Microstructure of shear-induced thixoformed Al-4.5Cu-1.5Mg alloy via RAP and SSTT processes

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Abstract: In this research, the effect of the thixoforming temperature on the microstructure and mechanical properties was investigated in the thixoforming of the feedstock produced by the RAP (recrystallization and partial melting) and SSTT (semi-solid thermal transformation) processes for Al-4.5Cu-1.5Mg alloy. In the RAP process, the percentage reduction in area was approximately 35%. Thixoforming was done at 610, 620, and 630 °C. Globular microstructure was observed at all temperatures and conditions. The minimum average globule size was 39 µm, and it was obtained in the thixoforming of the feedstock produced by the RAP process in the section of 4 mm in diameter at 620 °C after applying shear. Its corresponding compressive strength was 877.44 MPa. The maximum average globule size was 136 µm, and it was obtained in the thixoforming of the feedstock produced by the SSTT process in the section of 10 mm in diameter at 630 °C before applying shear. Its corresponding compressive strength was 769.18 MPa. The finest and most spherical globules, as well as the highest compressive strength were obtained at 620 °C in both RAP and SSTT states.

Key words: thixoforming; RAP; SSTT; aluminium alloys

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Wrought aluminum alloys have a wide variety of applications due to their preferred properties compared with casting aluminum alloys. So far, the most common processes to manufacture wrought aluminum alloys are methods that introduce plastic deformation, such as forging, extrusion, and rolling. These methods significantly cause an increase in the cost of the produced components. Therefore, there is an economical advantage to cast wrought aluminum alloys into components. The biggest problem in casting such alloys is their strong tendency to the formation of hot tearing in conventional casting processes^[1, 2]. Al-4.5%Cu-1.5Mg alloy has magnificent properties including formability, age hardenability, and high strength-to-weight ratio.

Semi-solid processing has been progressively enhanced. Semi-solid forming technology has abundant advantages compared to traditional casting and forging

such as near net shape, low forming efforts, reduction of porosity, increasing mechanical properties, and extending die life^[2-11]. Semi-solid forming technology includes thixoforming and rheocasting^[1, 5, 8, 11, 12]. Preparing semi-solid feedstock is fundamental to the thixoforming process. So to speak, this is important to obtain non-dendritic microstructure^[4-5]. There are several methods to create a globular microstructure to be used in the thixoforming process. In order to prepare semi-solid feedstock, mechanical and magnetic stirring, spray casting, electromagnetic vibration, strain induced melt activated (SIMA), recrystallization and partial melting (RAP), and semi-solid thermal transformation (SSTT) processes were used^[4-5, 8-9, 11]. RAP, SIMA, and SSTT processes do not require complicated equipment and are very simple compared with magnetic stirring. A fine globular and uniform microstructure is obtained by these processes^[9]. Then, feedstock is reheated to the temperature between solidus and liquidus. Similarly, it is isothermally held at various temperatures between solidus and liquidus to obtain a fine globular microstructure and uniform solid fraction distribution. At SSTT process, as-cast dendritic structure is reheated to the semi-solid state, and it is allowed for a sufficient time to evolve thixoformable and globular structure.

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At SSTT process, the introduced strain is thermal strain which comes from rapid chilling of materials, but at the RAP process, the introduced strain is originated from cold work before reheating to semi-solid state. The given liquid fraction can be obtained due to controlling temperature, and time is required to ensure complete transition from dendritic or rosette to spherical structure. Then this material is transferred into a preheated mould [2, 5, 7, 12-15].

Thixoforming temperature is the most important parameter, and holding time is the least effective parameter. At a short holding time, it is barely possible to achieve fine globules [10]. Although scores of studies have been carried out on semi-solid processing of Al-4.5%Cu-1.5Mg alloy, actually no significant effort has been done to compare the structure of shear-induced semi-solid samples after thixoforming of SSTT and RAP feedstock on this alloy at a short holding time.

In this research, the effect of thixoforming temperature on the microstructure of the shear-induced thixoformed AA2024 samples of which feedstock were produced by RAP and SSTT processes was investigated at a short holding time.

