock. No voids or pores are present in the feedstock, so there is sufficient binder to fill all interparticle spaces. Thus, the powder is selected for a high packing density. This might require adjustments to the particle size distribution or particle shape. Alternatively, differing particle sizes can be mixed to form a bimodal size distribution [1].

Mixing particles of different sizes is a common practice to increase the packing density over the monomodal compacts [2-4]. In bimodal mixtures, the key parameter for improving the packing density is the size ratio between fine and coarse powders, which the benefit being significant only for the coarse powder ratio. For size ratios close to unity, there is even some evidence that the relative density may decrease.

Starting from 0.67 for monomodal random dense spherical packing the relative density of bimodal mixtures can attain values as high as 0.85 for a size ratio of 100 [5]. The mechanism to increase the compact density is quite simple where fine powder particles must fill the interstices left by the coarse power particles without dilating the skeleton of the coarse powder. This can be achieved for large enough size ratios and for an optimal volume fraction of coarse particles.

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The packing density improves with coarse powder additions in the terminal region rich in fine powders, because the coarse particles substitutes dense region for porous clusters of fine particles. Alternatively, in the terminal region rich in coarse particles, the density improves with fine particles additions because fine particles fill the interstices between the coarse particles. This is an interesting topic in metal injection molding where the desire is to minimize the binder content and the sintering shrinkage using bimodal mixtures.

Most investigation pertaining the bimodal powder mixture are referring to the packing mechanism of Furnas model where fine particles are introduce and distributed to interstices of coarse pack particles to reduce porosity. The calculation of the ideal packing density is based on the assumption that the size ratio of coarse powder to the fine powder is infinitely large [6]. Zheng et al. [6] also observed from previous work that the compact density reaches the maximum when the volume fraction of fine powders is between 0.3 and 0.4. This has been clearly explained by German [2] that the green density of alumina is maximum at 70 % of coarse powder in the bimodal mixture. Likewise, in most high temperature sintering situations the maximum sintered density occurs at 100 % fine powder composition. Only in cases of relatively low sintering temperatures or short sintering times is the sintered density highest at compositions near 70 % coarse powder. More typically, the sintered density declines with the addition of coarse powder to fine powder matrix [3].

In the analysis to the bimodal iron powders German and Bulger [3] shows how the packed and sintered densities can be predicted with reasonable accuracy. The densities are treated using the normalized specific volume, which is the inverse of the fractional packing density. The packing density versus mixture composition is accurately predicted using four parameters: particle size ratio, packing density of fine powder, packing density of the coarse powder and mixture homogeneity. The study also indicates that bimodal powders will improve the powder loading, but degrade the sintered density when used in metal injection molding. The study has ignored chemical reaction between the powders that might occur if coarse and fine powders were of differing compositions.

In another investigation, literature [7-8] studied the molding behavior and the as-molded strength of 316L stainless steel powder at 65.5 % volume mixed with same binder system used by the authors. The fine powder fraction was varied from 10 to 50 % weight. The investigation discovered that the as-molded strength was increases when the fine powder fraction was increased from 10 -30 % weight. However, the as-molded strength is decrease when fine powder was added. The green density was also at the peak when 30 % weight of fine powder was added to the coarse powder.

This paper presents authors' investigation on the as-molded density and as-molded strength of a monomodal and bimodal mixtures. The powder loading was remains at 64 % volume and the bimodal fine powder fraction was varied at 30 % and 70 % weight. The temperature influence to the as-molded density and strength is presented in the later section.

# EXPERIMENTS

## Materials

The metal powder used in this study is the ANVAL 316L stainless steel gas atomized powder with the pynometer density of 7.93 g/cm$^3$. The chemical composition and the powder morphology are shown in Table 1 and Figure 1, respectively. Figure 1 (a) shows the morphology of monomodal powder and Figure 1 (b) is the morphology of the bimodal powder. A binder system based on polyethylene glycol (PEG) was prepared. The minor component is polymethyl methacrylate (PMMA) and stearic acid (SA) was added as the surface-active agent. The binder composition is 73 % PEG + 25 % PMMA + 2 % SA based on the weight fraction and the powder loading is remain at 64 % volume.

