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Research paper

Microstructure Evolution in Al-5.7Si-2Cu-0.3Mg alloy by Reheating in High-Frequency Induction Heating for Thixoforming Process

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Abstract

Thixoforming is a forming and shaping process of metal components in their semi-solid state. It can produce a near net shape product with fine globular microstructure and is highly reliable. The process involves preparing the feedstock material with non-dendritic microstructure, heating and consequently forming. The most important step to produce a successful product is reheating of the feedstock material in its semi-solid state and this is mainly achieved by induction heating, which guarantees precise and rapid heating. Thus, this paper discusses the high-frequency induction heating system utilised for this important reheating step. An approximation method of coil geometry is adopted to evaluate the operating condition on the coil current as an input parameter. Microstructural evolution of Al-Si-Cu-Mg at different liquid fraction corresponds to 35% to 50% liquid fraction at 575°C to 600°C was analysed. The result of the image analysis showed a transformation of dendritic, to a spherical morphology. All the microstructures in the semi-solid state range from 35% to 50% liquid fraction contain the primary α Al-globular grain surrounded by the uniformly distributed eutectic silicon. It was found that less entrapped liquid, uniform globule size, higher spherical morphology, shorter heating time and billet stability were obtained at 35% liquid fraction of 575°C with an average shape factor and globule size of 0.73 and 45.8 µm, respectively

Keywords: *Aluminum alloy, Induction heating, Microstructure, Thixoforming process.*

1. Introduction

In recent years, the induction heating process has been widely applied in thixoforming operation [1, 2]. When compared to the resistance electrical furnace, induction heating has shortened the heating time and provides the possibility of flexible process control [3, 4]. This enhancement induces the grain growth development and encourages the grain to become globular and to give a thixotropic flow behaviour when deformed in the semi-solid state [5].

The main influence of induction heating setup originates from the coil geometry, applied power, frequency and coil current [6]. The use of high-frequency induction heating in the reheating process is a combination couple of electromagnetic and thermal phenomena. Furthermore, it is the requirement that led to the globular microstructure without excessive coarsening effect and for grain growth development [7]. It directly limits the penetration depth of the electromagnetic fields. A previous study reported that the determination of coil current, as an input parameter of the operation machine, is important to confirm the success of induction heating [8]. The amount of energy transferred into the billet workpiece is controlled by the current through the inductor into the workpiece. Preliminary numerical simulation and experimental validation of the induction heating process parameters are successfully applied [9, 10].

The optimal operation condition of coil current was considered to avoid the undesirable phenomena of elephant foot, liquid segregation and electromagnetic end effect [11]. The workpiece should be heated to the desired liquid fraction uniformly and rapidly. Previous work has shown that a liquid content of 30% to 50% is required for thixoforming process [12, 13]. Establishment of induction heating method, with a determination of coil current for operating condition prior to thixoforming, is necessary to reduce the heating trial time and cost. However, there is still a lack of studies on the determination of coil current in the induction heating system.

In this paper, an approximation method of coil current was carried out to estimate the coil current parameter for reheating in the high-frequency induction heating setup. The effects of reheating on the semisolid microstructure of Al-5.7Si-2Cu-0.3Mg alloy were analysed at different liquid fraction correspond to 35% to 50% liquid fraction.

2. Experiment materials and procedures

The reheating experiment was performed on the cylindrical billet of Al-5.7Si-2Cu-0.3Mg alloy with radius 25mm and length 100mm fabricated by the cooling slope casting method. The chemical composition and the as-received microstructure are shown in Table 1 and Figure 1, respectively. Differential scanning calorimetry (DSC) was performed to estimate the solidus and liquidus temperatures and also the liquid fraction profile within the semi-solid transition range as shown in Figure 2.

