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Research Article

Effect of Heat Treatment and Rolling on the Microstructure and Tensile Behavior of Twin-Roll Cast AA8006 Aluminum Foils

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ABSTRACT

The Microstructure and tensile properties of 60 µm thick AA8006 aluminum foil were investigated in the present study. Sheets of AA8006 were produced by twin-roll casting (TRC) with a thickness of 8 mm and were reduced to 4.5 mm thickness by one pass of rolling. The sheets were heat-treated, homogenized and annealed. After heat treatment, both processes were subjected to cold rolling to compare their tensile properties in 60 µm thickness after final annealing at different temperatures. The results showed that after homogenization, the short rod like eutectic phase is dispersed homogeneously in Al matrix of homogenized TRC processed alloy. The EDS results show that the contents of iron and manganese elements in the eutectic phase of TRC processed alloys decrease after homogenization, with the difference that this decrease is more noticeable in the thickness of 4.5 mm after annealing. It was also found that the homogenized sheet with a thickness of 60 micrometers after a rolling step was compared to the homogenized sheet after casting, due to smaller spherical intermetallic particles and better grain structure after heat treatment, the relative elongation from 12% to 27.5% showed an increase.

1. Introduction

The twin-roll casting (TRC) is a method for the production of metallic sheets which provides some advantages such as low investment and operation costs and results in a product with finer microstructure when compared with other casting processes [1-3]. However, the high solidification rate encountered in TRC not only favors the supersaturation and metastable condition but also hinders the micro-segregation of the alloying elements. Followed by solidification, the hot rolling process would be utilized uninterruptedly which results in further grain refinement. Low production costs and a desirable microstructure are those that make the TRC process metallurgically and economically justifiable [4, 5].

AA8006 is an aluminum alloy with Fe, Mn and Si as

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alloying elements. Al-foil can be produced either by starting from a conventional direct chill (DC) cast ingot which is then hot rolled to a strip of about 2–5 mm, or from continuous casting a 6–7-mm-thick sheet (twin roll casting or belt casting) and then cold rolling it to an intermediate (foil stock) gauge of about 0.4–1 mm [6]. This alloy can be transformed into thin sheets and foils with a thickness of 10 µm. These alloys provide good formability and acceptable strength and are widely used in packing, disposable vessels, domestic foils with high strength. The alloy is most often used in O-temper mode [7, 8].

Fine and coarse precipitates may be produced in the AA8006 during the TRC process. Hence, homogenization plays a key role in the decomposition of the excess alloying elements from the solid solution [9-11]. In addition, the high solidification rate encountered in TRC not only favors the supersaturation and metastable condition but also hinders the micro-segregation of the alloying elements [12, 13]. The elements that are present are an important factor that influence recrystallization and texture development, and consequently, alloy properties. Iron, manganese, and silicon may be present in second-phase particles or dissolved in the matrix. Coarse intermetallic particles usually act as nucleation sites during recrystallization, giving a random or retained rolling texture. Fine particles inhibit grain growth by pinning grain boundaries. Thus, depending on dispersoid density and size, recrystallization can be accelerated or retarded. Alloying elements in a solid solution also affect the structure and properties. Solid solution element content and dispersoid distribution can be changed by heat treatment [14, 15].

A comprehensive understanding of how the microstructure and processing parameters relate to each other is essential for effectively controlling the properties of the final material [16, 17]. In the case of relatively clean aluminum foil alloys, the microchemistry of the material, specifically the state of alloying elements like Fe and Si, as well as other impurities, significantly impacts both the processing and properties of the foil at its final thickness. Due to the low solubility of Fe in aluminum, commercial aluminum alloys will typically contain large phases with high Fe content. The type, volume, size, and morphology of these constituent particles have notable effects on ductility and formability. Prior to hot rolling, pre-heating or homogenization annealing processes can influence both the processing and final properties of the foil by promoting the formation of small secondary intermetallic phases known as "dispersoids". It is crucial to maintain low solute levels during hot deformation, as excessive solid solution hardening can limit its strengthening effect. In dilute aluminum foil alloys, dispersion hardening becomes the primary strengthening mechanism, with some contribution from solutes. Therefore, the volume fraction and size distribution of the dispersoids play a significant role in dispersion strengthening [18, 19]. Higher hardness levels, often resulting from needle-shaped particles, can lead to reduced formability and fatigue resistance. Grain size, on the other hand, has a relatively minor impact on strength but greatly affects ductility, with finer grain sizes generally associated with higher ductility. It should be noted that alloys based on commercially pure aluminum will inevitably contain phases with high Fe content. Alloys with low Si content tend to have substantial amounts of the Al3Fe (or Al13Fe4) phase, which negatively affects the formability of aluminum foil alloys by forming needle-like particles [20].

