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ORIGINAL ARTICLE

Effects of Direct Thermal Method Processing Parameters on Mechanical Properties of Semisolid A6061 Feedstock

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ABSTRACT – This paper highlights the effects of pouring temperature and holding time on the mechanical properties of aluminium 6061 semisolid feedstock billets. The semisolid metal feedstock billets were prepared by a direct thermal method (DTM), in which the molten metal was poured into a cylindrical copper mould with a different combination of pouring temperature and holding time before it was solidified in room temperature water. The results show that the sample with pouring temperature slightly above aluminium 6061 liquidus temperature has the lowest porosity, thereby the highest mechanical properties value. The sample with a pouring temperature of 660 °C and holding time of 60 s has the density, tensile strength and hardness properties of 2.701 g/cm3, 146.797 MPa, and 86.5 HV, respectively. Meanwhile, the sample at a pouring temperature of 640 °C and holding time of 20 s has density, tensile strength and hardness properties of 2.527 g/cm3, 65.39 MPa, and 71.79 HV, respectively. The density and fractography tests were conducted to confirm the existence of porosity within the samples. The results from these experimental works suggested that the mechanical properties of DTM semisolid feedstock billet merely depended on processing parameters, which influenced the porosity level within the feedstock billet, thus directly affected their mechanical properties.

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INTRODUCTION

Near-net shaped products with excellent mechanical properties can be achieved by Semi-solid Metal Processing (SSMP) technique [1- 2]. The ability of the SSMP to produce near-net-shaped products with good mechanical properties make it widely used in metal casting industries. The SSMP enhanced the formation of a globular microstructure rather than the dendritic microstructure, which typically produced by the traditional metal casting process [3]. This globular microstructure helps to increase the formability of the products, thus reduces production time. There are two routes in SSMP, which are rheoforming and thixoforming routes [4]. In rheoforming route, the molten alloy was cooled into semisolid state condition before it was brought into a forming die without intermediate solidification step [3]. The molten alloy was cooled to acquire an ideal fraction solid before the forming process. Meanwhile, thixoforming process consists of two steps and involves an intermediate solidification stage [5- 6]. The prepared semisolid feedstock billets were cut into specific lengths, reheated into semisolid temperature range, and then were brought to thixoforming process. Reheating the feedstock billets into the semisolid state is a critical process in the thixoforming operation to achieve the desired fraction solid before cast into parts.

In SSMP, there were several methods used to produce globular microstructure feedstock for thixoforming operation. Direct Thermal Method (DTM) is among the techniques used to fabricate SSMP feedstock billets with globular microstructure in the primary phase of a metallic alloy [7- 8]. DTM is a simple method that uses less equipment and low processing cost to produce a globular microstructure. In the DTM process, the molten alloy was poured into a thin cylindrical copper mould [9- 10]. The high thermal conductivity of copper mould enhanced rapid cooling between mould and molten alloy provides multiple nucleations. The formation of the globular microstructure was achieved through optimum control of the processing parameters, such as pouring temperature and holding time [2]. The investigation on the effects of pouring temperature and holding time of aluminium 7075 DTM feedstock billets microstructure revealed that the high cooling rates were achieved with the lower pouring temperature that produced globular microstructures [9].

The processing parameters, such as pouring temperature and holding time, play a major role in SSMP to produce globular microstructure. The pouring temperature above the liquidus temperature, at 652 °C, provides a high cooling rate effect and improved the nucleation rate during the solidification stage [7, 11]. The low pouring temperature enhanced the formation of spheroidal formation. Therefore, the microstructure was more globular and in a uniform shape [12]. The key feature of holding time, on the other hand, is to provide adequate holding fraction solid before the solidification process. The fraction solid influenced the formation of globular microstructure during the solidification process as well. The development of globular microstructure was superior at a significant fraction solid [9]. The longer holding time leads to

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the bigger size of microstructure and higher mechanical properties [9]. The formation of nuclei become larger due to the rise in fraction solid during the solidification process.