Table 1: Chemical composition of Al-5.7Si-2Cu-0.3Mg alloy (wt %)

Al	Si	Mg	Cu	Fe	S	Ca	Zn	Mn
91.19	5.67	0.32	1.92	0.32	0.16	0.04	0.03	0.12

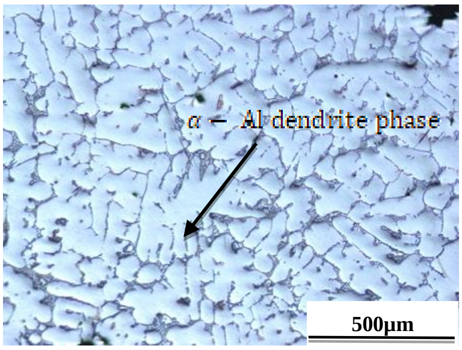


Fig.1: Microstructures of as received Al-5.7Si-2Cu-0.3Mg Alloy with dendritic structure

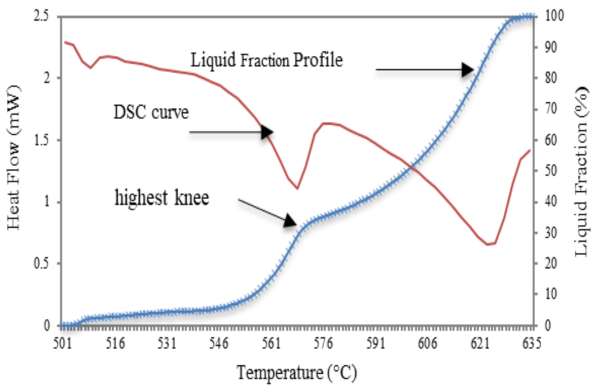


Fig 2: DSC heating flow and liquid fraction curves of Al-5.7Si-2Cu-0.3Mg Alloy.

An inductive heating system with a maximum power capacity of 35 kW and frequency range 30 to 80 kHz was applied in the reheating process. During the reheating process, a piece of kaowool approximately 3 mm thickness was placed between the billet and pedestal holder to reduce the heat losses. Two K-type thermocouples were inserted into the billet to monitor and measure the temperature evolution as shown in Figure 3.

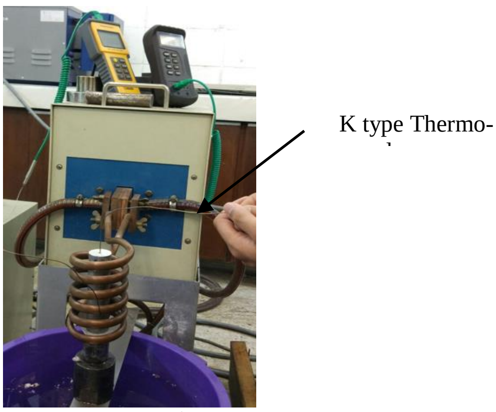


Fig 3: Experimental setup for reheating process via coil induction during the reheating process.

Four different liquid content between semi-solid state range of 35% to 50% liquid fraction at 575°C to 600°C were used in the experimental study for validation with input coil current for the globularization microstructure of thixoforming process. The billet was then held in the semisolid state range for up to one minutes to permit spheroidisation of the grains and then quenched with water to freeze the microstructure from the semisolid state. After quenching, the billet was cut, ground and polished to a mirror finish surface. The metallographic analysis was performed and captured using an Olympus Optical Microscope to observed the microstructural evolution. The shape factor (SF) and globule size (GS) was measured following the ASTM E112-96 standard. The α-Al phase of the liquid fraction content was evaluated using the software Image-J (automatic image analysis) on micrographs with small magnification microstructure are shown in Table 1 and Figure 1, respectively. Differential scanning calorimetry (DSC) was performed to estimate the solidus and liquidus temperatures and also the liquid fraction profile within the semi-solid transition range as shown in Figure 2.

3. Results and discussion

3.1 Determination coil current

The use of high-frequency induction heating needs coil currents as an input parameter to the machine set up. Hence, an approximation method for coil current parameter has been evaluated with a systematic approach. The basis of this method is the use of the design curved for coil efficiency, power factor and reflected impedance of turned square [14]. The curves are from the calculation of the equation of equivalent circuit as discussed by Song et al. [8]. Here, coil efficiency is that part of energy delivered to the coil, which is transferred to the workpiece and then generating precise amounts of heat. Determination of the coil efficiency is defined as the ratio of the induced power of workpiece; P_w [kW] to input power, P_o [kW] is given by:

$$\eta = \frac{P_W}{P_o} \tag{1}$$

The coil power factor, $\cos\phi$ is given by with the KVA_C [kW] is

the apparent power.

$$\cos\phi = \frac{P_o}{KVA_c} = \frac{P_o}{E_c I_c} \tag{2}$$

The coil impedance per turn square then is given by:

$$\frac{Z'}{N_c^{\,2}} = \frac{KVA_c}{(I_c N_c)^2} = \frac{E_c}{N_c\, K\, V\, A_c} \tag{3}$$