In this research, microstructure and tensile properties of AA8006 were investigated after TRC. The effect of homogenization treatment of an 8 mm thick sheet of alloy was investigated. The homogenization treatment was also applied to the sheets after one pass of rolling to reduce the thickness to 4.5 mm. The aim of the homogenization treatment was the eutectic phase of TRC processed alloy becomes much finer as the microstructure of as-cast TRC processed alloy is refined. Therefore, the evolution of the grain structure and particle distribution were investigated. After the rolling and homogenization treatment, the sheets were rolled to produce foils with 60 µm thickness. In most of the previous research, as mentioned in the introduction, AA 8006 is homogenized after the twin-roll casting process.

In addition to examining this process, which is referred to as TRC+ Hom in this research, Heat treatment was done after a rolling step with a thickness of 4.5 mm. This process change improves the elongation increase from 12% to 27.5%.

2. Experimental Procedure

In the present research, sheets of AA8006 aluminum alloy with the chemical composition shown in Table 1 were produced using TRC. According to Table 2, TRC-sheets were produced to achieve sheets with 8 mm thickness and width of 1360 mm.

Table 1. Composition of the alloy used in this investigation

Element	Al	Si	Fe	Cu	Mn	Zn	Ti	Cr
Wt.%	Bal.	0.25	1.5	0.1	0.5	0.007	0.02	0.001

Table 2. Specifications of TRC process

Liquidus temperature (K)	Solidus temperature (K)	Degassing speed (rpm)	Sheet speed (m/min)	Water temperature of the rollers (K)	Roll diameter (mm)
923	903	300	0.8	316	950

The produced sheets with 8 mm thickness were rolled to the thickness of 60 µm through two different procedures according to Fig. 1. In the first procedure, briefly named TRC+Hom, the TRC-produced sheets were first homogenized and then rolled to 60 µm in 9 passes according to Table 3. In the second procedure, which is briefly named TRC+43%Red+Anneal, the sheets were initially rolled to have a 43% thickness reduction, then annealed and eventually rolled down to 60 µm in 8 passes.

To determine the appropriate homogenization temperature, differential scanning calorimetry (DSC) was used. DSC was conducted at a heating rate of 10 °C/min using a TA-2 machine. Based on the achieved DSC results, the sheets of TRC+Hom procedure were homogenized at 540˚ C for 8 h prior to being rolled. Then, the rolling process was continued to 60 µm in 9 passes.

In TRC+43%Red+Anneal procedure, the sheets were rolled to 43% thickness reduction without homogenization and reached 4.5 mm thickness.

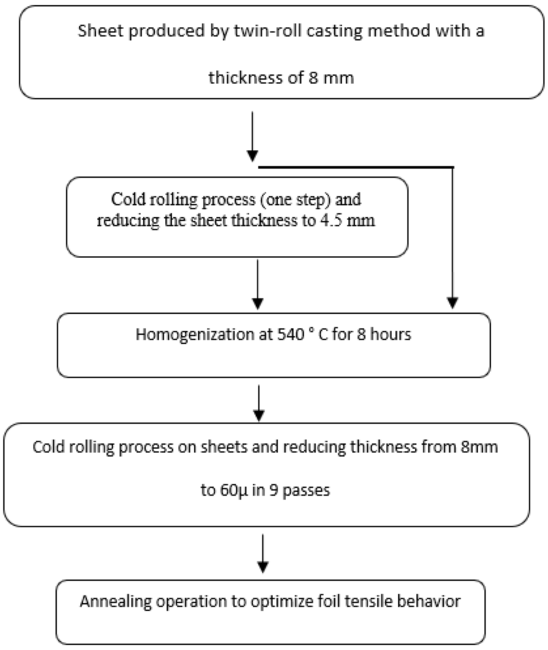


Fig. 1. Experimental procedures.

