Research Article

Electromagnetic Stirring versus ECAP: Morphological Comparison of Al-Si-Cu Alloys to Make the Microstructural Refinement for Use in SSM Processing

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This work evaluates the morphological evolution at the semisolid state of the Al-4.0wt%Si-2.5wt%Cu alloy produced by direct chill casting under electromagnetic stirring (EMS) and by one equal channel angular pressing (ECAP) pass. The ECAP emerged as a promising technique capable of reduction and homogeneous metals microstructure imposing large deformations occurs in a matrix that contains two channels of the same cross-sectional area and forms an angle of 120°. The materials were submitted to reheating treatment in condition of 60% solid fraction at treatment times of 0, 30, and 90 s. Comparing the two cases, we have the presented ECAP process that had an excellent response to the recovery and recrystallization mechanisms, and refined microstructures ideal for thixoforming were produced. Primary particle sizes of about 45 μm and grain sizes of about 75 μm and a circularity shape factor of more than 0.60 were obtained. The low silicon alloy, Al-4.0wt%Si-2.5wt%Cu, presented excellent refinement when processed via equal channel angular pressing, presenting good morphological stability at the semisolid state, without significant changes in size or shape of the solid particles. This fully globular structure is favourable for thixoforming processes.

1. Introduction

The semisolid material (SSM) processing is an alternative route to conventional metal shaping processes such as casting and forging; the advantages of SSM processing include high energy and production efficiency, low forming loads, near-net-shape capability, and reduced porosity. The automotive industry in the last decade has played a leading role in the development of new processes for manufacturing parts using semisolid materials. The use of aluminium in automobiles, primarily in the form of castings, has increased significantly due to the need to produce parts with high mechanical strength, low weight, and high reliability. The thixoforming process is nothing more than the semisolid processing of alloys in which two phases coexist: a solid and a liquid phase [1–3].

Several routes have been tested to produce these nondendritic structures [1–7]. One of the most promising routes is the raw material production via equal channel angular pressing (ECAP); the deformation ECAP occurs in a matrix containing two channels of the same cross-sectional area. Samples that pass through these channels undergo deformation by simple shear. As the cross section of the sample remains approximately constant, the process can be repeated many times allowing for controlling the microstructure and thus the final properties of the materials [8, 9]. It is known that Al-Si-Cu alloy content of low silicon does not have a fine structure by ECAP process [10], but alloys with the same content and greater than 5wt%Si have large refinement of the microstructure, with grain sizes/primary globules much lower when compared with the electromagnetic stirring [11].

Aluminium alloys used for processing in semisolid state are notably foundry alloys A356 and A357 [12]; thus, the development of new alloys especially designed for use in thixoforming is the new challenge in this area of research. Therefore, this paper aims to evaluate the morphological
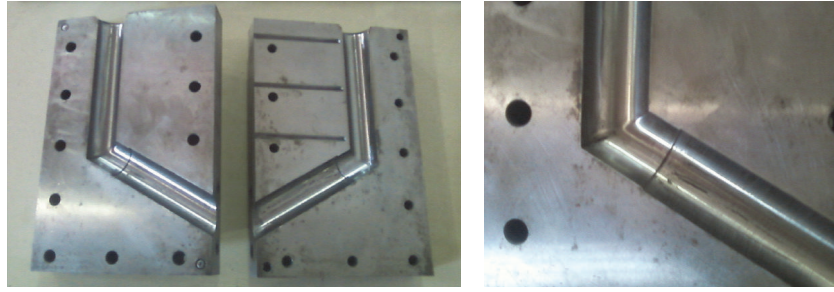
FIGURE 1: Details of the used ECAP die.

TABLE 1: Mass distribution for the preparation of alloy [in kg].

Alloy	A356	Al-cp	Cu-cp	Grain refining
Al-4.0wt%Si-2.5wt%Cu	2.7	2.0	0.1	0.2

evolution at the semisolid state of the Al-4.0wt%Si-2.5wt%Cu alloy produced by direct chill casting under electromagnetic stirring (EMS) and by one equal channel angular pressing (ECAP) pass in terms of microstructural characterization for different conditions of heat treatment by using microscopy, using conventional metallography (black and white), and using polarized metallography (colour) to determine the refinement of the microstructure of alloy Al-Si-Cu.

2. Experimental Procedure

For the preparation of 5 kg of the alloy, generating approximately 12 ingots, according to Table 1, the following mass distribution was reached. The Cu-cp content was increased by approximately 10% than expected due to the difficulty of copper dissolution into the molten bath.

