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An investigation on the microstructural evolution and mechanical properties of A380 aluminum alloy during SIMA process

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ABSTRACT

Microstructural evolution and tensile properties of thixoformed near net shape parts of A380 aluminum alloy have been studied. The effect of plastic deformation and holding time in the appropriate semi-solid temperature has been investigated in the strain-induced melt activating process (SIMA). The results of image analysis showed that by increasing the deformation value from 5% to 11%, the recrystallized α-Al grains gradually refined as a result of the increasing the nucleation rate. At the value of 11% plastic deformation a dominant globular structure of α-Al grains was obtained. However, further increasing in the plastic deformation (14%) reduced considerably the shape factor. The equivalent diameter and the shape factor of the globular grains were 70.3 μm and 79%, respectively, after about 11% of plastic deformation. Holding time of the specimens at the semi-solid temperature has been studied from zero to 30 min. It was found that the holding time of 25 min is the best to prevent grain growth. The mechanical properties of thixoformed alloys were also investigated. The results showed that the yield, tensile strength and elongation have been increased considerably using thixoforming, compared with the as-cast condition.

1. Introduction

Aluminum foundry alloys are commonly cast in the sand and permanent molds. The low production cost of such manufacturing routes comes with certain drawbacks, including the formation of porosity, hot tears and segregation which may act as potential crack source during service. Therefore, there have been considerable efforts to minimize these problems which resulted in introducing more advanced shaping routes such as rheoforming and thixoforming [1,2].

Thixoforming is a semi-solid metal processing route (SSM), which forms the alloys to near net shaped products. In thixoforming, the material is treated in such a way that the microstructure will be spheroidal in the semi-solid state; then a slug of alloy is heated up to reach the required semi-solid state and injected into the die [3,4].

The main requirement for the success of semi-solid state forming is the production of a non-dendritic, spheroidal microstructure, from which suitable viscosity and adequate flow behavior are expected. There are four main techniques for feedstock preparation, hereafter named microstructural conditioning: (i) mechanical stirring; (ii) electromagnetic stirring (Magneto Hydro Dynamic, MHD); (iii) new rheocasting; and (iv) a thermomechanical treatment (TMT), involving plastic deformation and recrystallization [5–7]. One of the TMT routes is the strain induced melt activated (SIMA) method. SIMA process consists of the following stages [8]. Firstly, the alloy is cast in convenient sizes to obtain a typical dendritic microstructure in the as-cast condition. Subsequently, it is hot deformed to obtain an oriented microstructure. An appropriate level of cold work should be applied to hot deformed sample. In this stage a critical level of stored strain is introduced in the deformed alloy. Finally, because of the rheological behavior is related to the solid volume fraction of the alloy [9], the deformed alloy should be partially re-heated in the semisolid state and isothermally held for a suitable time to produce the required slurry with an appropriate volume fraction of liquid phase [10,11]. Parameters such as heating time and the level of cold working are critical factors in controlling the semi-solid microstructures in the SIMA process [12–15].

The present study investigates the effects of heat treatment time and the level of cold working on the microstructure, grain globularization of SIMA processed A380 aluminum alloy. The mechanical properties of thixoformed alloys were also investigated and compared with the as-cast condition.

2. Experimental procedure

Material used for this study was A380 aluminum cast alloy. Appropriate amount of the alloy was charged in a preheated graphite crucible and then melted in an electrical resistance furnace under the protection of coveral fluxes. The melt was poured

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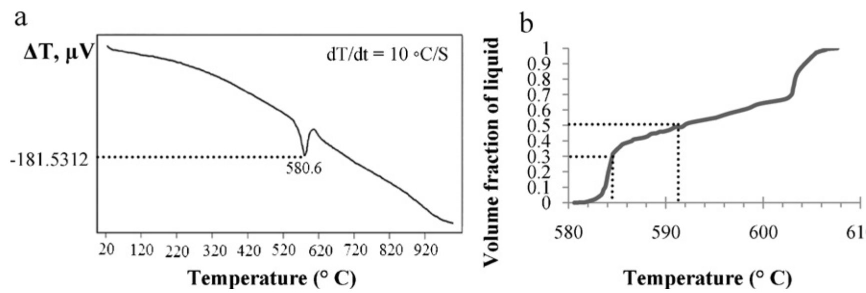

Fig. 1. (a) DTA curve of A380 aluminium alloy. (b) Variation of liquid volume fraction versus temperature.

