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COMPARISON BETWEEN THE NON-DENDRITIC METHODS OF AN A201 ALUMINUM ALLOY DEPENDING ON MECHANICAL PROPERTIES AND MICROSTRUCTURE

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Abstract

According to non-dendritic method, there are four main techniques working in Semi-Solid state. The four techniques for preparation non-dendritic samples were Semi-Solid Rheocasting (SSR), Cooling Slope (CS), Magneto-Hydrodynamic stirring (MHD) and Semi-Solid Rheocasting with Cooling Slope (SSR+CS). In this paper, the non-dendritic feedstocks prepared depending on the aluminum alloy A201. The feedstocks have been investigated using metallographic and Vickers hardness methods. The results of the work showed main difference between the non-dendritic samples and dendritic samples focusing in microstructure and hardness techniques. Comparing the non-dendritic techniques results, The Rheocasting (SSR) mothed was high result in the microstructure and mechanical properties.

Keywords*:* *Non-dendritic; semi-solid metal; semi-solid rheocasting; cooling slope; vickers hardness; microstructure properties; microstructural properties.*

Introduction

Aluminum alloy has been used in several applications in automotive, electronics, aerospace industries. Semi Solid Metal (SSM) forming processes of non-dendritic feedstocks are frequently employed for the near-net-shaping for metal and alloy especially for aerospace and automotive industry, resulting in the increased use of aluminum alloys [1-3]. Non-dendritic microstructure has many advantages, such as extensive die life due to the reduced thermal shock and its ability to reduce macro segregation, porosity and forming forces during the shaping process. Furthermore, SSM processing enhances good mechanical properties while minimizes the usage of feedstock materials to reduce the cost of manufacturing process [3].

Non-dendritic microstructures contain spheroids of solid phase in a liquid matrix which is typical in the SSM processing and possess a key role in feedstock production. Consequently, feedstocks have fine and homogenous globular solid particles distributed in a liquid matrix, and that could behave as thixotropic in semi-solid state. Thixoforming performance is a significant characteristic of the SSM alloy that can be described as a solid although flowing like a liquid when it is sheared [2].

There has been an increasing attention in producing non-dendritic microstructure feedstocks for SSM processing. Many methods have been developed to produce a non-dendritic microstructure such as Semi-Solid Rheocasting (SSR), Cooling Slope (CS), Magneto-Hydrodynamic stirring (MHD) and Semi-Solid Rheocasting with Cooling Slope (SSR+CS). Even though MHD is an ideal technique for producing the feedstock [4-10], it has led to extra cost in feedstock production to improve the non-uniformity of the microstructure in the billet, while the CS casting has very low-cost processing of feedstock [5-7].

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Aluminum alloys are widely used in aerospace industries, especially aluminum-copper (Al-Cu) alloys due to their good fluidity and mechanical strength. The adding of Cu raises the hardness, the strength, and helps completing supersaturation of the alloy, further it is reliant on the distance between particles after the Cu precipitate into spheroids and is consistently distributed [25]. The size, shape and particle distribution of Al-Cu microstructure has given a significant effect on the mechanical properties of the alloy. Preferably, the fine and homogenous globular microstructure of the primary α-Al phase is bounded by a eutectic mixture layer that acts as a bond between the components of the primary phase and enables the primary phase to resist an applied force [16]. While a lot of work has been carried out for the past 10 years using methods of non-dendritic, the number of alloys that have been selected for this processing are very limited [25]. Therefore, in this work, A201 aluminum alloy was chosen.

Experimental Methods

The chemical composition of A201 aluminum alloy used in this work is given in Table 1. The pouring temperature and superheat temperature of this experiment was selected based on differential scanning calorimetry (DSC) test. The DSC curve of A201 aluminum alloy showed a liquids temperature of 649°C and solidus temperature was 536°C. Based on the DSC curve, pouring temperature was set close to the liquidus temperature at 649°C to ensure rapid cooling to increase the grain growth [25].

