Direct thermal method pouring temperature and holding time effect on aluminium alloy 6061 microstructure

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Abstract. The microstructure variances of aluminium 6061 billet produce via direct thermal method with different pouring temperature and holding time are presented in this paper. The direct thermal method is one of the methods to create globular microstructure feedstock billet, which gives the material a thixotropic behaviour during semisolid metal processing. In this experimental work, a molten aluminium 6061 was poured into cylindrical copper mould before quenched in water at room temperature. The effect of pouring temperature of 660°C and 700°C and holding time of 20s and 60s were observed from the microstructure formation. The result shows that the combination of a pouring temperature of 660°C with a 20s holding time produces a finer near globular microstructure. These fines near globular microstructures gives a thixotropic behaviour improvement in better fluidity for a better flow during shaping. The pouring temperature just slightly above the liquidus temperature provides slower cooling rates from above to below the liquidus temperature. This process causes less superheat to be extracted by the cylindrical copper mould and gives a slow cooling rate action during the solidification stage that promotes the formation of further nuclei, which results in smaller grain size. The result also shows the combination of the lowest pouring temperature of 660°C with the lowest holding time of 20s produced the smallest grain size measured in area. However, the circularity and aspect ratio that indicates globular shape grain has a slight change in result which indicates that every feedstock billet has a near globular grain size. In conclusion, this work has shown that specific combination of pouring temperature and holding time has an effect on the microstructure formation of the feedstock billet produced by using direct thermal method.

Keywords: Direct Thermal Method; Pouring Temperature; Holding Time; Microstructure; Aluminium Alloy 6061

1. Introduction

Semi Solid Metal Processing (SSMP) is a method to process metals and alloys, which takes place between solidus and liquidus temperatures [1-5]. The SSMP is subjected to the material microstructure behavior in the semi-solid state condition. These materials microstructure behaviors are characterized by a solid-like behavior at rest and a liquid-like flow when submitted to shear. The microstructures flow when subjected to shear but thickening again when it is allowed to stand requires the
microstructure to be made of globular or spheroids of solid surrounded by a liquid matrix [6]. SSMP has the advantage of low shrinkage porosity defect over conventional processes [2, 7, 8].

SSMP technologies group into two categories based on the initial material state which is rheo-routes and thixo-routes. Rheo-route consist of preparation of SSMP slurry with globular grain from a liquid state solidified into semi-solid state and injects directly into the die for component shaping without an intermediate solidification stage. Rheo-route process generates the shear needed to obtain a globular microstructure by using mechanical stirring to stir the liquid metal. The slurry obtained is directly either use in die filling for component shaping or made as a feedstock production material with a thixotropic microstructure where globular and fine primary phases were homogeneously dispersed in a matrix of lower melting point. Thixo-route consists of the molten metal has an intermediate solidification stage, which the material was treated in such a way that it has a non-dendritic microstructure which is made as raw feedstock material. When it is heated in the semi-solid state, it is then injected into a die for component forming [9-11].

Direct Thermal Method (DTM) was developed by Brabazon and coworkers in 1997 as an alternative method to produce thixotropic feedstock by University College Dublin in 2002 [12-16]. DTM involves using a thin-walled cylindrical mould whose thermal conductivity is high but low in thermal mass commonly is made of copper to hold a low superheat liquid alloy. Rapid cooling action occurs during the first interaction between the molten metal and the mould wall result in the formation of multiple nucleations. The cooling action then continues to reach thermal equilibrium at a very low rate. Isothermal arrests state has resulted from heat matches between the mould and the alloy. This results in a low heat convection transfer by way of small thermal gradient [16]. Basically, the spheroidization mechanism of this method starts with nucleation at several locations during the first contact and slower cooling rate to prevent the growth of dendrite arms [12]. Quenching is done in order to freeze the formation of globular microstructure [17]. Previous research has remarked that certain parameter has an effect on a more spherical structure and need to be controlled, which were the pouring temperature, holding time before quenching or forming, and size of cooling mold. Lower pouring temperature and shorter holding periods give a result in more spherical structures [13]. This gives results in increasing the material fluidity for better flow during shaping. Pouring temperature closer to the liquidus temperature provides higher cooling rates from above to below the liquidus which causes less superheat to be extracted by the cylindrical copper mould. Hence, it gives a slow cooling rate action during the solidification stage that promotes the formation of more nuclei, which in turn results in a smaller grain size [13].