*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 |

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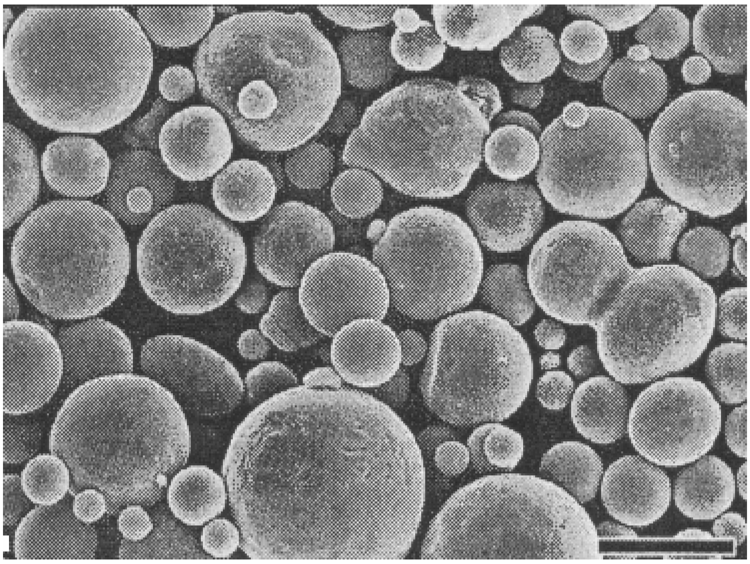
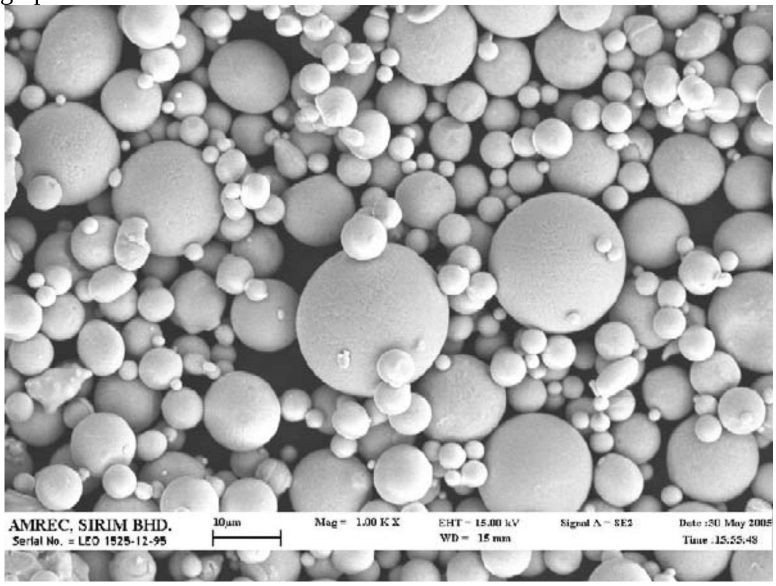
## Experiment procedure

Prior investigation, stainless steel powder were mixed with binders in the sigma blade mixer for 95 minutes at 70 °C. Four compositions of feedstocks consisting of different particles distribution were prepared for the investigation as shown in Table 2. The monomodal compositions are name as 31_64 and 16_64 for the 19.606 µm and 11.225 µm powder respectively while the bimodal are A1_64 and B1_64. A1_64 mixture contains 70 % of the fine powder and B1_64 contain 30 % of the fine powder. After mixing, the paste was removed from the mixer and will be fed into the strong crusher for granulation.