The decent properties of wrought aluminium alloy 6061, such as good formability, weldability and machinability, make that alloy 6061 used in manufacturing industries. The aluminium alloy 6061 has been used widely in a broad range of structural and welded assemblies. The heat-treatable properties of aluminium alloy 6061 make the heat-treatment process increased aluminium alloy strength. Aluminium alloy 6061 is a lightweight alloy with a density of 2.70 g/cm^3 [8]. The ultimate tensile strength of wrought aluminium alloy 6061 during the SSMP technique was found at 330 MPa, while the yield strength was at 290 MPa and elongation of 8.2 % [13]. The hardness value of wrought aluminium alloy 6061 was found at 95 HB. However, several factors affected the mechanical properties of the feedstock billets, such as porosity, primary phase area and secondary phase area. The small and globular grain structure was found to enhance the mechanical properties of the alloy [14].

During the DTM, the main processing parameters that affected globular microstructure formation were the pouring temperature and holding time. This globular microstructure, later on, influenced the formability and mechanical properties of the SSMP feedstock billet. The literature on SSMP has highlighted several findings on globular microstructure formability behaviour [7- 8]. However, there are limited information and lack of intensive research regarding DTM feedstock billets mechanical properties, especially on aluminium 6061. The main objective of this experimental works is to evaluate the impact of pouring temperature and holding time on the mechanical properties of aluminium alloy 6061 feedstock billets produced by the DTM process.

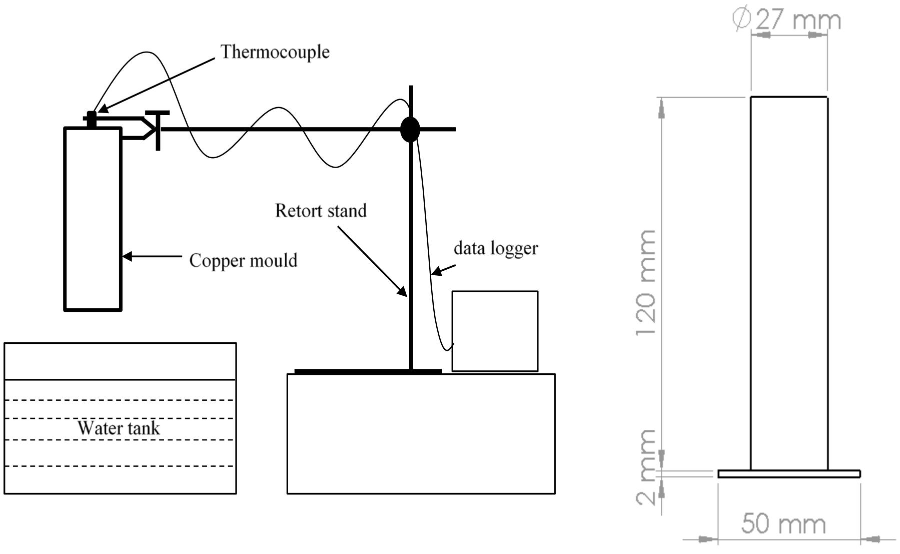
MATERIALS AND PROCEDURE

The chemical compositions of wrought aluminium alloy 6061 determined by Foundry Master Spectrometer are shown in Table 1. The wrought aluminium alloy 6061 sample was ground using grit paper of 320, 600, 800 and 1200 to make sure the flatness of the surface. The spectrometer produced sparks on the surface area, and the results were analysed.

Table 1. Chemical compositions of wrought aluminium alloy 6061.

Composition	Al	Mg	Si	Cu	Fe	Cr	Zn	Mn
wt. (%)	97.7	0.92	0.72	0.27	0.19	0.07	0.01	0.01

A copper mould was fabricated with a diameter of 27 mm and a height of 120 mm. The copper mould base was jointed with a 50 × 50 mm copper plate by brazing. The wrought aluminium alloy 6061 was placed in the graphite crucible and was heated in the resistance box furnace at 900 °C. After the alloy was utterly melted, the graphite crucible was taken out, and the temperature was measured. The molten alloy was then poured into the copper mould as soon as the desired pouring temperature was achieved. The pouring temperatures were 640 °C, 660 °C and 680 °C with the holding time of 20 s, 40 s and 60 s, respectively. The molten alloy was kept inside the copper mould for the desired holding time before it was then quenched into the room temperature water tank. The purpose of the quenched procedure was to freeze the microstructure formation inside the copper mould. Overall, 27 feedstock billets were produced by the DTM process. Each feedstock billet with a different combination of processing parameter was replicated three times to make sure the repeatability of the results. Figure 1 presented the schematic diagram of DTM used in this experimental works.