1 Experimental procedure

Al-4.5%Cu-1.5Mg alloy ingot was melted in an electric resistance furnace. The chemical composition of this alloy is shown in Table 1. This alloy was heated to 750 °C to ensure that the liquid phase was homogenized. Then it was poured into a preheated metallic mold. This metallic mold was cylinder with the size of 50 mm in length and 10.2 mm in diameter, and was preheated at 400 °C. Afterward, to eliminate previous thermal stress at 470 °C within 60 min, annealing process was done on some samples for RAP process. The annealed samples were swaged with the die of which input and output diameters were 10.2 and 8.2 mm, respectively. So the percentage reduction in area was approximately 35%. Swaged samples and as-cast samples were used to form feedstock for RAP and SSTT processes, respectively.

Swaged samples and as-cast samples were put in an injection chamber attached to a steel mold. This setup was held at different temperatures in semi-solid state for 5 min. It was noted that the holding time was considered constant (5 min) in all semi-solid processes. Furnace temperature was fixed by PID controller, and another thermocouple (K type) was inserted inside the mold to show the temperature accurately. Consequently, high accuracy was obtained on controlling the temperature. When samples were kept at desired temperature

within 5 min, the thermocouple was immediately removed from mold, and slurries were injected into the metallic mold by hydraulic press with the ram speed and pressure of 1 m·s⁻¹ and 200 MPa, respectively. After thixoforming, samples were quenched in water immediately. A scheme of the mold shape with its dimensions is shown in Fig. 1.

Fig. 1: A scheme of shape of mold

A sample was injected into the mold at 660 °C in the molten state. Different conditions for thixoforming are listed in Table 2. Figure 2 shows a sample after thixoforming.

The microstructure of samples was observed using an Olympus optical microscope. Linear intercept method was used to calculate the average grain size [16]. The average shape factor of solid grains was calculated with image J software.

Samples were cut along the diametric direction and mounted and ground, and then polished to a final finish of 1 μm using diamond suspension. Kroll's reagent was used to etch the samples.

Fig. 2: Sample after thixoforming process

Table 1: Chemical composition of AA2024 (wt.%)

Cu	Mg	Mn	Si	Fe	Zn	Al
4.5	1.5	0.4-0.7	0.2>	0.36>	0.1>	bal

Table 2: Different conditions of thixoforming process

State	Injection/thixoforming temperature (°C)		
RAP	610	620	630
SSTT	610	620	630
Injected molten sample	660		

Compressive tests were done on thixoformed samples using tensile testing machine. The specimens for the compressive test were cylinder with the size of 4 mm in diameter and 4.5 mm in length. Compressive strengths of samples were compared at elongation of 50%.

2 Results and discussion

Figure 3 shows how the mold was poured during injection of slurries. This figure also displays the definition of sections A

Fig. 3: Scheme of behavior of semi-solid metal in mold during thixoforming process

and B. Section A is the section with a diameter of 10 mm, and section B is the section with a diameter of 4 mm.

Figure 4 shows the microstructure of as-cast and swaged samples. An oval shape is put in Fig. 4(a), and Fig. 5 magnifies this oval shape. As seen in Fig. 5, the microstructure of these samples is dendritic. Figure 4(a) shows the microstructure of as-cast sample along the diametric direction, and Fig. 4(b) shows the microstructure of the swaged sample in the direction of perpendicular to the diameter. Stretched grains can be seen in Fig. 4(b) in the swaged sample.

During the thixoforming process when the samples were injected into the mold, shear was created because of reduction in area (from section A to B). So semi-solid materials sheared in section B, and compressive stress was just applied on the feedstock in section A.

Figures 6 and 7 show the microstructure of thixoformed samples at different temperatures at section A and B with feedstocks obtained by SSTT and RAP processes, respectively. Figures 8 and 9 demonstrate average globule size according to the thixoforming temperature in thixoforming of the feedstock obtained by RAP and SSTT processes at section A and B. The microstructure of feedstock produced by RAP and SSTT processes at section A (before thixoforming) were compared