(a). SEM photograph of monomodal mixture



(b). SEM photograph of bimodal mixture

*Figure 1: SEM photograph of ANVAL 316L gas atomized stainless steel*

*Table 2: Feedstock classification and the powder loading remains at 64 % V*

| Feedstock Abbreviation | Description |
|---|---|
| 31_64 | Monomodal: 19.606 µm |
| 16_64 | Monomodal: 11.225 µm |
| A1_64 | Bimodal: 11.225:19.606 µm at 70%:30% |
| B1_64 | Bimodal: 11.225:19.606 µm at 30%:70% |

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The MIMA tensile specimen as shown in Figure 2 was injection molded with the Battenfeld BA 250 CDC injection-molding machine. In order to evaluate the temperature influence, injection pressure was remains at 350 bars and the injection temperature was varied from 120, 130 and 140 $^{o}$C. Table 3 listed the injection parameter used for the injection molding.

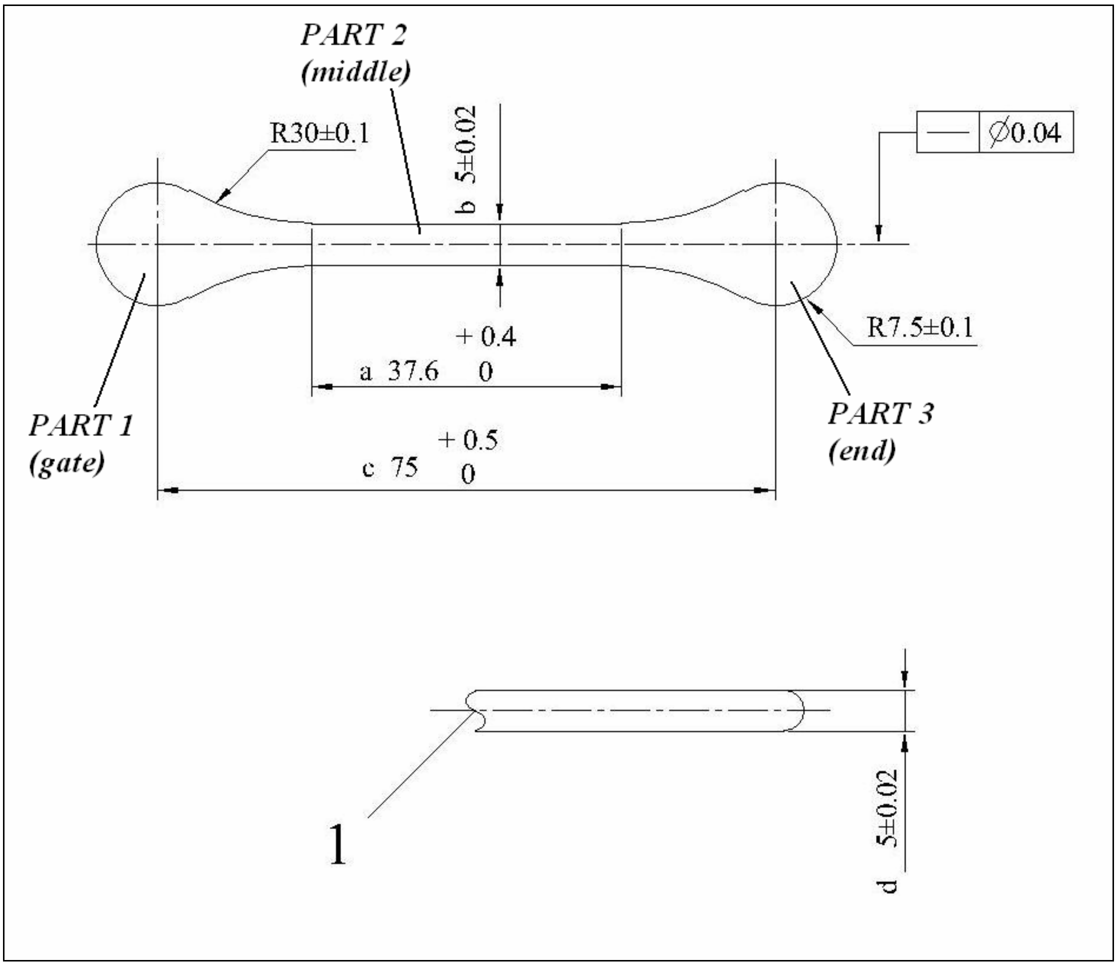


*Figure 2: MIMA tensile bar.*

*Table 3: Injection parameter.*

| | |
|---|---|
| Nozzle temperature | 120 $^{o}$C – 140 $^{o}$C |
| Barrel temperature | 120 $^{o}$C – 140 $^{o}$C |
| Mold Temperature | 45 $^{o}$C |