Followed by rolling, the sheets were annealed at 540 °C for 8 min. Finally, the rolling process continued up to 60 µm in 8 passes.

Samples were prepared with conventional metallographic techniques They were examined after etching with 0.5% HF solution with an optical microscope. The grain structure of strip samples was investigated after undergoing anodic oxidation with Barker's solution. The microstructure of the sheets were evaluated after each processing step using optical microscopy (HUVITZ model:HM-TV0.5xC) and scanning electron microscopy (Tescan Model vega/xmu, Chez Republic). The particles were analyzed using EDS spectrophotometer. To obtain the optimal tensile behavior, which is defined in terms of maximum fracture elongation at the final 60 µm thickness of the foil, the samples were annealed at 250-400 ℃ for 180 minutes and then their tensile properties were assessed by a tensile apparatus (SANTAM, SAF50). Tensile specimens were prepared according to an ASTM E8 standard and tensile testing of all samples was performed at a speed of 1 mm/min at room temperature. Tensile tests were performed three times in each thickness and its average value was measured and recorded.

Table 3. Factors affecting the rolled sheet or foil in the cold rolling process

Machine parameters	**Rewind tension (kg/mm^2)**	**Pay off tension (kg/mm^2)**	**Sheet speed (m/min)**	**Roller roughness (µm)**	**Roller crown (mm)**
Sheet roll	2-4	0.4-3	100-500	45	0.08
Foil roll	2.7-3.5	4-5	500-800	9	0.1

3. Results and Discussion

Before the homogenization, the temperature of homogenization was determined by the DSC test, the curve of which is shown in Fig. 2. The result shows that there is no significant change in the heat flow if the temperature is below 540 °C. In the first phase (<540 °C), the phase transformations are produced without a supply of energy, such as spinodal decomposition. At temperatures above 540 °C, the changes in the DSC curve can be ascribed to the nucleation of a new phase [21].

To compare the structure of the aluminum alloy 8006 prepared through TRC+Hom and TRC+43%Red+ Anneal before the annealing process, the microstructure of the samples with the thicknesses of 8 and 4.5 mm (before and after heat treatment) were imaged as depicted in Figs. 3 and 4. The grains were stretched in the TRC samples which can be due to the plastic deformation during the TRC process. As can be seen, recrystallization started in TRC+Hom While a more complete recrystallization is observed in the TRC+43% Red+Anneal sample due to the higher energy stored due to deformation and the number of grain boundaries. For this reason, as can be seen in Table 4, the average value of grain size in the TRC+43% Red+Anneal sample is smaller after heat treatment.

Table 4. Mean grain size of aluminum 8006 alloys under TRC+Hom and TRC+43%Red+Anneal

Sample	Process	Grain size (µm)
Before homogenization	TRC + Hom	50
After homogenization		70
Before anneal	TRC+43% Red+ Anneal	37
After anneal		54

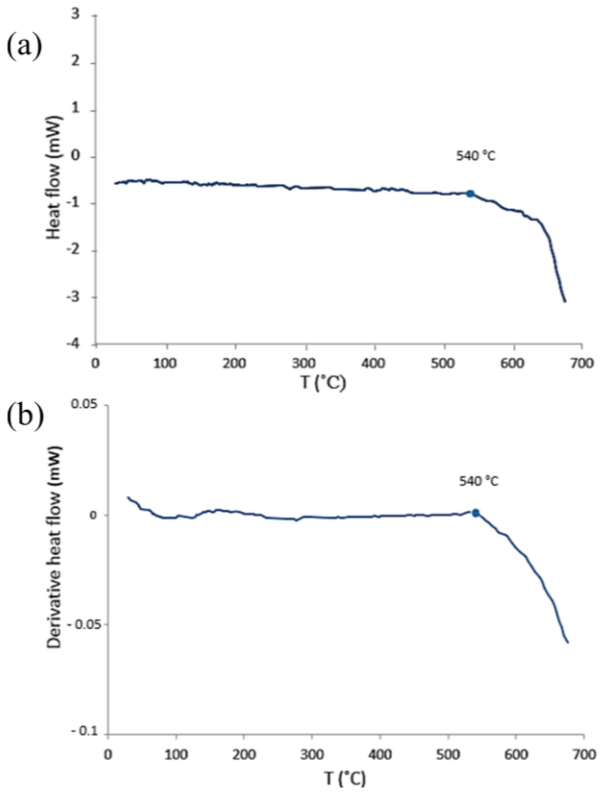


Fig. 2. Dynamic analysis on DSC with phase transformation of A8006 alloy.