(a) (b)

Figure 1. Schematic diagram of the DTM process with (a) apparatus set up and (b) copper mould dimension.

The density test of the feedstock billet was performed to measure the porosity level within SSM feedstock billets. The density test started with the mass of each of the feedstock billets using mass balance was measured. Then, the feedstock billets were immersed in a jug filled with water, and the water that spilt out from the jug was taken and measured. The mass of the beaker used must be considered in order to obtain accurate density values. The average density of the DTM feedstock billets was determined using Eq. (1):

$$\rho fb = \frac{Wfb\ \ x\,\rho H_2 0}{W\ H_2 0} \tag{1}$$

where ρfb indicates the density measured in g/cm^3, W_{fb} is the feedstock billets mass measured in g, ρH_2O is the water density with the value of 1 g/cm^3, and WH_2O is the mass of the DTM feedstock billets are entirely immersed in the beaker measured in ml.

The Vickers hardness machine was used to conduct the hardness test. The specimens were ground using abrasive paper with grit specifications of P120, P340, P600 and P1200 to ensure that the surface was cleaned and flatted. The load was set to 100 gf with a 20 s indentation time. The tensile test was carried out with the universal testing machine equipped with INSTRON Software with the circular DTM feedstock billets specimen. The SSM feedstock billet diameter was reduced from 27 mm to 11 mm before shaped with NEF 400 Gildemeister CNC lathe machine. The tensile sample diameter has not exceeded 11 mm in order to clamp the sample between the lower and upper grips properly. The test speed was set at 1 mm/min, with the preload set at 6 MPa.

The scanning electron microscope (SEM) Fei Quanta 450 was used to analyse the specimen fracture surface. The fractography sample was cut into 3 mm in height to fit in the vacuum chamber. The high vacuum mode was used due to its suitability for conductive and metallic materials. The oxidation on the fracture surface has been avoided with the fractography sample was placed in the SEM vacuum chamber directly after the tensile test process. The specimen was placed into the SEM chamber and analysed with the driving voltage at 15 Kv with a 10 mm long working distance. Sample 5 (with a pouring temperature of 660 °C and holding time of 40 s) and sample 6 (with a pouring temperature of 660 °C and holding time of 60 s) were chosen for the fracture surface analysis. The samples were chosen to differentiate the fracture surface of the lowest tensile strength and highest tensile strength. Sample 5 has the lowest tensile strength, while sample 6 has the highest tensile strength than other DTM feedstock billets.

RESULTS AND DISCUSSION

In order to assess the porosity level within the solidified feedstock billets, a density test was used. The results for the average density value for each DTM feedstock billet are presented in Table 2. It was apparent from these results, the sample with a pouring temperature of 640 °C (sample 1, 2 and 3) and 680 °C (sample 7, 8 and 9), was found to obtain a lower density value than 660 °C (sample 4, 5 and 6). Furthermore, sample 6 with a pouring temperature of 660 °C and holding time of 60 s has the highest density value at 2.701 g/cm^3. In the meantime, the sample with a pouring temperature of 640 °C and a holding time of 60 s has the lowest density value at 2.527 g/cm^3. These results suggest that sample with high density contained low porosity value, such as sample 2, 4, 5 and 9 (refer to Table 2). The combination of pouring temperature slightly above the liquidus temperature (at 660 °C) and a longer holding time (of 20 s) was found to produce the lowest porosity within the feedstock billet.

Table 2. Average density and porosity level of SSM feedstock billets.