Table 2 describes the chemical composition of the Al-4.0wt%Si-2.5wt%Cu alloy produced by electromagnetic stirring combined with grain refinement; approximately 8 kW of power was used to produce a magnetic field of 13 gauss [3]. The chemical composition was determined via Bill OES optical emission spectrometry. The alloy was produced using A356, commercially pure aluminium (Al-cp), and commercially pure copper (Cu-cp). The A356 alloy was heated to 750°C in a SiC crucible in an electric furnace, and the commercially pure aluminium and commercially pure copper were added and mixed properly. The mixture was kept and held at 750°C for about 10 min and stirred periodically to ensure that it dissolved and homogenized, and finally grain refining Al-5.0wt%Ti-1.0wt%B was added in order to obtain a nondendritic structure [3, 9]. Then, each molten alloy was poured at a temperature about 50°C above its expected melting temperature into a copper refrigerated mould to produce ingots 250 mm in length and 30 mm in diameter; due to errors inherent in processes, casting, and chemical analysis, an acceptable deviation range of 0.30wt%Si and 0.15wt%Cu was adopted.

ECAP deformation was performed in a metallic mould with cylindrical channels with cross sections of 30 mm and 120° outer angle; Figure 1 shows the details of the used ECAP die. A 50-ton hydraulic press operating at maximum speed of approximately 7 mm/s was used to impose a single ECAP pass in ingots lubricated with MoS_2 [10]. Before the ECAP process, the ingots 30 mm in diameter and 150 mm long were heated to 300°C sufficient to prevent surface cracks but also to allow better passage thereof through the ECAP die. According to previous studies, the die must be heated to 100°C, so that it is avoided that adiabatic heat generated during the extrusion, along the preheating temperature of the ingot, does not reach the material recrystallization temperature.

Heat treatment globularization aims to verify the stability of alloy at high temperatures in order to evaluate the microstructural evolution and correlate these characteristics with the mechanical and rheological properties of these materials. The treatments were carried out in approximately 6 min (25 mm tall × 30 mm diameter samples) in a Norax induction furnace (25 kW, 8 kHz) with a heating rate of 80°C to 100°C/min [3, 10]. When the samples reached the temperatures of the 60% solid fraction, they were held at those temperatures for 0, 30, and 90 s, after which they were cooled in water. The samples produced were characterized by optical microscopy to morphologically evaluate the semisolid state. All the samples were subjected to conventional metallographic (black and white) and polarized metallography (colour) to evaluate their structures. For microstructural characterization by conventional metallographic, the samples were abraded with sandpaper in a particle size of 220, 320, 400, 600, 800, 1200, and 1500 and polished with diamond paste 1 μm; after polishing, the samples were etched with hydrofluoric acid (HF 1 mL and 99 mL H_2O); the attack was performed with total immersion of the sample in the reagent for a period of 10 s. For the microstructure characterization via colour metallography, the same samples used in the B&W characterization were etched using an electrolytic solution of 2% HBF4 under 25 V for 6 minutes. For image acquisition, we used a Leica DM ILM optical microscope. Polarizing filters were used to obtain colour images of the samples grains, causing grains with the same crystal orientation to exhibit similar colour, facilitating their identification and characterization. For measuring globule size (GLS) in conventional metallography and grain size (GS) in colour metallography, the Heyn intercept method was used as recommended by the

TABLE 2: Chemical composition of the Al-4.0wt%Si-2.5wt%Cu alloy [in wt%], obtained by optical emission spectrometry.

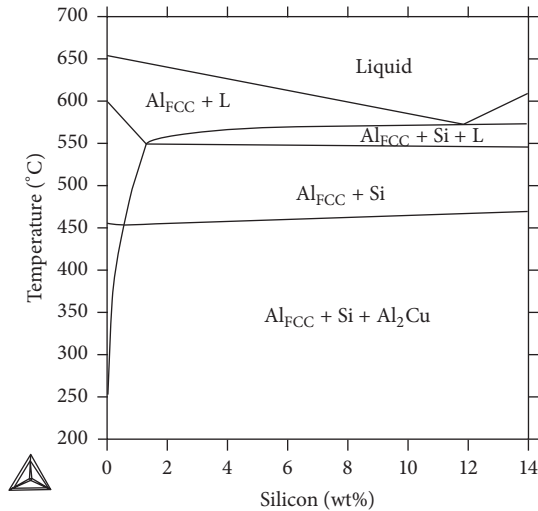| Alloy	Si	Cu	Mg	Ti	Fe	B	Mn	Al
Al-4.0wt%Si-2.5wt%Cu	3.84	2.54	0.18	0.15	0.14	0.002	0.01	Bal.