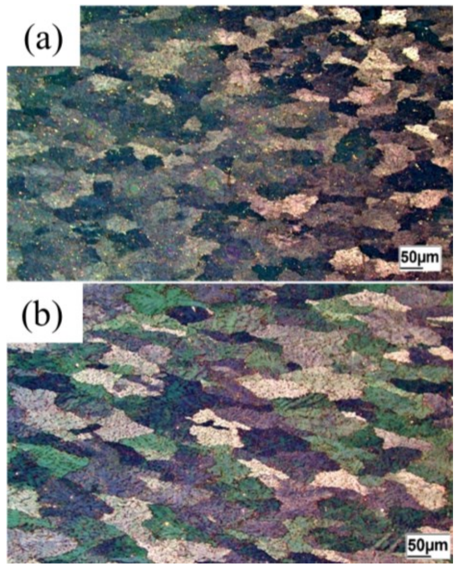


Fig. 3. Microstructure of aluminum 8006 alloy produced under TRC+Hom (a) prior to and (b) after homogenization.

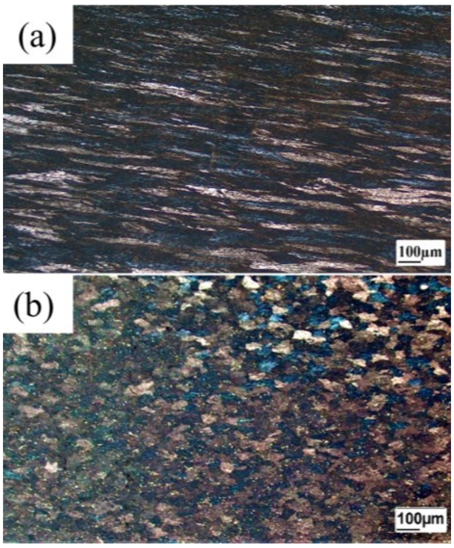


Fig. 4. Microstructure of aluminum 8006 alloys under TRC+43%Red+Anneal (a) before and (b) after annealing.

After applying the mentioned procedures, Figs. 5 and 6 depict the eutectic phase distribution of these alloys. As can be seen, for both processes, the eutectic phases got finer and smaller after the heat treatment. Moreover, in the samples with a thickness of 4.5 mm, the eutectic structure was stretched by the rolling procedure and even fractured in some points as compared with the one with a thickness of 8 mm.

Figs. 7 and 8 show the SEM image of the samples undergone TRC+Hom and TRC+43%Red+Anneal processes before and after homogenization and annealing, respectively. Fig. 7 is related to the TRC+Hom sample with a thickness of 8 mm. the EDS results indicate a decline in Fe and Mn contents in the eutectic structure after the homogenization. The table in Fig. 7 lists the weight percentage of this analysis before and after homogenization.

Fig. 8 depicts the SEM image of TRC+43%Red+ Anneal sample with a thickness of 4.5 mm. The microstructure of a significant percentage of the eutectic phases turned into spherical after annealing which can be due to the crushing of the eutectic phases during the rolling process. Regarding the increase in the hysteresis energy and more interface of the eutectic phase with the matrix, the diffusion was enhanced and the microstructure turned into a spherical shape. EDS results of this sample can be found in the table of Fig. 8.

The stress-strain curve of the samples is presented in Fig. 9 before and after homogenization and annealing processes for TRC+Hom and TRC+43%Red+Anneal samples, respectively. As can be observed, the tensile strength of the samples significantly decreased during the mentioned processes and the relative elongation showed a 3 and 40% increase. According to microstructural comparison before and after heat treatment, grain growth and recrystallization occurred in the samples with a thickness of 8 and 4.5 mm, respectively. Thus, the decline in the strength can be attributed to the recovery, recrystallization, and fading of the work hardening effects due to the deformation in the