Sample	Pouring temperature (°C) / holding time (s)	Density (g/cm^3)	Porosity level
1	640 / 20	2.573 ± 0.06	High
2	640 / 40	2.638 ± 0.03	Low
3	640 / 60	2.527 ± 0.07	Highest
4	660 / 20	2.667 ± 0.17	Low
5	660 / 40	2.687 ± 0.12	Low
6	660 / 60	2.701 ± 0.14	Lowest
7	680 / 20	2.566 ± 0.13	High
8	680 / 40	2.570 ± 0.24	High
9	680 / 60	2.601 ± 0.08	Low

The density test set out with the aim to evaluate the porosity level within the feedstock billets. The difference in density values that occurred between samples was due to the porosity within the DTM feedstock billets. The porosity inside the feedstock billets occurred when molten metal shrinks and the gas trapped within the feedstock billets during the solidification [9, 11]. The combination of pouring temperature, which closes to liquidus temperature, and longer holding time allowed the gas within the copper mould to vanish to the environment. This helps to reduce the shrinkage and porosity content within the feedstock billet. The porosity within the DTM feedstock billets also was due to the air bubbles formation and the shortage of liquid in the dendritic arms [15]. The air bubbles become enriched in the liquid next to the solid-liquid interface during the growth of dendrites. The development of air bubbles, which had relocated from the inter-dendritic zone, would not have enough time to leave the mould and thus developed large porosity within the sample [15].

The density of aluminium alloy 6061 in the literature is 2.70 g/cm^3 [8]. The average density value that exceeds 2.70 g/cm^3 in this density test indicated that the DTM feedstock billets have a low porosity level. In comparison, the sample with an average density lower than 2.70 g/cm^3 indicates a high porosity level within SSM feedstock billets. These findings suggest that, in order to produce less porosity within aluminium alloy 6061 feedstock billet for SSMP, the pouring temperature should be kept close to the liquidus temperature of the alloy with a longer holding time.

The mechanical properties of the DTM feedstock billets were retrieved by hardness test. The average hardness values for the DTM feedstock billet are presented in Figure 2. From the hardness results obtained, it was apparent that significant changes between samples occurred, especially with sample 6. Apparently, the hardness test results show that sample 6 obtained the highest hardness value at 86.5 HV. Meanwhile, sample 3 has the lowest hardness value at 68.85 HV compared to other samples. Taken together, these results indicated that there was a relationship between the hardness test and the density test results.

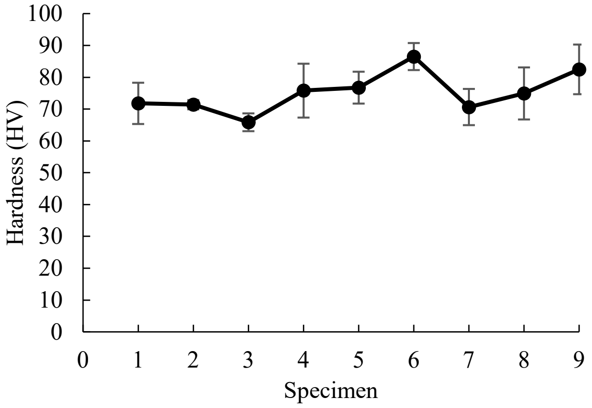
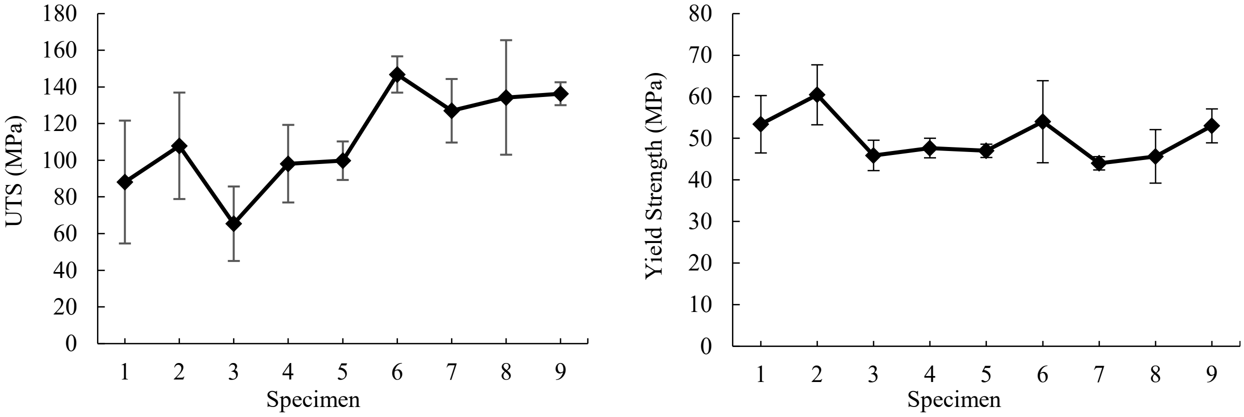