Fig. 4: Microstructure of samples: (a) as-cast sample, (b) swaged sample

Fig. 5: Microstructure of oval shape shown in Fig. 4

with the microstructure of thixoformed feedstock at section B obtained by RAP and SSTT process, respectively. It is observed that the microstructure of feedstock before thixoforming is similar to the microstructure of thixoformed feedstock at section A. Based on Figs. 6–9, average globule sizes of the thixoformed feedstock obtained by SSTT process at 610, 620, and 630 °C at section A were 84, 64, and 136 μm, respectively, and at section B were 68, 45, and 91 μm, respectively. Average globule sizes of thixoformed feedstock obtained by RAP process at 610, 620, and 630 °C at section A were 66, 49, and 81 μm, respectively, and at section B were 54, 39, and 67 μm, respectively. It is worth noting that globular structure was observed at all conditions and temperatures. According to Figs. 6–9, average globule size is smaller in the thixoforming of the feedstock produced by the

Fig. 6: Microstructure of thixoformed feedstock in SSTT state: (a) at section A at 610 °C, (b) at section B at 610 °C, (c) at section A at 620 °C, (d) at section B at 620 °C, (e) at section A at 630 °C, (f) at section B at 630 °C

Fig. 7: Microstructure of thixoformed feedstock in RAP state: (a) at section A at 610 °C, (b) at section B at 610 °C, (c) at section A at 620 °C, (d) at section B at 620 °C, (e) at section A at 630 °C, (f) at section B at 630 °C

RAP process than in the thixoforming of the feedstock produced by the SSTT process at constant temperature and the same section. In the RAP process, samples were swaged to form the great number of dislocations, and in the SSTT process, samples were as cast. Therefore, dislocation density of the swaged

samples was far more than that of as-cast samples because dislocation of swaged samples was originated from mechanical strain, and dislocation of as-cast samples was originated from thermal strain.

It is supposed that the major mechanism for formation of

globular structure in the feedstock produced by RAP and SSTT processes was recrystallization. As a result, the reason for the difference in average globule size at different temperatures was recrystallization of feedstocks obtained by RAP and SSTT processes. Distortion energy provided the driving force necessary for recovery and recrystallization during heating process under solidus temperature. Therefore, thermal energy was sufficient that dislocations were allowed to provide their arrangement and turn their energy into the least level. After the recovery process, residual distortion energy stored in an alloy provided driving force for recrystallization. In the recrystallization process, grains containing a high density of dislocations were replaced by grains with low density of dislocations. Since the dislocation density of the grains of the swaged sample was greater than that of the grains of as-cast samples, high-energy sites in the grains of the swaged samples were more than those in the grains of the as-cast samples. As a result, recrystallized grains in thixoforming of the feedstock obtained by the RAP process were finer than those in thixoforming of the feedstock produced by the SSTT process.

In Figs. 8 and 9, the uniformity of globule size is shown in

all conditions and temperatures. As observed in this figure, the uniformity of grain size increased and then decreased in all conditions with increasing thixoforming temperature (whether in swaged state or in as-cast state). Therefore, the finest and the most uniform globules were obtained at 893 K (620 °C).

As shown in Figs. 6–9, average globule size first decreased and then increased in all conditions with increasing thixoforming temperature (whether in swaged state or in as-cast state) and the same section. The percentages of liquid phase in mushy zone at 610, 620, and 630 °C are theoretically 20, 30, and 50, respectively^[4]. According to Figs. 8 and 9, as thixoforming temperature increased, average globule size decreased, and then increased at section A in both feedstock produced by the RAP process and feedstock produced by the SSTT process. The major mechanism of globular grain coarsening was coalescence at 610 °C. This is because the percentage of liquid phase was 20%, and the amount of liquid at 610 °C could not prevent the coalescence process compared with 620 and 630 °C. Therefore, some low energy grain boundaries were coalesced. Increasing the temperature up to 620 °C, the percentage of liquid phase reached 30%, and also the smallest globule size

Fig. 8: Average globule size according to thixoforming temperature in RAP and SSTT states at section B

Fig. 9: Average globule size according to thixoforming temperature in RAP and SSTT states at section A

was obtained. At this temperature, the amount of the liquid phase simultaneously prevented the occurrence of coalescence, and the Ostwald ripening phenomena was compared with 610 and 630 °C. The amount of liquid phase at 620 °C prevented coalescing subgrain boundaries, and did not cause the Ostwald ripening phenomenon. With a further increase in thixoforming temperature up to 630 °C, the liquid phase reached 50%. At this temperature, the amount of liquid phase was so high that grain coarsening occurred by the Ostwald ripening mechanism compared with 610 and 620 °C. The driving force of grain coarsening at this temperature was reduction of interfacial free energy.