Table 1. Chemical composition of Aluminium A201 alloy [3].

wt%	**Al**	**Cu**	**Ag**	**Mn**	**Mg**	**Si**	**Fe**	**Ti**
A201	Bal.	4.7	0.59	0.31	0.28	0.10	0.05	0.21

The potential for achieving specific mechanical and physical properties is determined by the composition of the alloy. The basic structure consists of cored dendrites of aluminum solid solution, with a variety of constituents at the grain boundaries or interdendritic spaces, forming a brittle more or less continuous network of eutectics [3]. In preparing alloys for semi-solid forming, the dendrites are broken up during spheroidizing and the constituents are distributed more uniformly

Copper is the major alloying element in A201. Cu-Mg-Al is formed when Cu:Mg > 2 and Mg:Si > 1.7. Copper increases the strength, ductility and overall supersaturation of the alloy but this depends on the nature of copper, explicitly as in the solid solution, spheroidised and evenly distributed particles or as a continuous network at the grain boundaries. Strength depends on the mean free path between particles when Cu and Al is spheroidised and evenly distributed. The recrystallization temperature is the least when copper is present as a fine precipitate [2]. A cellular structure of solid solution is obtained on casting an Al-Cu alloy, however this reduces the hot tear resistance and increases the potential for inter dendritic shrinkage [3].

Magnesium increases the strength and hardness of the alloy. With Mg < 2%, room temperature aging can be performed but this makes the alloy more susceptible to intergranular corrosion and thus reduces corrosion resistance. The grain size is affected negligibly by the presence of magnesium.

Manganese is usually considered as an impurity in aluminium alloy but is added to improve elevated temperature properties and to reduce stress corrosion susceptibility. It also increases the recrystallization temperature and coarsens the grains.

Silver enhances the mechanical properties and is used to destroy the effect of impurities. It contributes to stress corrosion resistance and precipitation hardening. Titanium reduces twinning in cast ingots. It also increases the recrystallization temperature and reduces the grain size thus refining the grains.

The feedstock materials could be used in two different techniques that are depending on the route: rheo-route or thixo-route. The slurry used is either a liquid-like slurry or solid-like slurry. The liquid-like slurry has consistently discrete solid particles besides exhibits fluid behavior below exterior forces. The solid-like slurry requires unified solid phases and gains well-defined yield strength [2]. Regardless of which route is used, processes need the structure to be non-dendritic or near globular, therefore feedstock production is crucial [2]. The four methods which are used in this processing consist of Semi-Solid Rheocasting, Cooling Slope, Magneto Hydrodynamic and Semi-Solid Rheocasting with Cooling Slope [11, 12].

Semi-solid rheocasting

In Semi-Solid Rheocasting (SSR), the raw material is taken which is originally from ingot processes without an intermediate solidification step. The molten metal which is slightly above the liquidus temperature is poured into a steel or ceramic crucible and then treated to form a globular microstructure [3]. The molten metal is detained above the liquidus temperature and a cold finger (copper or graphite) is immersed into the pool. This rod, being at a much lower temperature than the liquid, comes into interaction with the liquid metal and then partial solidification of the melt on the rod surface begins. As a result of the rotating motion of the cold finger, the nuclei consequently are shaped then sent into the melt, resulting in a globular microstructure of fine grains [9-12].

Magneto hydrodynamic stirring procedure

In the Magneto Hydrodynamic (MHD) stirring procedure, a dynamic electromagnetic field is applied to the melt to produce high local shear [4]. There are three methods for this technique: horizontal agitation, vertical agitation and helical agitation. The resulting effect is a non-dendritic microstructure slurry which is cast into billets. The billets could be then cut into slugs of the required size, re-heated to the semi-solid state and shaped or cast into the desired shape. The rate of solidification could be additionally controlled by coolants about the mold wall [13-18].

Cooling slope technique

The cooling slope (CS) was established to overcome the limits of the MHD method of not having standard size ingots. It basically consists of a water-cooled plate situated over a mold. Through a cooling slope of 60° incline to the mold, the semi-solid slurry is produced [7]. Also, the cooling slope introduces nucleation of granular crystals that are eroded away by the fluid motion [12, 13]. With that a great number of these nuclei initiated in the melt that solidifies in the mold, concisely it is resulting in a globular microstructure. The mold diameter besides the weight of the molten metal determines the size of the slab. The ingot is formerly heated to the appropriate semi-solid temperature and thixoformed, depending on the type of metal used [16]. The total length of the slope, the correct angle of slope and the cooling system have a direct effect to the solidification of the molten metal that of the quantity of superheat. In this process, the cooling rate of the ingot is contingent on the mold material [12, 13].