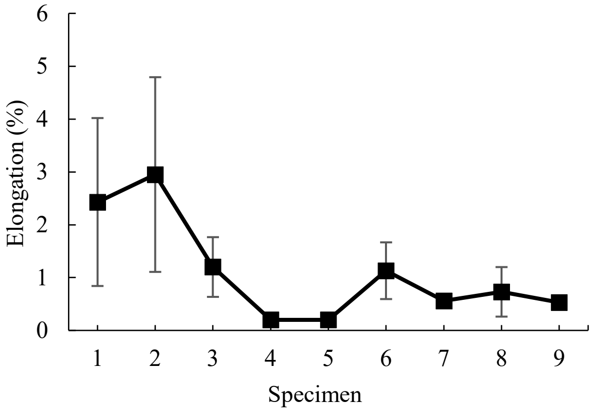
Figure 2. Average Vickers hardness value for DTM feedstock billets.

A strong relationship between porosity and mechanical properties has been reported in the literature [8, 15]. This hardness test result confirms that the porosity was associated with the mechanical properties of the feedstock billet. Sample with the highest Vickers hardness value is correlated with the sample of the highest density value, obtained from the sample with a pouring temperature of 660 °C and holding time of 60 s. These findings may help in determining the optimum combination parameters for DTM, which produced better quality feedstock billet with less porosity content. The relationship between porosity and mechanical properties in DTM can be explained by selecting suitable pouring temperature and holding time produced high density (low porosity) feedstock billets that led to better mechanical properties.

Average result of the tensile strength (TS), yield strength and elongation for each sample is presented in Figure 3(a), Figure 3(b) and Figure 3(c), respectively. From the result obtained, it was apparent that sample 6 with a pouring temperature of 660 °C and a holding time of 60 s has the highest ultimate tensile strength value, which at 146.797 MPa. Meanwhile, the yield strength and elongation for sample 6 were 54 MPa and 1.13%, respectively. Further analysis shows that sample 3 with a pouring temperature of 640 °C and a holding time of 60 s obtained the lowest ultimate tensile strength value at 65.39 MPa. Meanwhile, the yield strength and elongation of sample 3 were at 45.9 MPa and 1.2 %. Interestingly, these results were found similar to the hardness test results, with sample 6 was dominant compare to other samples. These results suggest an obvious relationship between the porosity and mechanical properties of DTM semisolid metal feedstock billets.



(a)
(b)