| Barrel pressure | 345 bar |
| Injection pressure | 350 bar |
| Injection speed | 20 cm$^{3}$/s |
| Cooling time | 10 s |
| Holding pressure | 400 bar |
| Holding time | 5 s |

The densities were determined by Archimedes water immersion method according to the MPIF Standard 42. The three-point bend test was performed using INSTRON 5567 to measure the green strength according to the MPIF Standard 15.

# RESULTS AND DISCUSSION

## As-molded density

Figure 3 shows the mean density at various temperatures. The result demonstrates that, in general the mean green density shows its proportionality. At 120 °C, 16_64 density was the highest (4.98 g/cm$^3$) compared to 31_64 (4.88 g/cm$^3$) and the bimodal feedstocks, A1_64 (4.79 g/cm$^3$) and B1_64 (4.53 g/cm$^3$). However, when the temperature goes up to 130 °C, 31_64 demonstrate higher density than the others does but A1_64 shows higher density at 140 °C (5.074 g/cm$^3$). Figure 3 shows that the density of B1_64 was always the lowest at all injection temperatures.

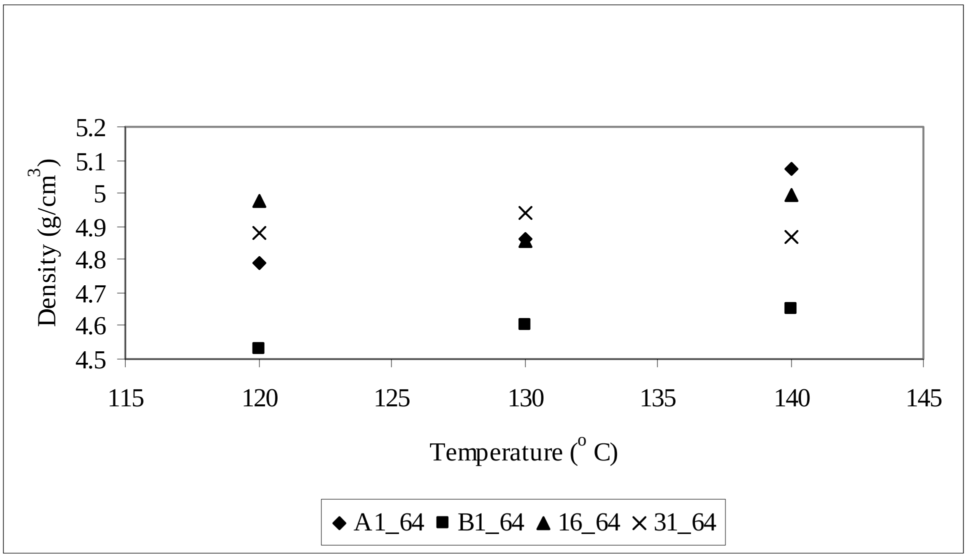
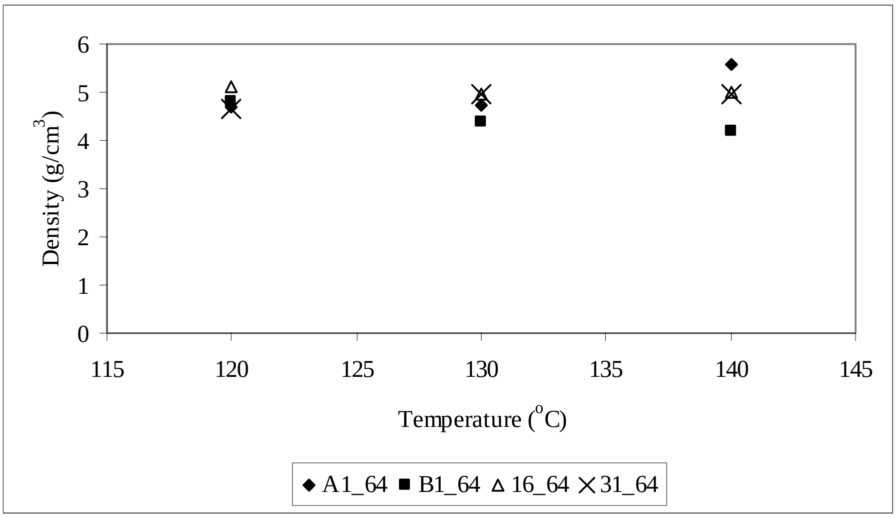