Consequently, from the relationship of the coil impedance per turn squared and Equation 1 to Equation 3 the coil current, I_c [A] can be obtained as:

$$I_c = \frac{KVA_c}{Z'/N_c^{\,2}} \times N_c \tag{4}$$

Hence, 440A was estimated to be the most appropriate for coil current with another standard condition was selected as follows; frequency: 60 kHz, total maximum work power: 35kW coil voltage: 415kW while induction coil parameter; inner diameter: 52mm and coil length: 110mm

4. Microstructure in reheating process

In semi-solid processing, thixoformability criteria knowledge is very important as it may affect the overall forming process to produce a fine globular microstructure and control the semi-solid temperature during reheating. The smaller the temperature sensitivity and wide solidification temperature of the liquid fraction, the easier it is to control the processing temperature. Based on the DSC result in Figure 2 the solidus and liquidus temperatures were estimated to be 501°C and 635°C, respectively. For thixoforming purposes, the semi-solid temperature range of the Al-5.7Si-2Cu-0.3Mg Alloy is 575°C to 600°C corresponds to 35% to 50% liquid content. The solidification temperature range approximately 134°C and temperature sensitivity at 0.01°C^{-1} The binary eutectic reaction occurs at the highest knee on the fraction liquid versus temperature curve. It represents an indication of eutectic evolution with the melting of α -solid solution [12]. Hence, the temperature above the "knee" was estimated the most appropriate for thixoforming to obtain a homogenous temperature.

Figure 4 shows the feedstock microstructure of Al-5.7Si-2Cu-0.3Mg Alloy via the cooling slope casting under the cooling slope plate at length 400mm at a pouring temperature of 650°C. The dendritic microstructure in Figure. 1 has disappeared and been replaced by α–Al globules and rosettes. Near globular microstructure was obtained with the shape factor and globule size of 0.6 and 35 μm in average values, respectively. The feedstock material had undergone a reheating process in high frequency induction heating.

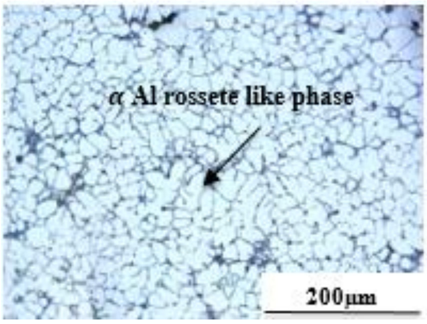


Fig 4: Microstructures of as cooling slope casting of Al-5.7Si-2Cu-0.3Mg alloy at 650℃ with a cooling slope length of 400m.

Figure 5 shows the microstructure of the Al-5.7Si-2Cu-0.3Mg alloy quenched after reheating at a different liquid content of 35%, 40%, 45% and 50% corresponding at 575°C, 587°C, 595°C and 600°C, respectively. Comparing all the reheating temperatures, the microstructure contains almost perfectly globular grains and the eutectic is uniformly distributed for all liquid content. As can be seen from Figure 5(a-d), the microstructure was predominantly consisting in the light primary α -Al phase and the dark eutectic phase representing to the solid and liquid phases of semi-solid state respectively. It was also observed that an entrapped liquid by the surrounding of α -Al phase appears during rehthe eating process. As confirmed by the quantitative analysis, Figure 6 shows the percentage result of entrapped liquid at different liquid content. With increasing liquid content, the entrapped liquid increased linearly. Hence, the presence of entrapped liquid has an impact on viscosity. Less entrapped liquid, as in low liquid fraction will directly result in better fluidity. According to Wang et al. [15], it will affect the result in defects such as shrinkage porosity during the forming and solidification of the thixoformed component.

During the induction heating process, grain growth was activated by the heat from the induction coil and grain grows with increasing temperature [16]. Measurements with thermocouple were taken to ensure rapid heating at a different liquid fraction. An approximate reheating time to achieve semi-solid temperature was 455s, 475s, 510s and 535s corresponding to liquid preventing

excessive grain growth. Figure 7 shows the reheating trial experiment content of 35%, 40%, 45% and 50%, respectively.