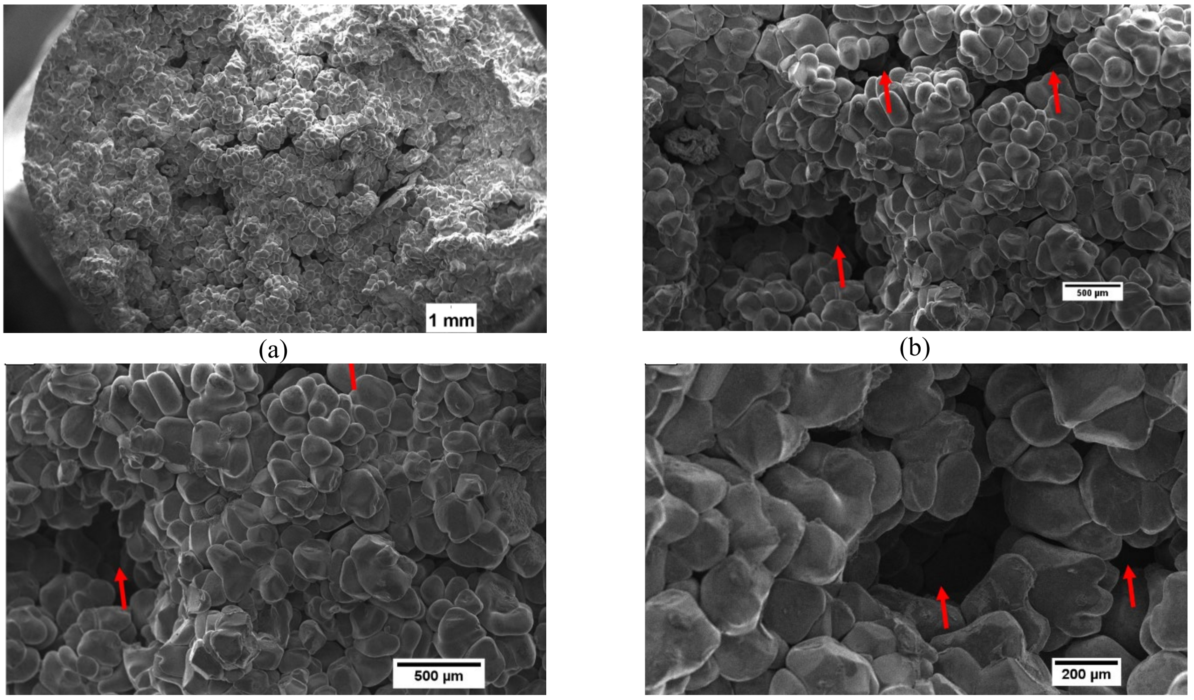


(c)

Figure 3. The average result of (a) ultimate tensile strength, (b) yield strength and (c) elongation for DTM samples.

Several reports in the literature have shown that the mechanical properties of wrought alloy components were typically higher than the SSM processing feedstock billets [15]. The difference in ultimate tensile strength values was due to the porosity content within the feedstock billets. Sample 6 has the highest ultimate tensile strength value compared to other samples, which can be related to its lower porosity content. Meanwhile, sample 3 has the lowest ultimate tensile strength value and can be attributed to high porosity content. This result correlates with the density measurement and hardness test, which indicated that the sample with low porosity led to better mechanical properties. The porosity inside the feedstock billets has been reported as a common problem in SSMP [16]. According to Atkinson et al. [16], the failure that occurred around the spheroidal microstructure, also known as porosity, was the main factor affecting the mechanical properties of SSMP. The formation of porosity inside the feedstock billets was caused by the pouring action which molten metal was fed into the small entrance of the mould caused air entrapment. On the other hand, Shulin et al. [17] found that the existence of pores in diecasting samples reduced the mechanical properties of aluminium alloy 5083. The formation of pores due to the decreasing of hydrogen solubility in the aluminium liquid alloy and formed holes within the samples. These findings suggested that the combination of pouring temperature just close to the liquidus temperature produced high density and enhanced mechanical properties of SSMP feedstock billets.