Aluminium alloys is an ideal material to be used for automotive, aerospace and transportation components with casting alloy such as A356 due to their fluidity behaviour. However, while the cast series of aluminium alloys has the excellent fluidity properties advantage, it has relatively poor mechanical properties compared to wrought aluminium alloys. Wrought aluminium alloys provide significant advantages in terms of the higher ultimate tensile strength (UTS) and yield strength. Wrought aluminium alloy 6061 is among the wrought alloy series that known to have various benefits of medium strength, formability, weldability low cost and also corrosion resistance [18].

Fraction solid is an important aspect to be considered during the process of SSMP due to its impact on the material mechanical properties. Fraction solid is a comparison between the amounts of solid-phase when compared to the liquid phase within the semisolid microstructure of the alloy. Previous research stated that for a fixed cooling rate and shear rate, viscosity has increased parallelly with solid fraction. The process slowly occurs at low solid fraction and sharply at high solid fraction [4]. In SSMP, to obtain a low viscosity at a high fraction solid is important. Low viscosity will allow the material to flow easily within the mould and high fraction solid helps to prevent major defects, better globular microstructure, and high-quality feedstock.

Pouring temperature plays a significant role in the formation of the globular microstructure of the feedstock billet. The proper combination of the pouring and holding time will greatly affect the formation of a globular microstructure within the billets. Previous research shows that smaller primary
and secondary phases within the microstructure were formed for lower pouring temperature which approaching the semisolid temperature [19].

Holding time affects the formation of the globular microstructure of the feedstock billet. The purpose of holding time was to ensure a sufficient fraction solid before quenching. Previous work shows that longer holding time for a set pouring temperature resulted in larger primary phase grains formation[20]. Therefore, a proper combination of pouring temperature and holding time should be considered as it will greatly affect the billet spheroidization mechanism.

2. Experimental Method

Aluminium 6061 was used in this work and Table 1 presents Chemical compositions of aluminium 6061 determined by using Optical Emission Spectrometer.

| Composition | Al   | Si   | Fe   | Cu   | Mn | Mg  | Zn   | Cr   | Ni   | Ti  |
|-------------|------|------|------|------|----|-----|------|------|------|-----|
| Wt (%)      | 97.4 | 1.0  | 0.29 | 0.03 | 0.53 | 0.57 | 0.009 | 0.011 | 0.019 | 0.02 |

In this work, 1kg aluminium 6061 was placed inside a graphite crucible and was melted by using a resistance heated Carbolite 1600 box furnace at a temperature of 800°C. After the aluminium completely melt, the graphite crucible contained molten aluminium 6061 was taken out of the furnace and the temperature was measured using k-type thermocouple connected to a data logger. After achieved the desired temperature for pouring temperature, the molten aluminium was then poured into a copper mould of 1mm of wall thickness, 25mm diameter, and 100mm in height hold by retort stand and clamp. The pouring temperature was set to 660°C and 700°C. Once the copper mould was completely filled with the molten aluminium, holding time was counted by using a stopwatch. The copper mould was then dropped into the water tank for quenching after the holding time was achieved. The holding time before quench was set to 20s and 60s for every pouring temperature. The schematic diagram of DTM was present in Figure 1 as follows:

![Schematic diagram of experiment rig for DTM.](image)

The microscopic samples were then taken at the center of solidified feedstock billet. The sample was then mounted by using SimpliMet 1000 Automatic Mounting press mounting machine and grind by using Metkon Forcipol 2V grinding machine with rotation of 240-300rpm and grit specification P600, P800 and P1200 of abrasive paper respectively. The sample was polished and etched with Keller solution and microstructure image of the sample was taken. The microstructure image was analyzed with ImageJ software in order to obtain grain size area, circularity and aspect ratio. The
circularity and aspect ratio were calculated with equation (1) and equation (2) where P and A are representing a perimeter and an area of the particle respectively:

\[
C = \frac{4\pi A}{P^2}
\]  

\[
AR = \frac{\text{major axis}}{\text{minor axis}}
\]