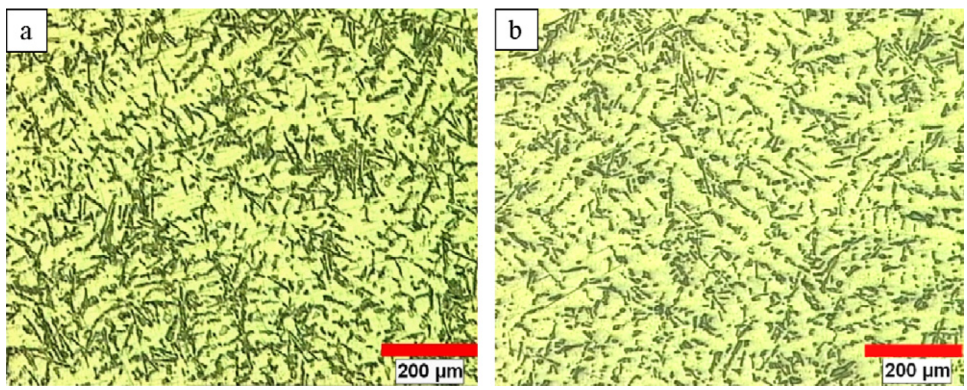

Fig. 2. The microstructures of (a) undeformed and (b) predeformed, A380 alloy.

at 700 °C into a copper mold preheated to 200 °C. The samples were mechanically cut into a series of cubic specimens required for the microstructural observation and tensile properties test.

A380 aluminum alloy has a relatively high Si content (9 wt%) which decreases the ductility at room temperature. Therefore, the specimens should be rolled at higher temperatures to avoid cracking [16]. However, in order to increase the dislocation density, which is a prerequisite of the SIMA process, the specimens had to be deformed at the lowest possible temperature to avoid annealing during working. Cubic ingots with a thickness of 30 mm were preheated to 400 °C for 25 min and rolled to different levels of predeformation (5, 8, 11, and 14% reduction) at this temperature. The rolling temperature corresponds to the temperature of 70% of the eutectic temperature of the alloy on the absolute temperature scale, which

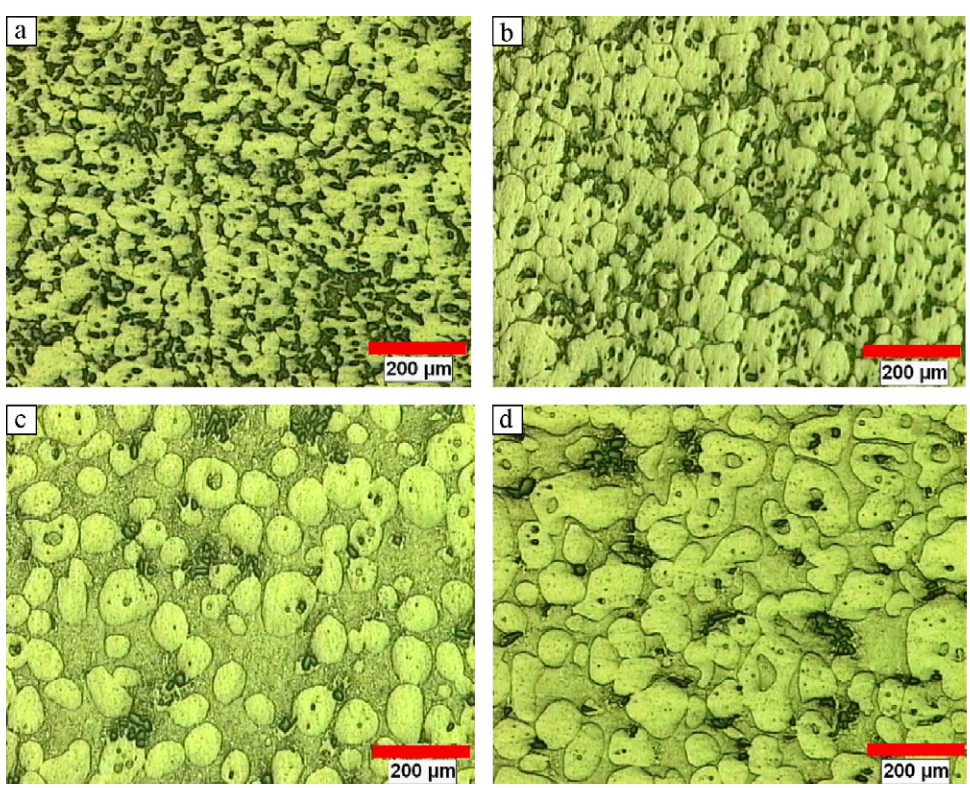

Fig. 3. Microstructure of 11% predeformed specimens after holding at 590 °C for 15 min (a), 20 min (b), 25 min (c) and 30 min (d).