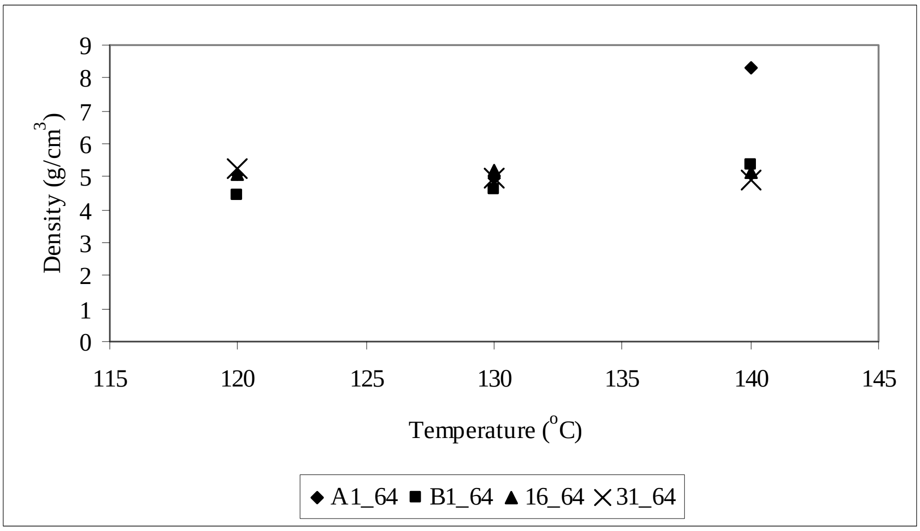
*Figure 3: As-molded mean density as function of temperature*

Figure 4 shows the specimen's density distribution at three specific locations namely as Part 1, Part 2 and Part 3 as specified in Figure 2. The molten MIM feedstock will enter the cavity through Part 1 (gate) and it flow through the small area (Part 2) and finally ended at Part 3. Result shown in Figure 4 (a) demonstrated that A1_64 has better mean density compared to the B1_64 while the monomodal powder shows nearly the same density. Part 2 (middle) that shown in Figure 4 (b) is the most important part because this part will determine the mechanical properties. At 120 °C and 130 °C, density of B1_64 is the lowest but it was increased at 140 °C. However, a density of A1_64 is still the highest. Figure 4 (c) shows that the end of specimen B1_64 (Part 3) has the highest density when it was injection molded at 140 °C although the density was nearly the same at 120 °C and 130 °C.