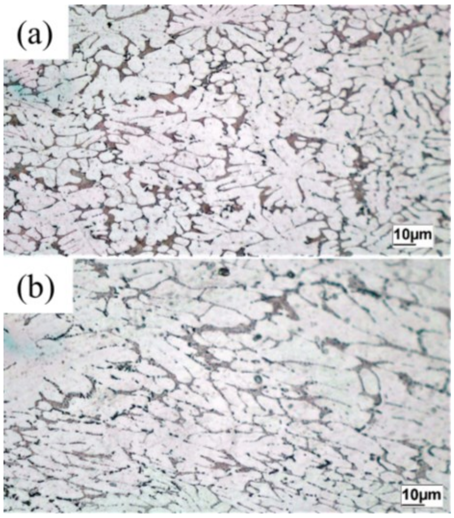


Fig. 5. Eutectic phase distribution in aluminum 80064 alloy under TRC+Hom process (a) before and (b) after homogenization.

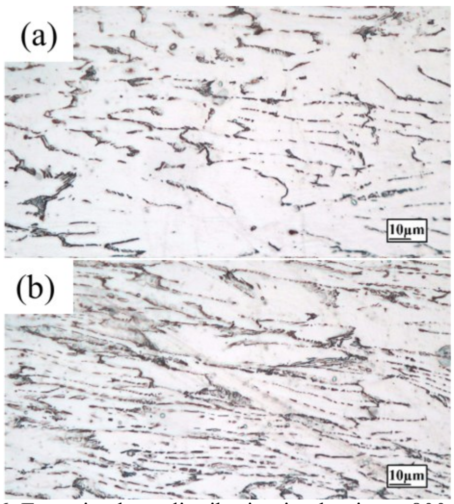
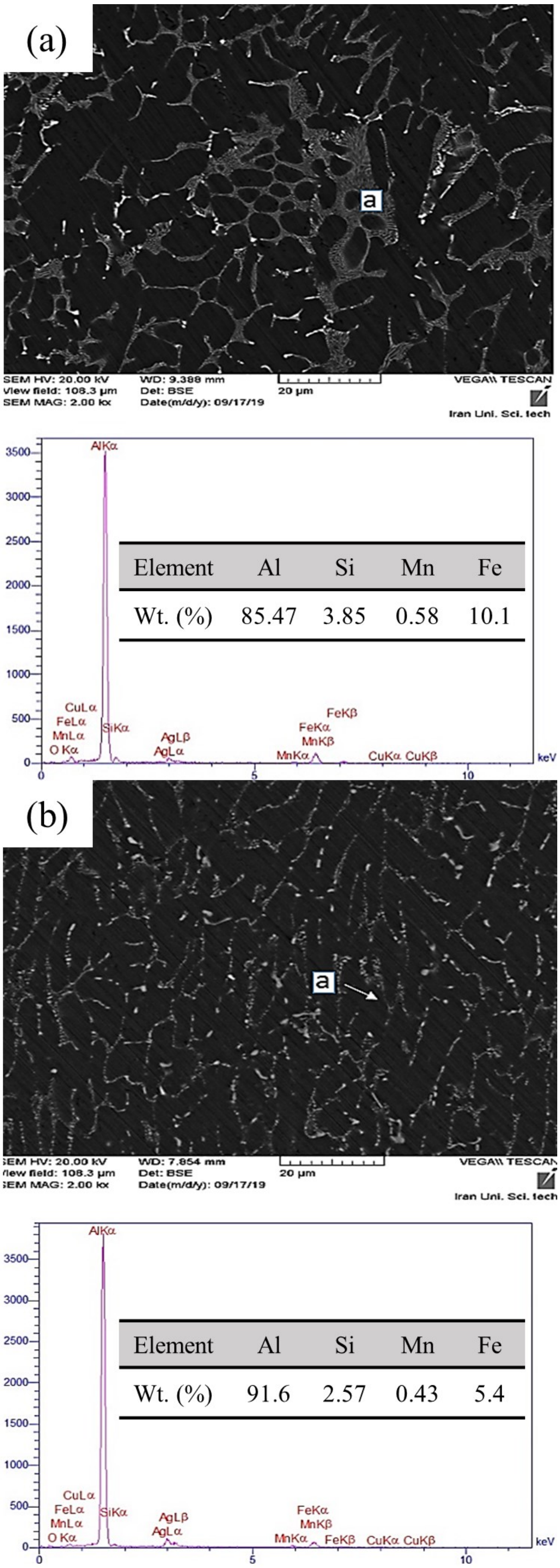