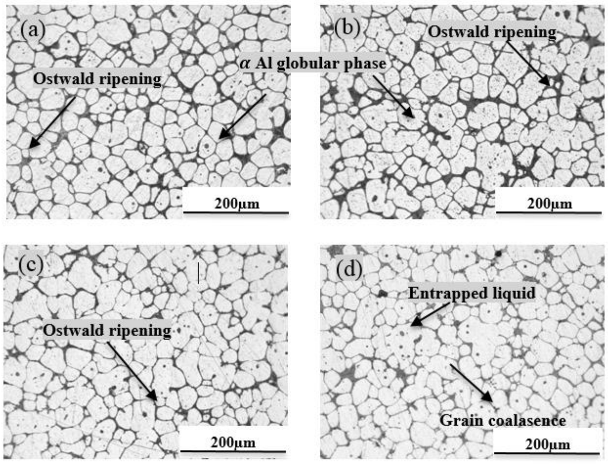


Fig 5: Microstructure of Al-5.7Si-2Cu-0.3Mg Alloy quenched after reheating. (a) at 35%liquid content (b) at 40% liquid content.(c) at 45% liquid content (d) at 50% liquid content.

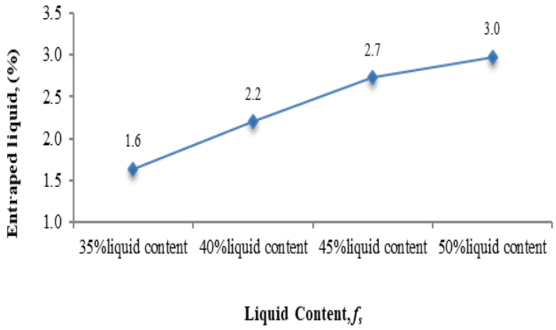


Fig 6: Entraped liquid measurement at different liquid fraction.

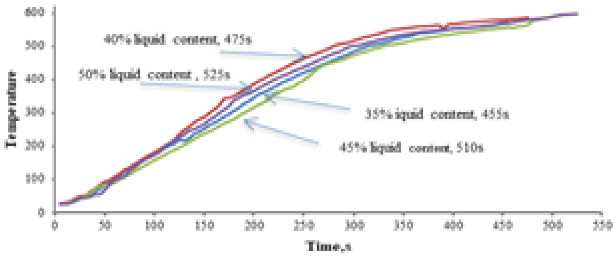
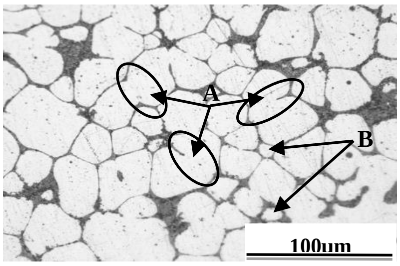


Fig 7: Reheating trial at different liquid content.

Two mechanisms may describe the microstructural evolution in semi-solid condition, namely coalescence of solid grain and Ostwald ripening, whereby small particle is dissolved to the large particle by a solute diffusion process. Haghdadi et al. reported that coarsening behaviour is controlled by diffusion (Ostwald) rather than coalescence [16]. An Ostwald ripening mechanism much more significant obvious as shown in Figure 5(a-d) while in Figure 5d shows the evidence of coalescence when the billet is reheated using the high-frequency induction heating. This is a dominant grain coarsening mechanism in semi-solid microstructure which exhibit grain growths coarsening with increasing temperature. The grain coarsening was prominent at 600℃, producing average globule grain size of 49.6 ± 7 μm after 535s and was supported with a close examination of the microstructure, as shown in Figure 8.



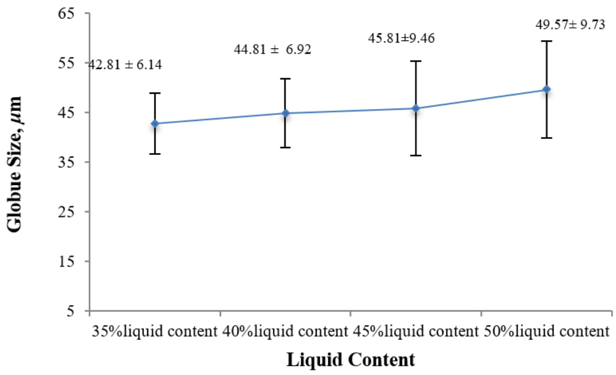
A= Coalasence
B = Ostwald ripening

Fig 8: Close-up microstructure of Al-5.7Si-2Cu-0.3Mg alloys after reheating trial at 600 ºC.