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The semi-solid rheocasting processes with the cooling slope technique

In the Semi-Solid Rheocasting processes for the Cooling Slope (SSR+CS) processes, the raw material is heated to molten temperature [22]. The molten material temperature is controlled by a thermocouple at the same time as it is slowly cooling down to a semi-solid temperature. It is stirred vigorously using a rotating rod attached to an electric hand drill for 10 seconds, followed which, the melt is decanted down the Cooling Slope, finally collected at the bottom of the device in a mold and left to cool [22, 17].

A201 alloy billets were thixoformed in the semi-solid state and the resulting products were heat treated with a T7 followed by T6 heat treatment before being mechanically tested. In T6 heat treatment billets are solution treated for 2h at 513°C and for 17h at 527°C followed by water quenching and then ageing for 20h at 153°C. The T7 heat treatment was followed which differs from T6 only in the ageing treatment of 5h at 190°C [8].

Result and Discussion

Microstructural evolution

The as-cast dendritic microstructure of A201 aluminum alloy that was directly poured into the mold after being heated at 649°C is shown in Fig. 1. The dendritic microstructure shows an irregular shape, distributed homogenously in the sample.

Fig. 2-5 shows the microstructures for the preparation methods, the microstructures were different from the conventionally cast feedstock. Even though the grain of the α-Al did not yield homogenous fine globular microstructure, the dendritic microstructure had fully transformed to the non-dendritic microstructure due to the effect of the technique of casting.

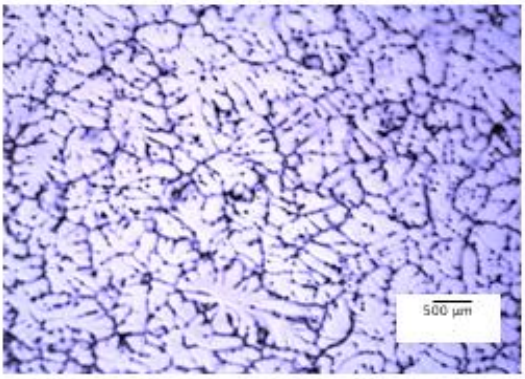

Fig. 1. Dendritic microstructure of aluminium A201

The feedstock was prepared from the alloy by the procedures described in Section 2. Samples were prepared for metallographic analysis. In the microstructural images, the shape factor and grain size were determined to characterize the non-dendritic structure. The shape factor (SF) of the grains is measured according to equation (1).

$$SF = 4\pi \frac{A}{p^2} \tag{1}$$

Where A is the average area, and p is the average perimeter of the grains. If SF approaches 1, then the morphology turns into a spherical shape, and when SF is below 0.3 the morphology can be considered as dendritic [6].

The SF achieved in MHD stirring was about 0.39 and the grain size was 29 µm. The as-cast MHD sample shape of non-dendritic microstructure with well-spaced arms typical of conventionally solidified cast. The shape factor associated with this structure is not of a suitable size for thixoforming, this could be made better by increasing the holding time [8]. At this circumstance, the interface develops unstable hence the formation was more dendritic microstructures, Fig. 2 shows the MHD structure [8].

Fig. 3 shows the CS method results that disrupts the dendrites as they are shaped though the molten metal as it cools flowing down the feed channel [10]. The molten metal in The CS method runs down the feed channel for about 8 seconds [10]. Number shape factor could be noted in the result because of the dendrites structure were broke up to became more globular structures when the molten metal runs down the feed channel. The number of shape factor was about 0.7 and the grain size was around 38 µm Table 3 shows the structure.