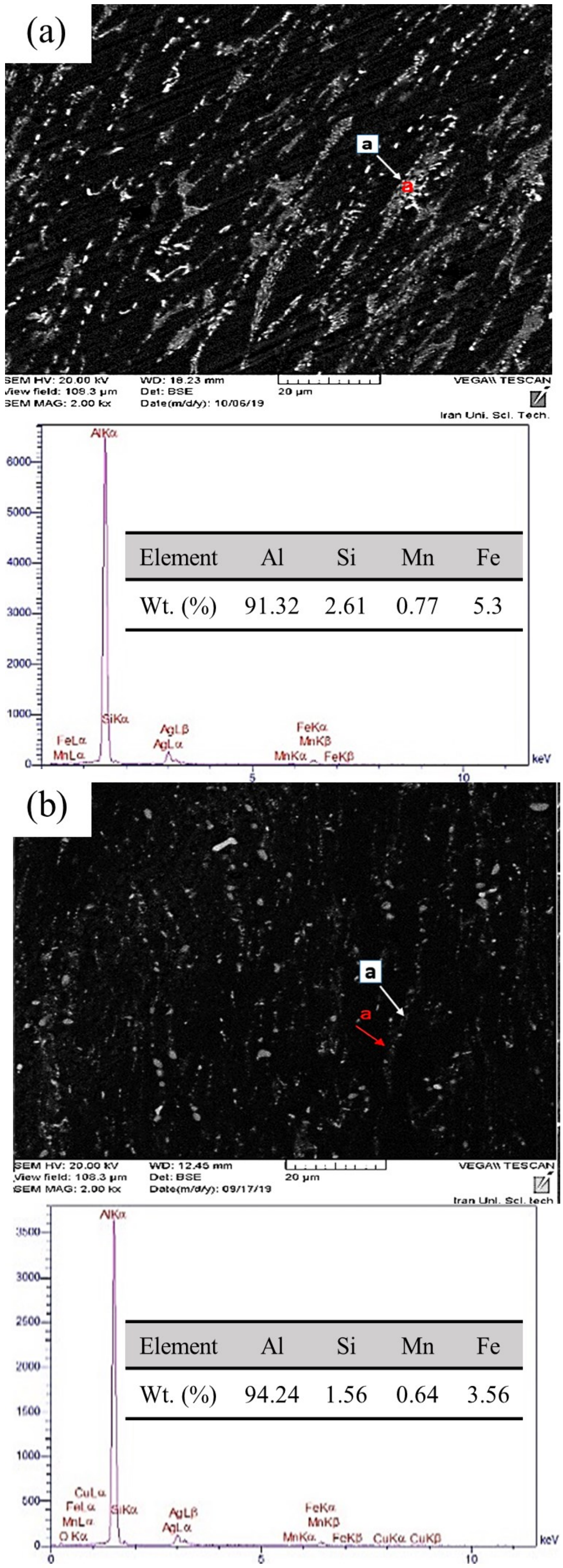
Fig. 6. Eutectic phase distribution in aluminum 8004 alloy under TRC+ 43%Red+Anneal process (a) before and (b) after annealing.



Element	Al	Si	Mn	Fe
Wt. (%)	85.47	3.85	0.58	10.1

Element	Al	Si	Mn	Fe
Wt. (%)	91.6	2.57	0.43	5.4

Fig. 7. SEM image and EDS analysis of the samples with the thickness of 8 mm (a) before and (b) after the homogenization.



Element	Al	Si	Mn	Fe
Wt. (%)	91.32	2.61	0.77	5.3

Element	Al	Si	Mn	Fe
Wt. (%)	94.24	1.56	0.64	3.56

Fig. 8. SEM image and EDS analysis of the samples with the thickness of 4.5 mm (a) before and (b) after annealing.