3. Effect of Pouring Temperature and Holding Time on Microstructure

Direct Thermal Method (DTM) was used to produce thixotropic feedstock billet with pouring temperature was set to 660°C and 700°C. The holding time before quench was set to 20s, and 60s for each pouring temperature. Figure 2 shows the aluminum alloy 6061 feedstock billet. The microstructure formation indicates that different pouring temperature and holding time affect the microstructure.

**Figure 2.** Aluminium alloy 6061 feedstock billet.

Figure 3 (a) shows the combination of pouring temperature of 660°C with a 20s holding time produces a fine near globular microstructure. These fine near globular grain gives a better fluidity for better flow during shaping. The pouring temperature just slightly above the liquidus temperature provides slower cooling rates from above to below the liquidus temperature. This process causes less superheat to be extracted by the cylindrical copper mould. Hence, it gives a slow cooling rate action during the solidification stage that promotes the formation of more nuclei, which turn to results in smaller grain size.

Figure 3 (b) shows the combination of pouring temperature of 660°C with a 60s holding time still produce near globular microstructure. However, the grain size has increased because of the longer holding time has allowed the grain to join with the nearby nuclei when the secondary phase starts to solidify. The holding time before quenching was obviously crucial as a mechanism that will instantly freeze the small grain size formed and to ensure a sufficient fraction solid before quenching.

Figure 3 (c) shows the combination of a pouring temperature of 700°C with a 20s holding time still produces a little near globular microstructure. However, the grain size was not uniform and bigger in size with the presence of a dendritic mixture. Pouring temperature higher than the liquidus causes more superheat to be extracted by the cylindrical copper mould. Hence, it will not have a slow cooling action effect during solidification stage. The short holding time before quenching has instantly frozen the microstructure before the microstructure reaches a uniform grain size.
Figure 3 (d) shows the combination of pouring temperature of 700°C with a 60s holding time still produces a near globular microstructure. The result shows with holding time increase, the grain size starts to develop into uniform structure. However, because of the high pouring temperature, the grain size is bigger due to the fast cooling rate action during solidification stage.

![Figure 3](image)

Table 2 presents the average grain sizes measurement for aluminium alloys feedstock billet produced by using direct thermal method. The result shows obvious and significant changes which are the combination of the lowest pouring temperature of 660°C with the lowest holding time of 20s produced the smallest grain size measured in area. The circularity and aspect ratio that indicates globular shape grain has a slight change in result which expresses that every feedstock billet produces a near globular grain size.

| Area (μm²) | Circularity | Aspect Ratio |
|------------|-------------|--------------|
| 660°C 20s  | 27965.14    | 0.78         | 1.51        |
| 660°C 60s  | 34629.64    | 0.78         | 1.51        |
| 700°C 20s  | 38903.35    | 0.77         | 1.39        |
| 700°C 60s  | 43029.93    | 0.75         | 1.61        |
4. Conclusion
In conclusion, the result obtained from this work has shown that a specific combination of pouring temperature and holding time produced a globular microstructure of the feedstock billet. The pouring temperature and holding time has an effect on microstructure of aluminium 6061 feedstock billet. The specific combination of pouring temperature and holding time will produce a finer and globular microstructure of the feedstock billet. Lower pouring temperature at 660°C with holding time of 20s produced a finer globular and uniform microstructure compare to other processing parameter combinations. This characteristic gives results in increasing the material fluidity for better flow during shaping. The lower pouring temperature delivers a slower cooling rates effect from above to below the liquidus temperature, which in turn causes less superheat to be extracted by the copper mould. Hence, the slow cooling rate condition during the solidification stage promotes the formation of more nuclei, which turn to results in smaller and uniform grain size.

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