In the SSR+CS (Fig. 4), the overall metal disturbance time is extended, letting more dendrites to be broken up and better globular structures being formed. The value of the average shape factor is about 0.73 and the grain size is 41 µm. The microstructures observed for SSR sample shows combination of imperfect and perfect spherical structures. The semi-spherical structures are evenly distributed within the microstructure with large particles being predominant. Spherical particle results during stirring. When the stirring rod is introduced in the cooling molten alloy it interferes with the interface hence preventing branch of dendrites

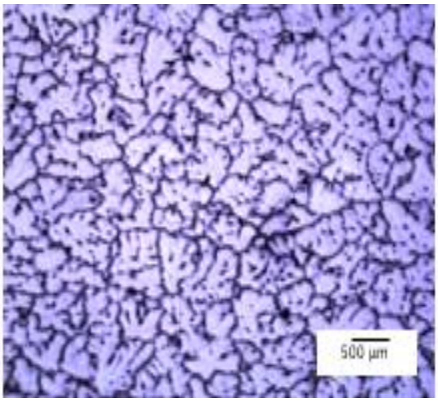

Fig. 2. MHD micrograph

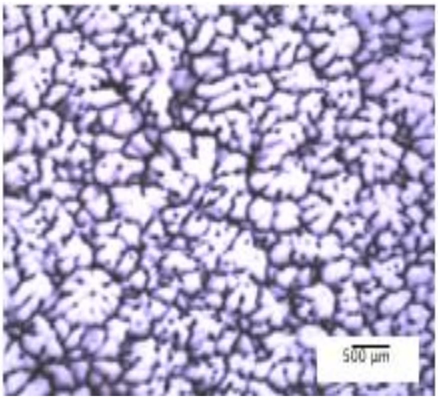

Fig. 3. CS micrograph

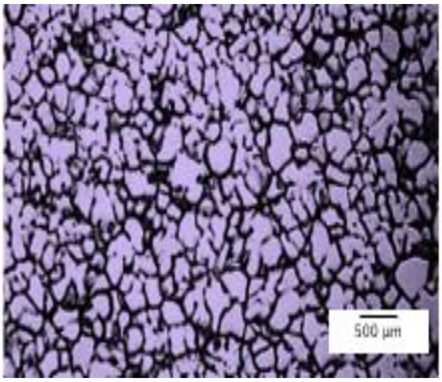

Fig. 4. SSR + CS micrograph

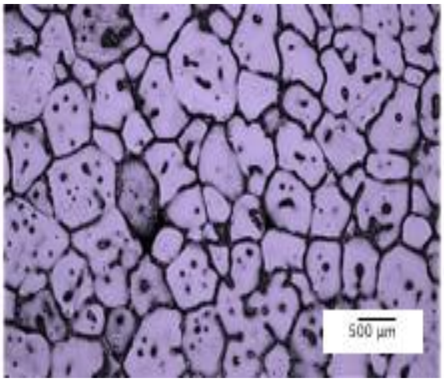

Fig. 5. SSR micrograph

Finally, the value of the average SF in the SSR is about 0.77 and the grain size is about 47 µm. The SF values in the SSR are high caused by the dendrites breaking up through the agitation imposed on the melt by the hand drill. This value is less than that of CS process [7], due to the general metal disturbance time is somewhat lower. The spherical particles are mainly created throughout stirring but the process starts when the stirring rod was dipped in the cooling molten alloy that is shown in Fig. 5, interfering with the nucleation surface and the rotation of the surface sending nucleated sites into the melt, henceforth stopping branches of dendrites developing fully [8, 9].

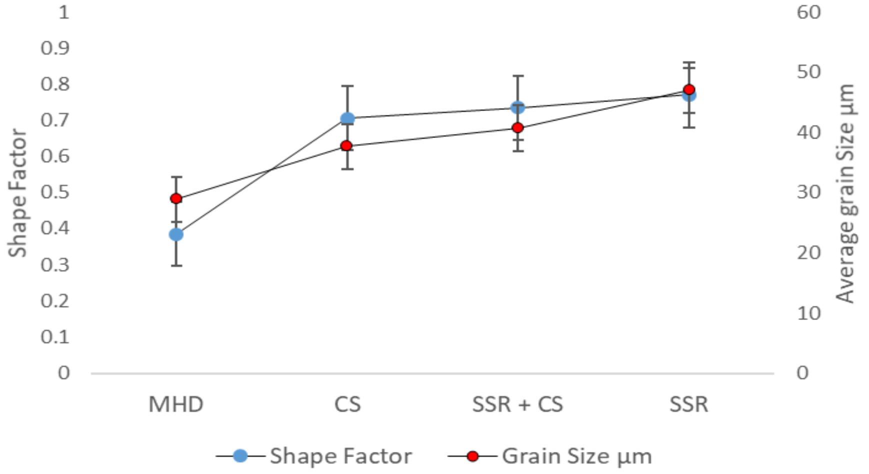

Fig. 6. The average grain size and shape factor of all methods

The average grain size and shape factor for SSR, CS, MHD and SSR+CS are shown in Fig. 6. The shape factor (0.385) and average grain size (28.85 µm) of MHD was smaller than the other methods. Surprisingly, the shape factor and average grain size of SSR was higher than the other methods, it was 0.73, and 46.95 µm, respectively.