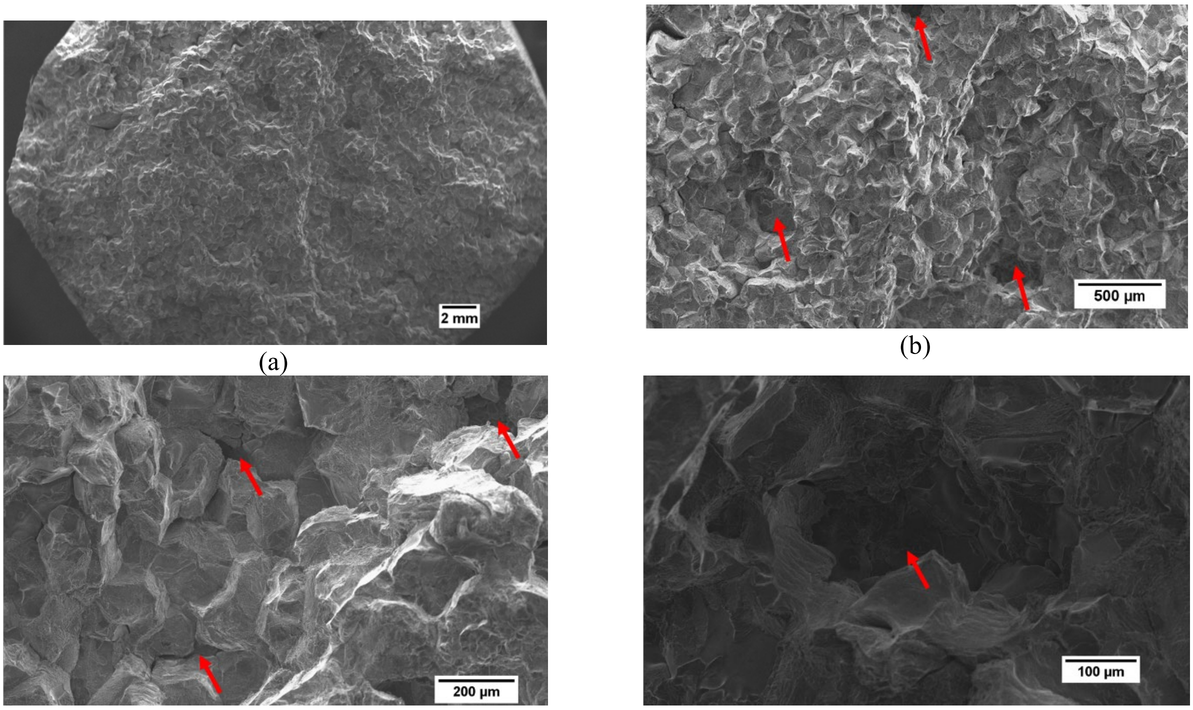
The fracture surfaces after the tensile test are presented in Figure 4 and Figure 5. Four images with varying magnification are presented to allow for better understanding. The red arrow in Figure 4 and Figure 5 indicated the existence of pores within the feedstock billets. The samples were chosen to distinguish the fracture surfaces between the lowest and highest tensile strength. Four images with different magnifications power are presented to analyse the sample failure as in Figure 4 and Figure 5. Overall, the samples showed a ductile fracture mode with intergranular failure.



(a) (b)

(c) (d)

Figure 4. Scanning Electron Microscopic (SEM) images for sample 5 (a) dimple fracture surface; (b) fracture image with 200× magnification power, (c) fracture image with 250× magnification power; and (d) fracture image with 500× magnification power.