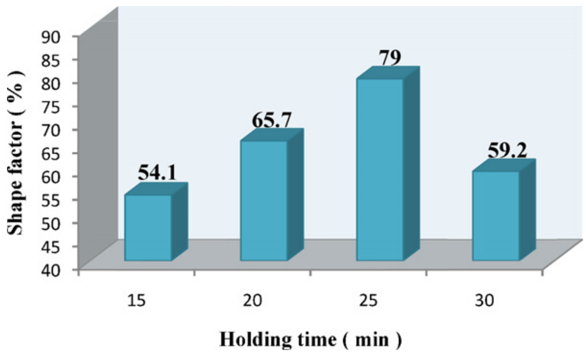

Fig. 4. Variations of shape factor with holding time in 590°C after 11% predeformation.

is referred as a typical annealing temperature. As a result, the alloy would store a significant amount of warm work.

In order to study the effect of holding time on the recrystallization, the rolled samples were heated in a proper temperature for 15, 20, 25, and 30 min. To preserve the content and morphology of the recrystallized grains, the samples were quickly quenched into the cold water at room temperature.

Differential Thermal Analyzes (DTA) was used to determine the solidus and the liquidus temperatures of the alloy. Samples having 3 mm diameter and about 15 mg weight were cut and heated to 1000 °C at a heating rate of 10 °C/s and then cooled to room temperature at the same rate. The heat flow and temperature were monitored using DTA. The changes of liquid volume fraction versus temperature was calculated and plotted.

In thixoforming, specimens were reheated to 590 °C for 25 min in an electrical resistance furnace having the temperature accuracy of ±1 °C, according to the DTA results. Specimens were then transferred from the furnace to the die on the press and subjected to 30% hot working. A hydraulic press (max. load 150 t, max. velocity 200 mm/s) was used for compression. In this experiment, the compression velocity and applied pressure were 200 mm/s and 50 t, respectively. In order to maintain a constant die temperature, the die was heated by cartridge heaters, which was inserted in the upper and lower dies. The applied pressure was held for 20 s after filling. The forged sample was rapidly quenched with water to investigate the mechanical properties.

Microstructure of the samples was studied using a Nikon Epiphoto 300 optical microscope (OM) and a CAMSCAN MV2300 scanning electron microscope (SEM), respectively. Tensile tests were performed at a strain rate of $1 \times 10^{-3}\ s^{-1}$. Tensile properties values represent the average value of at least five test results.

3. Result and discussion

Fig. 1a shows the variation of heat flow versus temperature obtained from DTA curve of A380 aluminum alloy. It is observed that the solidus and the liquidus temperatures of the alloy are 580.6 °C and 607.6 °C, respectively. Fig. 1b indicates the variation of the liquid volume fraction of the alloy versus temperature. The thixoforming temperature suitable for the alloy corresponds to the liquid volume fractions between 30 and 50%. Therefore, 590 °C will be a proper temperature for thixoforming.

Fig. 2 shows the optical micrograph of the alloy in the as-cast condition and deformed alloy after 11% deformation. It consists of the primary dendritic α-Al phase and the eutectic Al–Si. As can be seen in Fig. 2, the deformation has no great influence on the size of the secondary dendrite arms of the alloy. However, the arrangement of the dendrites changes considerably. All the dendrites oriented themselves in the same way due to the effect of the predeformation in the deformed alloy.

Fig. 3a–d shows the effect of holding time at 590 °C after 11% deformation. In Fig. 3a and b it is clearly seen that the sphericity of α-Al globules and contiguity of the eutectic phase in specimens with 15 or 20 min holding time are not sufficient. The sphericity of α-Al globules and contiguity of eutectic phase were improved in sample with 25 min holding time, Fig. 3c. At longer times the coarsening of the grains is obvious, Fig. 3d. So, the best sphericity and contiguity have been obtained in the sample held for 25 min which is suitable for semisolid forming.

Fig. 4 shows the variations of shape factor with holding time at 590 °C. The maximum shape factor is 79% which is obtained in 25 min holding time.