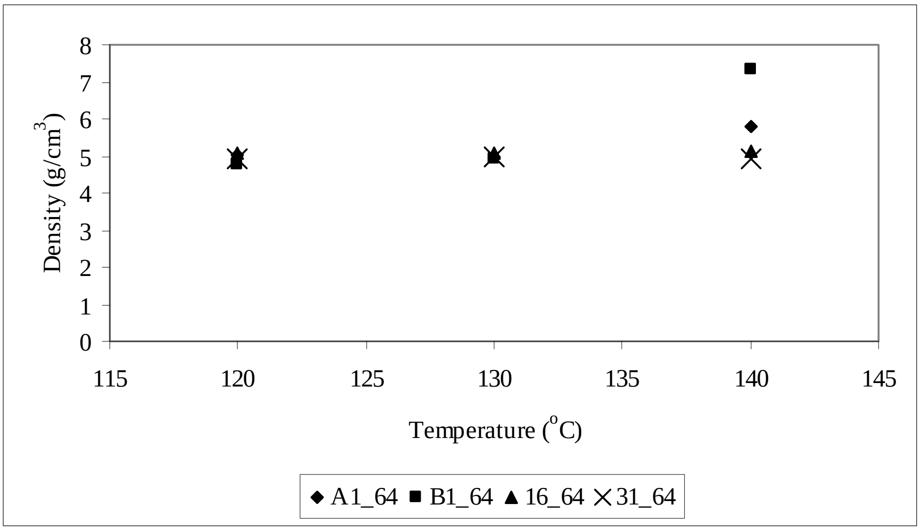
Investigation done by Muhammad Hussain Ismail [9] on the same specimen that was injection molded with carbonyl iron powder mixed with a commercial binder known as Hostamont EK583 discovered that the middle part of the specimen is denser. Result shown in Figure 4 indicate that there are no significant density change at temperature 120 °C and 130 °C except at 140 °C.



*a) Part 1 (gate)*



*b) Part 2 (middle)*



*c) Part 3 (end)*

*Figure 4: Mean density distribution as function of temperature*

Figure 5 shows the maximum and minimum density distribution along the specimens when it was injection molded at 140 $^{o}$C. Result shows that the peak density of A1_64 and 16_64 was in Part 2 which shows an agreement with Muhammad Hussain Ismail’s work [9]. However, B1_64 has better density than 16_64 and

31_64 at Part 2 but A1_64 is denser than B1_64. The result also indicated that the B1_64 density was increasing gradually when the melt flows to the downstream of the mold cavity. This is possibly due to the gravity effect that pulls the metal powder to the downstream before the feedstock was completely freeze in the mold cavity.

The middle part of the specimen (Part 2) should be denser than other parts because that area has small cross section. The melt velocity will increase dramatically thus reducing the hydrodynamic pressure causing more metal powder to stay at that portion. This is a significant reason why the middle part of the specimen has higher density.

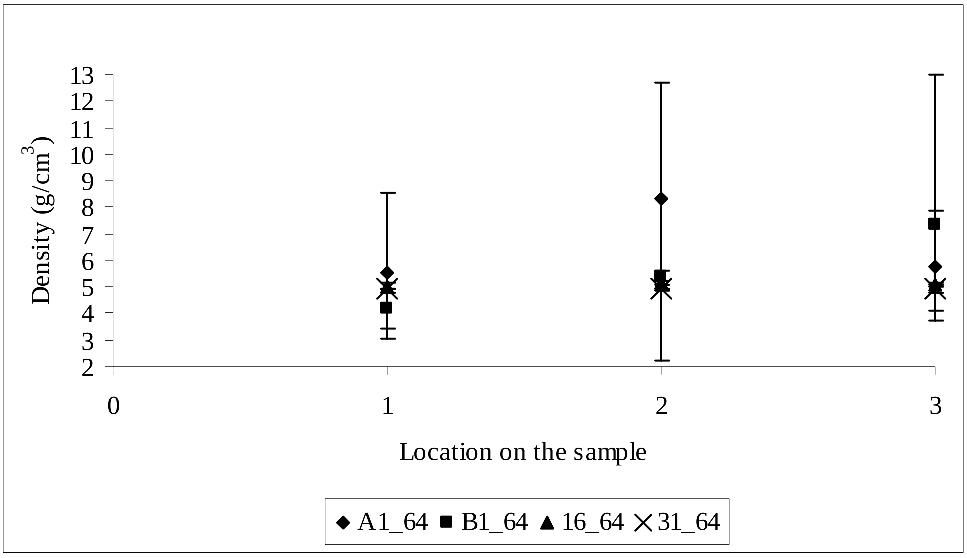


*Figure 5: Density distribution along the specimen when injection molded at 140 °C*

The density of specimen B1_64 when injection molded at 120 °C, 130 °C and 140 °C is shown in Figure 6. The result shows the as-molded density increase progressively when the injection temperature increases but the effect is not significant, as the increment was very little.