FIGURE 2: Expected phase diagram for the Al-4.0wt%Si-2.5wt%Cu alloy.

ASTM E112 (1996) standard. For the circularity, shape factor (SF) of each sample was used for conventional photographs, ImageJ 1.40 g software, and the value varies from 0 (for acicular particles) to 1 (a perfectly round sphere). B&W metallography was used to measure the globule size (GLS) and shape factor (SF) and colour metallography is used to determine the grain size (GS). The Rheocast Quality Index (RQI = (GLS∗SF)/GS) gives the relationship of those features where a perfect structure in which a grain is a perfect globule leads to a RQI = 1.

As described in previous paper [14], this work also used Thermo-Calc® simulation; the percentages of copper, magnesium, iron, and titanium were taken into account, but residual elements, such as manganese, chromium, nickel, and zinc, were not. Thermo-Calc predicts solidus temperature of 525°C, liquidus temperature of 627°C, and, for expected 60% solid fraction, processing temperature of 584°C. Based on the chemical composition of the alloy obtained by optical emission spectrometry, the expected phase diagram was drawn using the Thermo-Calc software. Figure 2 shows the expected phase diagram taking into account the amount of copper for the 2.5wt%Cu. Because of the instability of the eutectic melting (characterized by the competitive growth), the semisolid processing should be done between the solidus temperatures and temperature liquidus. It was realized that, to have the thixoforming process of these hypoeutectic alloys correctly applied, it is necessary to achieve a temperature where Al_{FCC} coexists with the liquid rich-silicon; nevertheless, the semisolid behaviour will depend on the remaining solid's morphology and shape.

3. Results and Discussion

Figure 3 shows the conventional metallographic of the original microstructure of the Al-4.0wt%Si-2.5wt%Cu alloy produced by EMS and the corresponding microstructure after one ECAP pass for all performed experiments. The original structures rapidly evolve from rosette shape (EMS) or elongated rosettes (ECAP); it is possible to observe that the globule size is severely deformed and the small dendritic branches evolved into a deformed and elongate rosette shape. Figures 4 and 5 show the microstructure (conventional and colour metallography) of the material reheated at temperature of 60% of solid fraction for times of 0, 30, and 90 s produced by ECAP, since the alloy produced by electromagnetic stirring has been the subject of studies [3]. Note that the reheating treatment of the ECAPed sample at only 0 s was enough to produce a fully globular structure, and the maintenance at this temperature during long periods of time (90 s) does not change the structure significantly (i.e., the structure is stable at semisolid range). Note the maintenance of the primary globule/grain size during reheating to the semisolid material range in the treatment time of 0 s to 90 s. Therefore, the use of ECAP process is suitable for obtaining raw material for thixoforming, since it produces small and fully globular grains.

When the raw material is deformed during the ECAP process, the grains are strained and hardened and strain energy is stored. During the reheating in the semisolid state, energy is released during recovery and recrystallization. As recrystallization involves the nucleation and growth of an entirely new arrangement of crystals, they already have a globular morphology. The heating for recrystallization at temperature lower than solidus temperature achieves, in fact, lower grain size, but the heating up to the semisolid state introduces new mechanisms as coarsening that leads to a bigger grain size, but this new grain is, still, smaller than that produced by EMS [9]. Therefore, the use of the ECAP process is suitable for obtaining raw material for thixoforming, since it produces globular grains. According to Proni et al. [11], using the Al-2.0wt%Si-2.5wt%Cu alloy (low silicon), the values of primary globule/grain size are almost identical for both the procedures tested, EMS and ECAP (i.e., there is no significant improvement using the ECAP process for low silicon alloys, but it is highly recommended for high silicon due to the poor effect of the EMS refinement in terms of grain size and its shape); this is due to the fact that in the aluminium-silicon alloys with low silicon content the effect of stirring is enough to produce the desired globular structure, but with higher silicon content, the results diverge [13]. It is possible to conclude that the use of ECAP is recommended only for high silicon alloys, (> 4wt%Si).

TABLE 3: Microstructural characterization of the Al-4.0wt%Si-2.5wt%Cu alloy.