The microstructure shows clearly that coalescence (A) occurs at two adjacent α -Al grain with same grain boundaries and Ostwald ripening (B) leads to the dissolution of smaller α -Al and the growth of larger α -Al. Therefore, it is important to prevent coarsening mechanism, to ensure a homogenous material flow of thixotropic behaviour. Further investigation is needed to study the impact flow of the semi-solid during the forming process.

The quantitative results evolution of Al-5.7Si-2Cu-0.3Mg alloys in semi-solid range presented as a function of globule size and shape factor were summarized in Figure 9. This result represents the average of the measurement of 50 grains from quenched billet. The effect of the liquid content had little effect on the size and shape factor of the globules. The globule size increase from an average of 42.81 μm to 49.51 μm while the shape factor at an average of 0.73. Thus, the microstructure in the liquid content interval [35% to 50%] is considered to be suitable for the thixoforming process. However, higher liquid content tends to make the billet collapse.

Figure 10(a) shows the billet condition at the early stage before reheating trial, while Figure 10(b) and 10(c) show the billet condition at 45% liquid contents and 50% liquid content respectively. The billet tends to collapse under its own weight effect at 45 % liquid content and 50% liquid content, with the undesirable effect such as elephant foot phenomena with non-uniformity temperature profile from top to bottom in the billet.



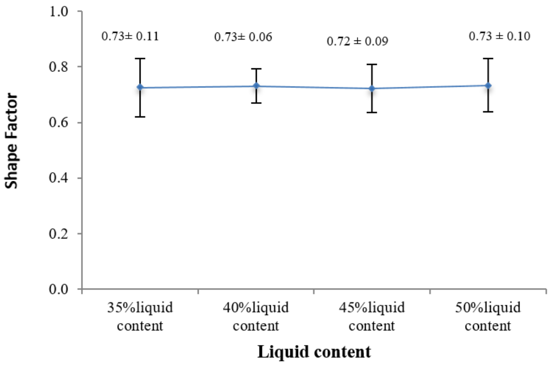


Fig 9: Globule size and shape factor of Al-5.7Si-2Cu-0.3Mg alloys at different liquid content.

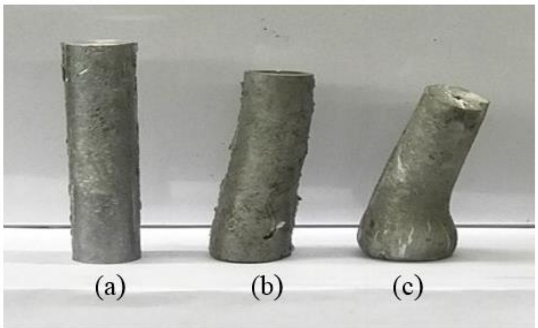


Fig 10: Billet of Al-5.7Si-2Cu-0.3Mg alloy
(a) Initial condition before reheating, t =0s (b) 45% liquid contents at 595 ºC, t = 510s (c) 50% liquid content at 600 ºC, t =535s.

Overall, rapid heating with high-frequency induction heating produces quite similar semi-solid microstructure. Furthermore, a short heating time to the required semi-solid temperature successfully prevented significant grain growth to theα.-Al solid phase. Compression of Al-5.7Si-2Cu-0.3Mg billet into die for the thixoforming process would probably best be carried at just above the knee temperature at approximately 35% liquid content.

5. Conclusion

Al-5.7Si-2Cu-0.3Mg were successfully reheated at 575ºC to 600 ºC correspond to 35% to 50% liquid fraction at high-frequency induction heating. Coil current parameters from the approximation method are useful to reduce the heating trial and time. The microstructure transformed producing fine α -Al globular grain and uniform distribution of eutectic silicon between semi-solid state range temperature. At high liquid fraction, approximately above 45% liquid fraction, entrapped liquid, coarsening effect and non-stability of billet were reported which is not desirable for the thixoforming process. Hence, the thixoforming process would probably be the best to carry at just above the knee temperature at approximately 35% liquid content average shape factor and globule size of 0.73 and 45.8 μm respectively.

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