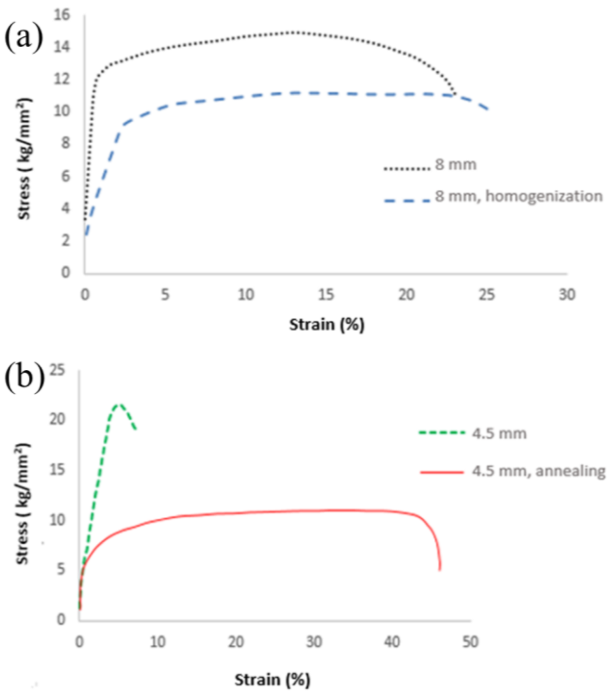


Fig. 9. Strength vs elongation before and after heat treatment for (a) TRC+Hom and (b) TRC+43%Red+Anneal samples.

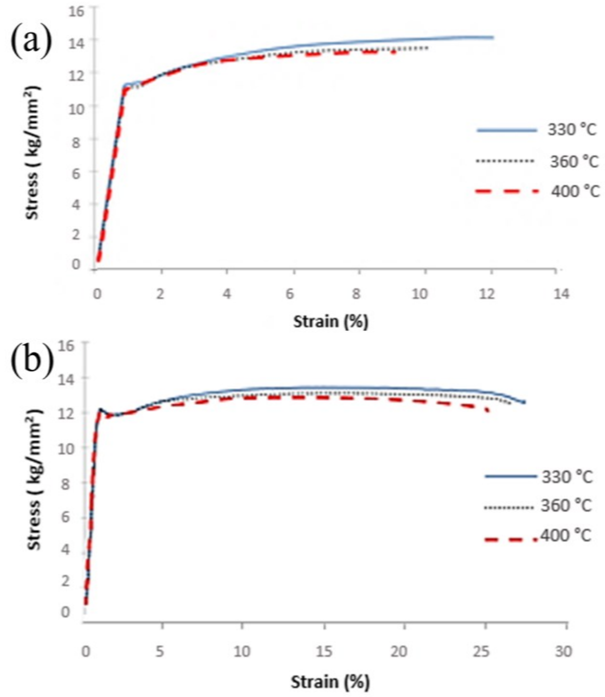


Fig. 10. Stress-strain curve of 60-μm foils at three different temperatures.

sheets. After heat treatment through both processes, the particles changed into separate spherical particles; the only difference was the higher number of spherical particles in the sample with a thickness of 4.5 mm. Therefore, the relative elongation can be attributed to the morphological changes. Overall, the sample with a thickness of 4.5 mm showed better tensile properties after heat treatment which might be attributed to its higher number of spherical particles and small grain size of the samples due to recrystallization.

After heat treatment, the thickness of the samples declined to 60 μm by 9 passes of rolling. To optimize the tensile properties, the samples were annealed at 250-400 °C. Regarding the higher elongation of the foils in the mentioned temperatures compared to 250 and 300 °C, their stress-strain curves are depicted in Fig. 10. In both mentioned processes, the tensile strength decreased by 43 and 42% compared to the non-annealed sample at the optimal temperature; while the elongation showed a 12 and 27.5%, respectively. As can be seen, the elongation showed a significant increase in TRC+43%Red+Anneal samples.