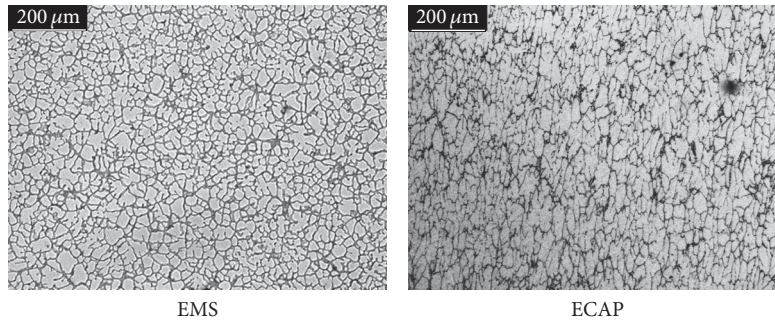|	Treatment time [s]	Globule size [μm]	Circularity	Grain size [μm]	RQI
As, cast		35 ± 3	0.43 ± 0.19	75 ± 11	0.20 ± 0.07
EMS	0	49 ± 4	0.52 ± 0.17	109 ± 30	0.24 ± 0.08
	30	58 ± 4	0.52 ± 0.17	100 ± 24	0.30 ± 0.08
	90	62 ± 6	0.54 ± 0.17	110 ± 26	0.31 ± 0.10
ECAP	0	38 ± 3	0.62 ± 0.15	71 ± 12	0.33 ± 0.08
	30	44 ± 3	0.65 ± 0.14	72 ± 13	0.40 ± 0.09
	90	47 ± 4	0.66 ± 0.15	75 ± 10	0.41 ± 0.09

FIGURE 3: Conventional B&W metallography of the as cast Al-4.0wt%Si-2.5wt%Cu produced by EMS and after one ECAP pass.
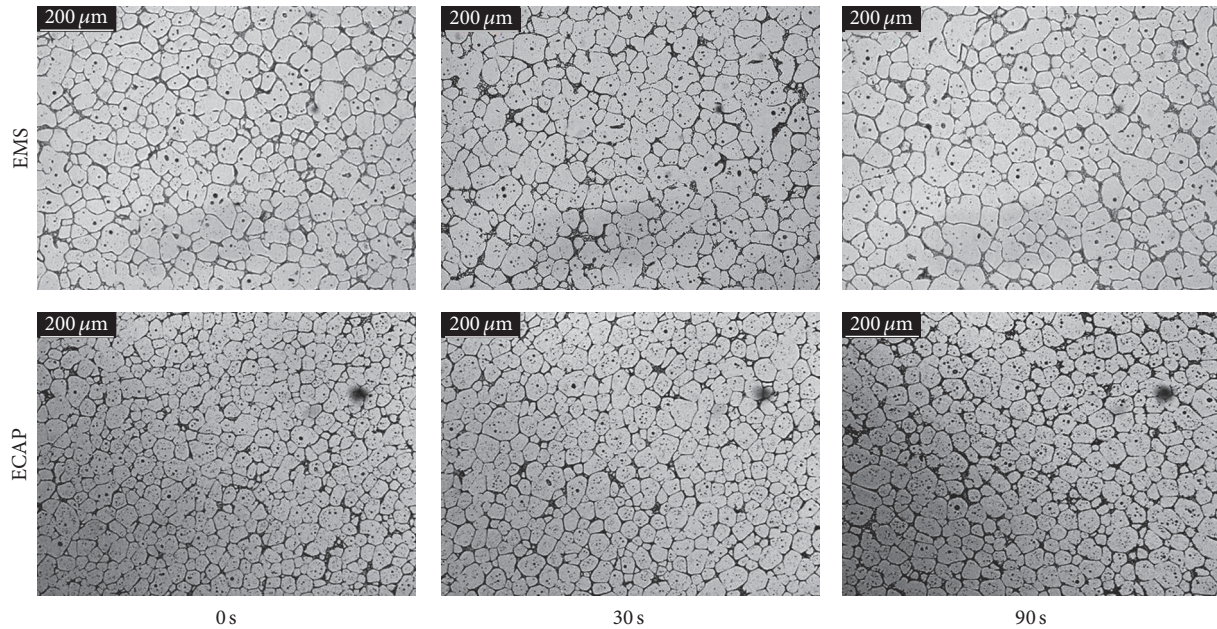

FIGURE 4: Conventional B&W metallography of the EMS and ECAP samples heat treated at 584°C in which is expected to be 60% of solid fraction during 0, 30, and 90 s holding time, showing the morphology of the globules.