As can be seen in Fig. 6 (a, c, e) and Fig. 7(a, c, e), the coarse globules are indicated with circle. This coarsening occurred at section A. When semi-solid materials sheared, globules are turned while entering section B. Therefore, inducing shear on semi-solid materials resulted in deagglomeration of globules indirectly.

Based on Fig. 6(b) and Fig. 7(b), some plastically deformed globules are shown inside the drawn rectangles. The percentage of liquid phase at 610 °C is low compared with 620 and 630 °C. When shear induced on semi-solid material, globules became partially deformed at 610 °C because of a low amount of liquid. On the contrary, at 620 and 630 °C, shear could not deform globules because high amount of liquid prevented the globule deformation.

According to Figs. 6–9, the average globule size at section B is smaller than that at section A at constant temperature and condition. After recrystallization was complete, a series of subgrain boundaries appeared. When the misorientation of such subgrains is greater than a critical angle, the solid/liquid interface energy (γ_{sl}) becomes less than half of the grain boundary surface energy (γ_{gb}). When this condition is fulfilled ($\gamma_{gb} > 2\gamma_{sl}$), liquid penetrates the grain boundary to minimize the local surface energy. At section A, solid particles became interconnected by coalescence and created agglomerates because their low-energy grain boundaries were not wetted. As a result of reduction in area (from section A to section B), during thixoforming process, shear was applied on semi-solid metal,

and led to a decrease in globule size. This is because applied shear resulted in turning recrystallized grains and subsequently preventing the coalescence of the recrystallized grains with low-energy grain boundaries that were not wetted^[17]. Therefore, from this point, inducing shear on semi-solid materials directly decreased the globule size.

On the other hand, when semi-solid feedstock was transferred from section A to section B, preferred fine globules entered section B. It is worth mentioning that the viscosity of globules in section B slightly decreased because preferred fine globules moved from section A to section B. So, in this case, inducing shear on semi-solid materials indirectly decreased the globule size.

An increase in temperature increased roundness of globules. The interface energy of polygonal grains is higher than that of spheroidal grains. To lessen the surface energy as temperature increased, polygonal grains were approximately spheroidized. Shear (resulted from reduction in area from section A to B) could affect the roundness of the globules. In other words, the more spheroidal globules could preferably enter section B. In the RAP state, surface curvatures of the grains led to a decrease in equilibrium melting point. Therefore, the sharp tips of the grains in the RAP state were melted, and grains were gradually spheroidized without sharp corners^[4].

In Fig.10, stress-strain curves in compression are plotted for both thixoformed feedstock obtained by RAP and SSTT processes at different temperatures and the injected molten sample. As observed in Fig. 10(a), compressive strengths of thixoformed samples in SSTT state at 610, 620, and 630 °C were -783.41, -834.24, and -769.18 MPa, respectively. According to Fig. 10(b), compressive strength of the injected molten sample was -797.96 MPa, and compressive strengths of thixoformed samples in RAP state at 610, 620, and 630 °C were -841.87, -877.44, and -787.54 MPa, respectively. The lower the globule size, the higher the compressive strength. As shown in Fig. 10, the compressive strength of the injected molten sample was less than that of thixoformed feedstock in the SSTT state at 620 °C and in the RAP state at 610 and 620 °C.

Fig. 10: Stress-strain curves in compression: (a) in SSTT state, (b) in RAP state and injected molten sample

3 Conclusions

(1) At constant thixoforming temperature, the average globule size of thixoformed feedstock in the RAP state is less than that in the SSTT state.

(2) Applying shear on semi-solid metal during thixoforming as a result of reduction in section area, the average globule size can be approximately decreased by 20%–33%.

(3) The desired thixoforming temperature was 893 K (620 °C) because the finest and most spherical globules, and the highest compressive strength were obtained at this temperature in both RAP and SSTT states.

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