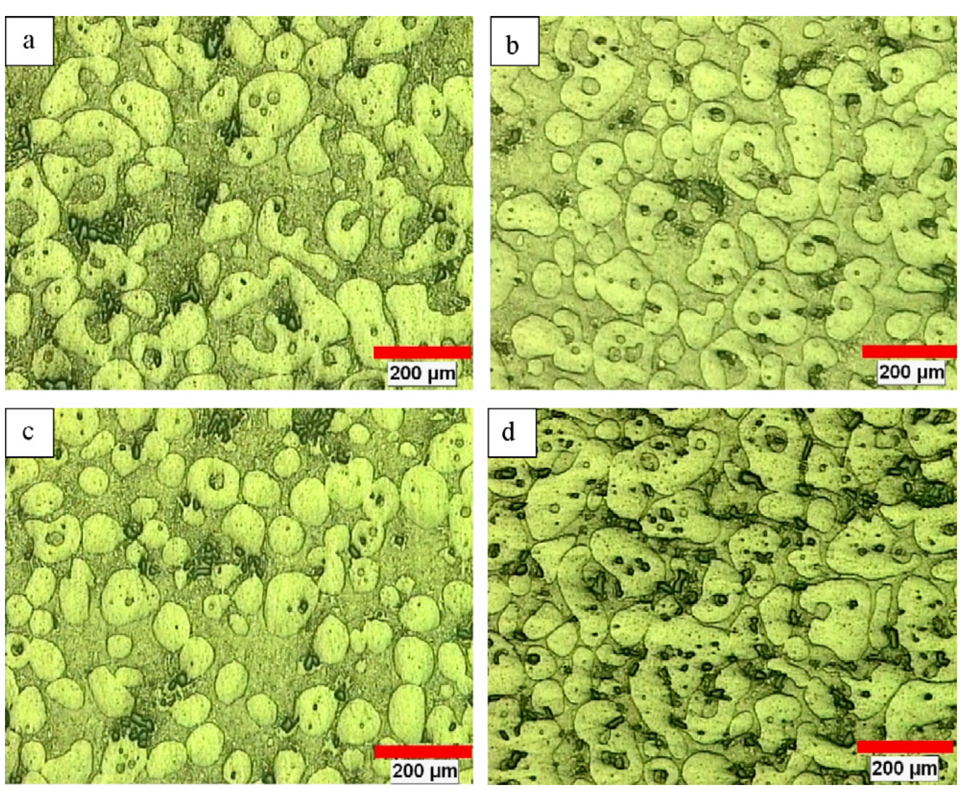

Fig. 5. Microstructure of the specimens after isothermal holding in 590°C for 25 min (a) 5% deformed, (b) 8% deformed, (c) 11% deformed and (d) 14% deformed.

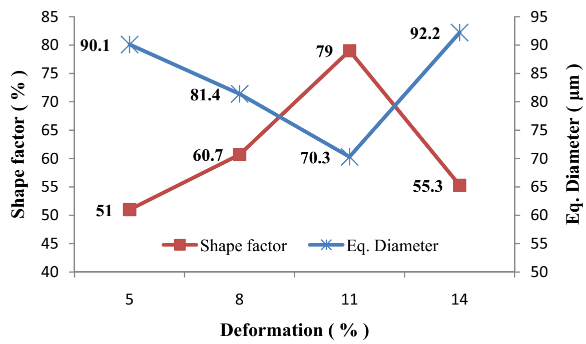

Fig. 6. Variation of the shape factor and α-Al grain size with the amount of predeformation.

Deformation of the α-Al matrix is an important parameter to achieve proper spherical microstructure in the semi-solid state. The microstructure of the specimen after isothermal holding of the deformed specimens in 590 °C for 25 min is shown in Fig. 5. It is clearly seen in Fig. 5a that the sphericity of α-Al globules in specimen with 5% deformation and contiguity of the eutectic phase are not sufficient. The sphericity of α-Al was improved in samples having 8% deformation, Fig. 5b. The best sphericity of α-Al and contiguity of the eutectic phase have been obtained in the sample having 11% deformation which is suitable for semisolid forming, Fig. 5c. Further increasing of predeformation alters the globularization of the microstructure, Fig. 5d.

The variation of shape factor and grain size vs. deformation is shown in Fig. 6. The shape factor achieves to a maximum of about 79% and grain size achieves to a minimum of about 70.3 µm at 11% of deformation. However, at higher level of deformation, globularization of the microstructure is changed severely.