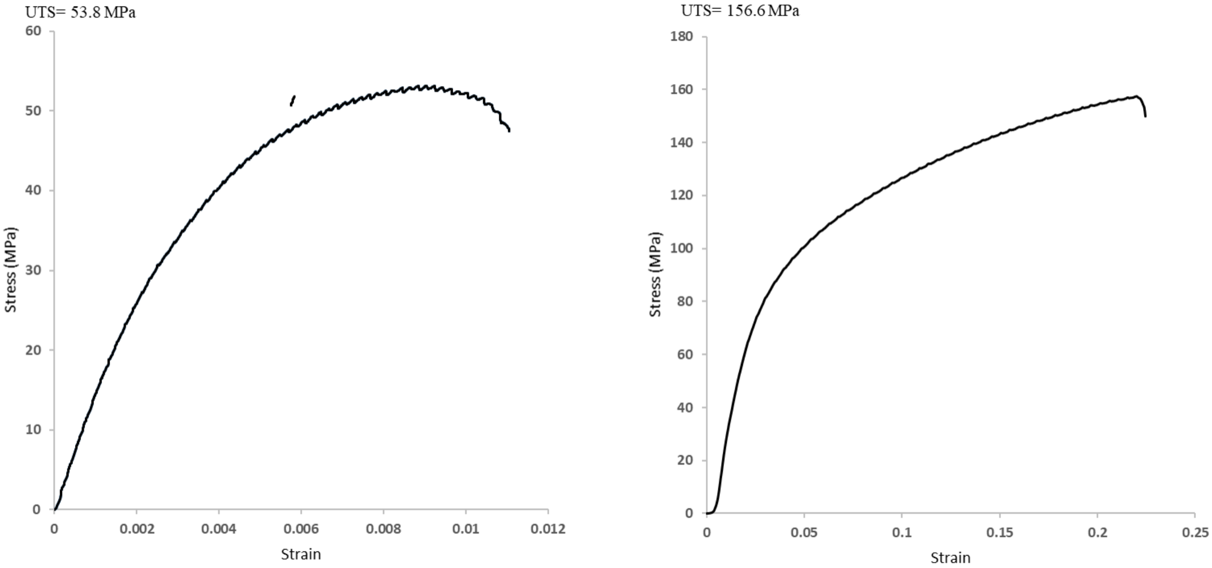


(a) (b)

(c) (d)

Figure 5. Scanning electron microscope (SEM) images for sample 6 (a) dimple fracture surface; (b) fracture image with 200× magnification power, (c) fracture image with 250× magnification power; and (d) fracture image with 1000× magnification power.

Figure 6 demonstrated the stress-strain graph for sample 5 and 6. The stress-strain graph shows that sample 5 and 6 experienced large plastic deformation before fracture. The large plastic deformation suggests that the fracture involved a high degree of energy absorption and has low propagation before fracture [18]. Typically, the ductile materials have the ability to support the load when ultimate tensile strength has been achieved. The formation of dimples on the ductile fracture surface corresponded to the microvoids that initiated the crack formation. The mechanical properties were found highly influenced by the porosity level within the SSM feedstock billets [15]. The dimples in the images (Figure 4 and Figure 5) indicated that the porosity was caused by the entrapment of gas and shrinkage porosity during the DTM process. These results broadly support the work of other studies in this area linking mechanical properties with porosity.



(a) (b)

Figure 6. Stress-strain graph for (a) sample 5 and (b) sample 6.

The pouring temperature of 660 °C is just beyond the aluminium 6061 liquidus temperature of 652 °C. This provides high cooling rates effect on the microstructure formation [2]. The high cooling rates from the extraction of the heat process between the mould and the molten alloy provided fine grain size with more globular microstructure [19]. The suitable pouring temperature used in the DTM process retarded the primary phase microstructure development, thus increased the secondary phase area. The high volume of secondary phase area within the microstructure gives better fluidity during the forming process but reduced DTM feedstock billets mechanical properties [7].

The holding time mainly to ensure the adequate fraction solid before the quenching process. In the previous study, the fraction solid was found to influence the formation of globular microstructure [2]. The increment of the fraction solid volume before the quenching process produced a larger grain size structure. The longer holding time allowed the grain to expand within the molten and created a larger grain size, thus increased the mechanical properties of the SSMP feedstock billet [15]. Therefore, the findings in these experimental works have explained and countered the correlation between fraction solid, grain size, porosity and mechanical properties.

CONCLUSION

The effect of different pouring temperatures and holding time on the mechanical properties of aluminium alloy 6061 has been investigated intensively. The pouring temperature slightly above liquidus temperature enhanced the properties of the DTM feedstock billets due to a low porosity level within the DTM feedstock billets. The density results show no unusualness results compared to aluminium standard density which is 2.7 g/cm^3. The average density value collected marginally lower than 2.70 g/cm^3 designated higher porosity level. The samples with a higher average density value showed a lower porosity level within the SSM feedstock billets. The mechanical properties results show that the ultimate tensile strength values were between 65.39 MPa and 146.797 MPa. Meanwhile, the Vickers hardness values ere between 65.85 HV and 86.5 HV. Based on the result obtained from the mechanical properties test, it was satisfied to conclude that the mechanical properties of DTM semisolid feedstock billet purely depended on the proper selection of pouring temperature and holding time, which influenced the porosity level within the feedstock billet.

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