Mechanical properties

The Vickers hardness of the as-cast sample of A201 was 74±2.98 HV, whereas the hardness of A201 for SSR was 75.3±2.95HV and the hardness of CS was 88.8±1.94HV higher than the as-cast and SSR. An increase in the hardness of the sample produced by CS casting was due to the progressive growth of the primary α-Al phase in the alloy [19-23]. Also, the hardness of SSR+CS was 79±2.12 HV and hardness for MHD was 95±3.52 (Fig. 7). Generally, small grain size would provide higher strength to the alloys, however, an increase of spherical shape, 1, drove to a drop of elastic modulus while a decrease in spherical shape would increase the cohesion and internal friction angle. Moreover, small particle size would increase the hardness of the alloy known as the Hall-Petch relationship. Though, inverse Hall-Petch effect could also occur below a critical grain-size where the hardness of the alloy could be reduced with the decrease of grain size. The relationship of the mechanical properties is straight proportional to the shape factor of the primary α-Al alloy [19, 24].

Therefore, the mechanical properties could be affected by the grain size of the primary α-Al alloy and the shape factor in the sample. Moreover, the intermetallic compounds of the alloy had a significant effect on the mechanical properties of the A201 alloy. Base elements in the aluminum alloy were aluminum and copper, however, silver, manganese, magnesium and iron were also present to enhance the strength and corrosion resistance. The adding of Mn improves the properties in high temperatures and decreases the stress corrosion defenselessness [6]. The Mg_2Si played an important role in order to refine the size and sphericity of α-Al particles.

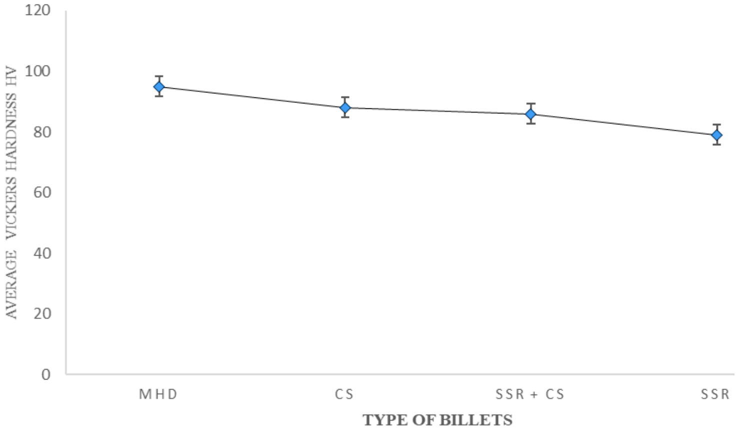

Fig. 7. Vickers hardness of all methods

However, among all these compounds, the iron-rich metallic compound is the most unwanted because it causes brittleness, thus reduced the strength and ductility of the aluminum alloy [20-24].

Conclusion

From this study, there was a clear change in hardness and microstructure comparing the dendritic microstructure to a fine and non-dendritic microstructure after stratify different preparation methods. The melt flow in the SSR processing results in the dendrites are broken into fine particles, therefore the thixotropic behavior of the non-dendritic feedstock is improved. The deformation promotes the morphological transition from dendrite to fine and homogenous globular structure. It was found that SSR feedstock resulted in better microstructures than the other feedstocks because of grain size of around 47 µm while the second feedstock of SSR+CS sample was around 40 µm, which is the maximum spheres obtained at a pouring temperature of 649°C. The hardness of MHD feedstocks was 95±3.52 because of the small grain size, when the grain size was increased the value of hardness decreases so the value settled at 75.3±2.95 HV for SSR feedstocks.

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