According to Fig. 11, the particles were more uniformly distributed in the 60-μm TRC+43% Red+Anneal

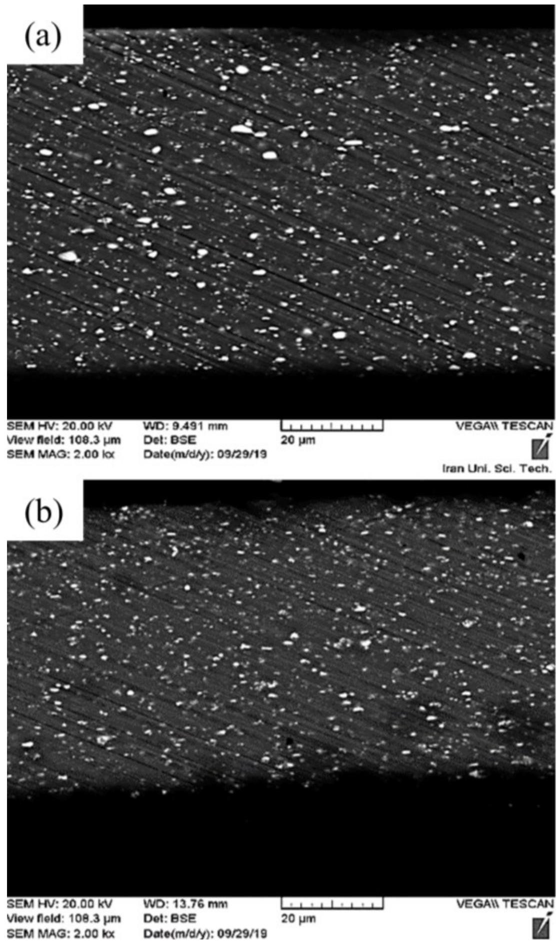


Fig. 11. Final microstructure of the rolled samples (a) TRC+Hom and (b) TRC+43%Red+Anneal.

samples. Fig. 12 shows the size distribution of the intermetallic compounds in both processes. The frequency of the particles ranging from 0-0.5 µm was higher in the samples processed by the TRC+43% Red+Anneal method. In the TRC+Hom process, the percentage of the particles larger than 2 µm was higher. In some regions, the placement of the larger particles and the concentration of stress can result in foil failure. Therefore, the relative elongation is related to the morphological changes of the particles as well as grain size. That's why the 60-µm samples in the mentioned process exhibited 66% higher elongation as compared with those treated by TRC+Hom. As suggested by Fig. 12, the intermetallic particles larger than 1.5 µm was about 8% in the TRC+Hom process which can result in stress concentration and foil failure [22].

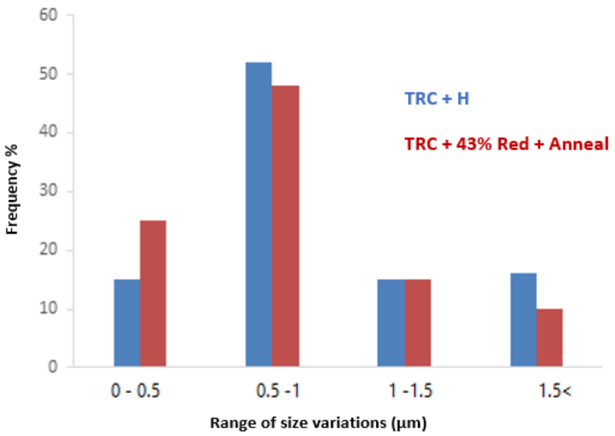


Fig. 12. Distribution of the intermetallic particles in both process (thickness: 60µm).

4. Conclusion

- Heat treatment (homogenization and annealing) can significantly affect the microstructure of alloy 8006. The heat treatment can result in smaller eutectic phase particles in the microstructure. These phases are the source of dynamic diffusion occurring during the heat treatment which produces small and dispersed precipitates at high temperatures.
- In alloy 8006, the size of intermetallic particles in the foils with a thickness of 60 µm ranged from 0 to 5 µm. In the TRC+43%Red+Anneal process, the intermetallic compounds were smaller with a more uniform distribution, which can be assigned to the higher population of spherical particles during the annealing process that got finer and more uniform after being rolled into a 60-µm thickness. In some regions, the placement of larger particles or the stress concentration caused a failure in the foil.
- The foils were annealed at 250-400 °C at the final thickness of 60 µm to achieve higher elongation. At 330 °C, the relative elongation increased by 50 and 81% in the samples treated by TRC+Hom and TRC+43%Red+Anneal, respectively (compared to the pre-annealing stage). The relative elongation was higher in TRC+43%Red+Anneal samples (about double) which can be assigned to the smaller grain size after annealing of 4.5-mm thickness as well as uniform and fine intermetallic particles.

Conflict of Interests

The authors have no relevant financial or non-financial interests to disclose.

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