### As-molded strength

Figure 7 shows the as-molded strength as function of injection temperatures. The as-molded strength of 16_64 is the lowest when injection molded at 120 °C and 130 °C, and 31_64's is the highest at 120 °C and 130 °C respectively. This is possibly due to the feedstocks were less homogeny when injection molded at 120 °C and 130 °C. Mohd Afian Omar [7] found that in his investigation that the coarse powder should have less as-molded strength compared to the fine powder. However, as shown in Figure 7, the 16_64 is stronger than 31_64 at 140 °C.

The as-molded strength of a bimodal powder feedstock A1_64 was decrease from 3.86 MPa to 3.61 MPa when the injection temperature was increase to 140 °C. Moreover, 16_64 also shows small reduction of the as-molded strength when it was injection molded at 120 °C to 130 °C (2.12 MPa - 2.09 MPa) but was drastically increased to 3.62 MPa at 140 °C.

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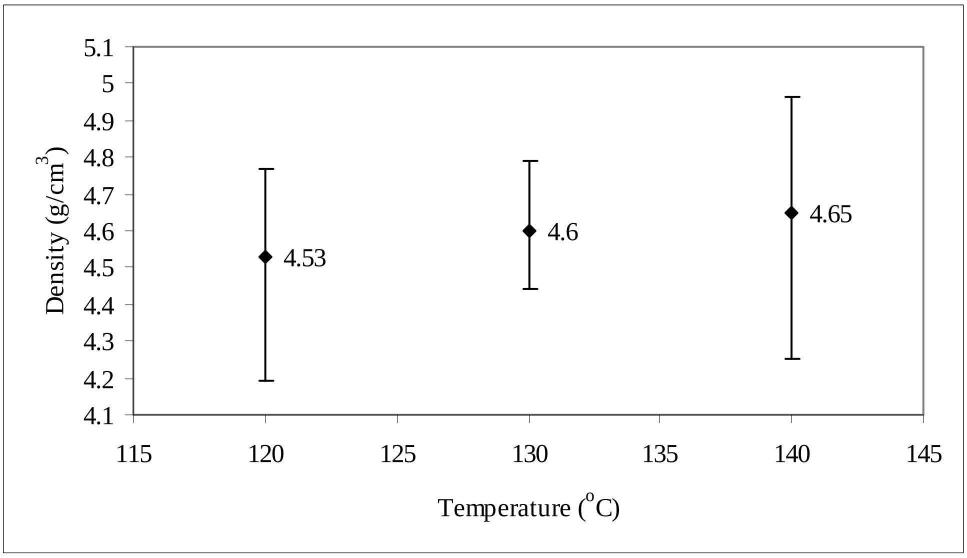

*Figure 6: B1_64 density as function of temperature*

Further, Mohd Afian Omar [7] found that the bimodal powder feedstock with fine powder distributions which less or more than 30 % was weaker than that formed with 30 % fine powder. However, due to low injection temperature A1_64 was found stronger than B1_64 at 120 °C. Further, when the injection temperature was increased to 140 °C, the result shows an agreement with Mohd Afian Omar's work [7].

The as-molded strength of 31_64 was shown initially increased when injection molded at 120 °C and 130 °C but it decreased drastically at 140 °C. On the other hand, the as-molded strength of B1_64 was increase gradually when injection molded from 120 °C to 140 °C.