As illustrated in Fig. 6, there exists an optimum condition for the required amount of deformation which results in the occurrence of recrystallization. In the recrystallization process, the nucleation and growth rates associated with the continually accumulated systemic strain energy by deformation [16], so the final average size of recrystallized α-Al grains in the A380 alloy had an indirect relationship with the deformation. On the other hand, after deformation, the density of vacancies and dislocations increases, which increases the atomic diffusion capacity and the rate of Al and Si to diffuse from the liquefied eutectic phase to α-Al in the semi-solid temperatures. After the melting of the eutectic structure, the elements diffuse into the recrystallized grains rapidly, so that the elements become distributed uniformly and decrease the amount of the liquid. In the specimens with a little amount of deformation, the density of the vacancies and dislocations are low, which results in a low atom diffusion rate. However, when sufficient amount of deformation is exerted to the alloy, the final semi-solid microstructure may have equiaxed morphology by diffusion of the eutectic melted phase into the high stress containing regions of the dendrites [10,17]. At 14% of deformation the mean shape factor of the grains decreases. According to Arami et al. [18] study, higher amount of deformation introduces more vacancies and dislocations in the specimen and therefore the sample deformed at a high degree, spherodized in a relatively shorter time and lower temperature.

In order to investigate the effect of initial microstructure on the tensile properties, Fig. 7 shows a comparison of mechanical properties of A380 alloy samples produced via permanent mold casting and thixoforming. The thixoforming process provides samples with slightly higher yield strength and much higher ultimate tensile strength and elongation. The ultimate tensile strength and elongation of the thixoformed samples are approximately 14% and 30% higher than that of the cast samples, respectively. The good combination of strength and elongation of thixoformed samples

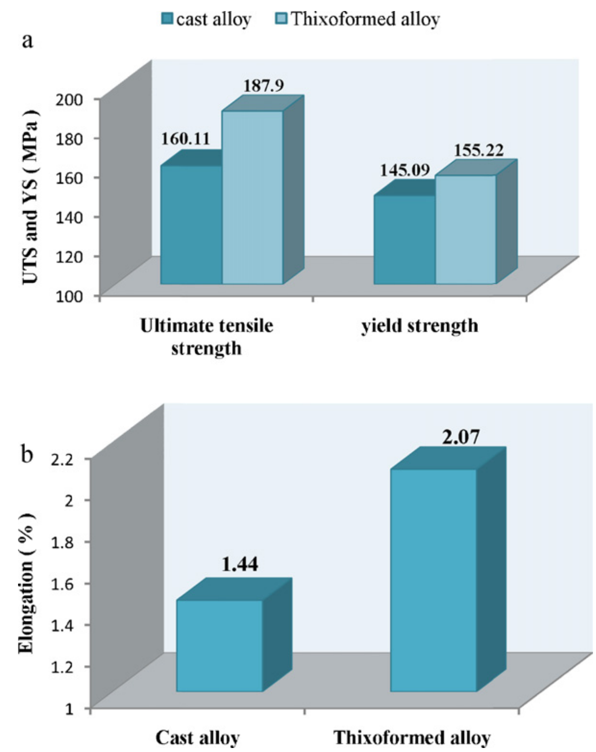

Fig. 7. Comparison of mechanical properties of A380 alloy produced via permanent mold casting and thixoforming. (a) Ultimate tensile and Yield strength, (b) Elongation.

is mainly derived from the extremely low porosity, fine size and equiaxed morphology of the α-Al grain, and more importantly, the fine and uniform microstructure throughout the entire sample.

4. Conclusion

The effect of plastic deformation and holding time in the semi-solid temperature has been investigated in the A380 aluminum alloy through SIMA process. The following results can be concluded:

1. The DTA results indicate that 590 °C is a proper temperature for thixoforming of A380 alloy. The optimum uniformity was obtained for holding time of 25 min at 590 °C in the semi-solid state.
2. A dominant globular structure and contiguity of the eutectic phase were developed by 11% of predeformation. At higher predeformation, the coarsening of the grains was observed.
3. The thixoforming process increased the ultimate tensile strength of the alloy about 14% and elongation about 30%, compared to the as cast condition. It has been caused by the extremely low porosity, fine and equiaxed morphology of the α-Al grains, and uniform microstructure throughout the sample.

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