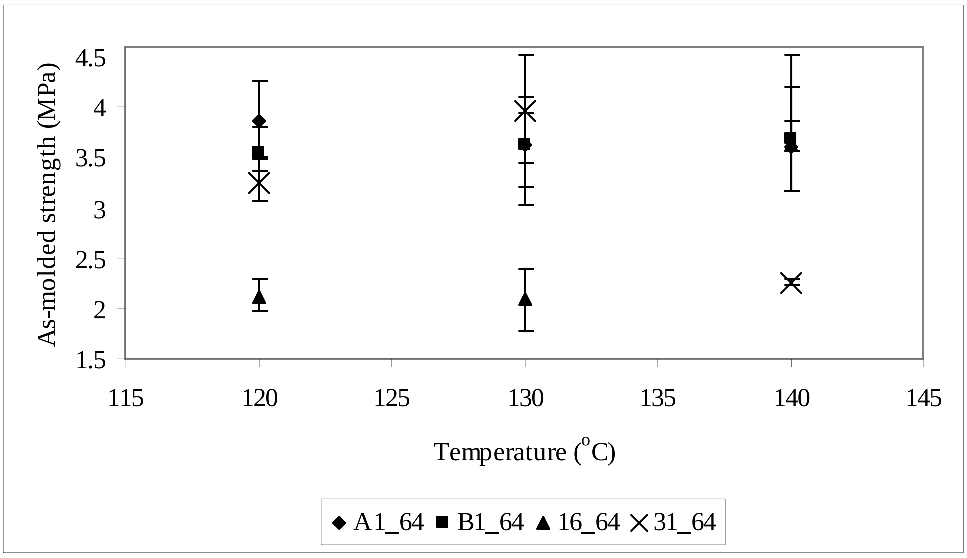

*Figure7: The as molded strength as function of temperatures*

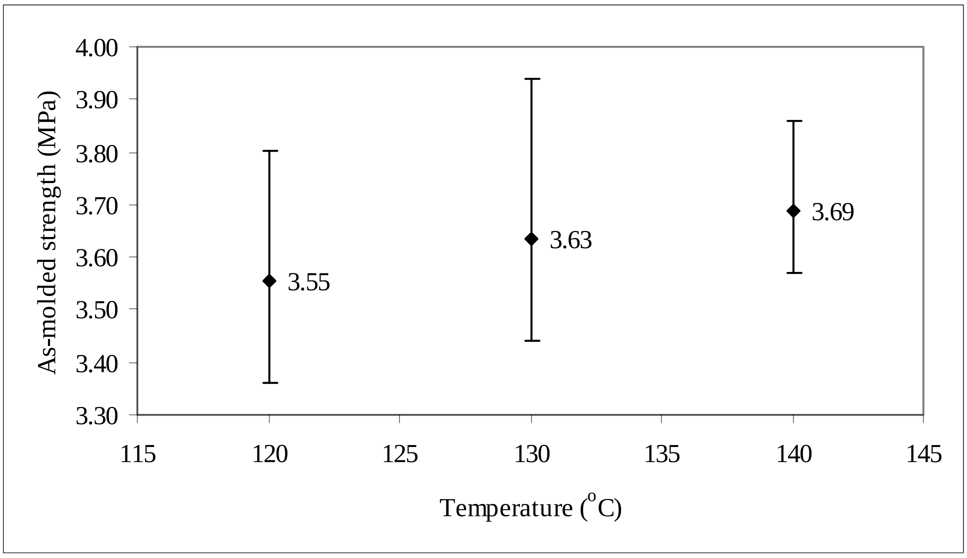

*Figure 8: B1_64 as molded strength*

Figure 8 shows the B1_64 as-molded strength improvement when the injection temperature was increased. B1_64 feedstock has shown that the as-molded density (Figure 6) and the as molded strength (Figure 8) was proportional to the injection temperature.

## CONCLUSIONS

An investigation to study the influence of injection temperature to the as-molded density and as-molded strength has been presented. The results showed that bimodal powder mixture can improve the as-molded density and strength when injection molded at 140 $^{o}$C and 350 bar. The results obtained at 120 $^{o}$C and 130 $^{o}$C are less significant due to the binder separation.

Results also show that the as-molded density and the as-molded strength were proportional to the injection temperature. The B1_64 feedstock, which follow Furnas model (30 % weight of fine powder distribution), has the best as-molded density and strength when injection molded at 140 $^{o}$C and 350 bars.

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