Table 3 shows a summary of the microstructural characterization in all tested conditions. The largest reduction in grain size (colour metallography) occurs with 60% solid fraction, where there was a reduction of approximately 40 μm. It is important to notice that the high solid fraction used in this paper facilitates the coalescence phenomena due to the contact amongst solid particles. And even with

these phenomena, the material produced by electromagnetic stirring followed by the ECAP process can rearrange and distribute better during heating to the semisolid state.

The quantitative data presented in Figure 6 highlights the microstructural changes caused by reheating treatment in the condition of 60% solid fraction, at treatment times of 0, 30, and 90 s, indicating the changes in globule size (Figure 6(a)),
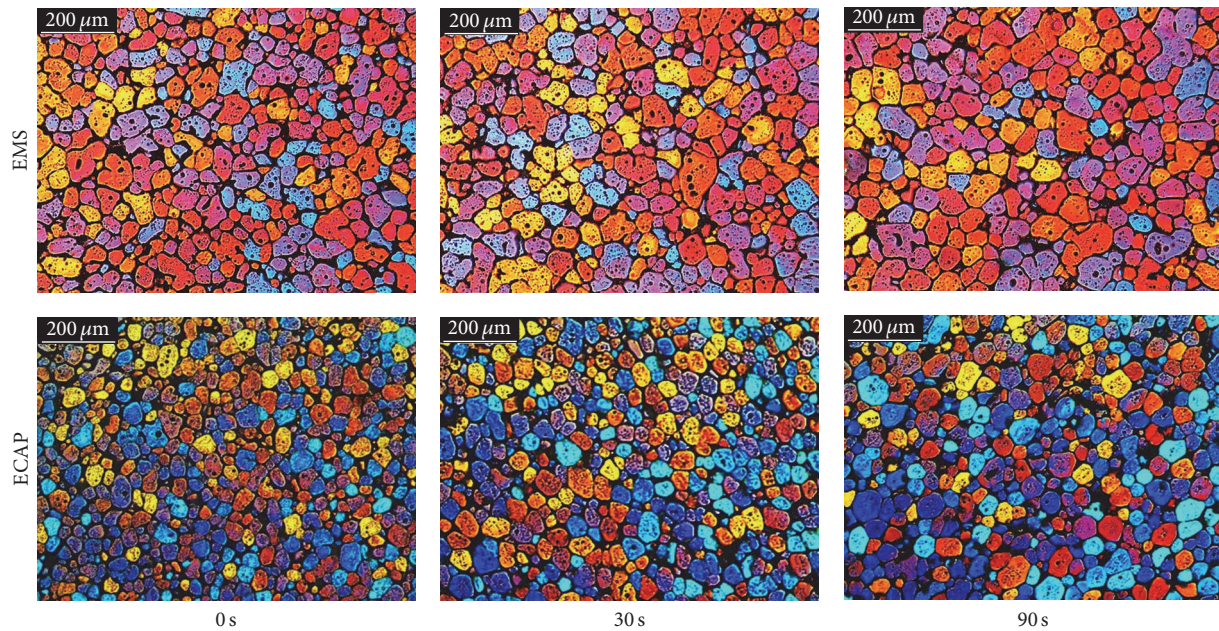
FIGURE 5: Polarized colour metallography of the EMS and ECAP samples heat treated at 584°C in which is expected to be 60% of solid fraction during 0, 30, and 90 s holding time, showing the morphology of the grain.

grain size (Figure 6(b)), circularity shape factor (Figure 6(c)), and the Rheocast Quality Index (Figure 6(d)) for the two processing routes tested.

As mentioned earlier, the samples produced by EMS showed increased globule size and grain size which was described in a previous paper [3]. The samples produced by ECAP samples showed significantly diminishing grain sizes. The recrystallization process, which precedes the semisolid stage in the ECAP route, caused small new grains to nucleate within the structure, facilitating their detachment during partial melting, resulting in very fine grains and homogeneous grains after solidification. The value of the shape factor (SF) indicates the globular structure. In general, it can be noted in Figure 6(c) that the Al-4.0wt%Si-2.5wt%Cu alloy microstructure is globular with values above 0.60. Figure 6(d) shows the evolution of the Rheocast Quality Index in the samples after reheating treatment to the semisolid state. The RQI can be helpful in indicating good or poor rheological behaviour in terms of the microstructural features, because dividing the globule size by x grain size, you have the rate for which it is expected that the value found is the closest to "1," because in these conditions the grain size would be equal to globule size, a fact that would imply a less complex structure. The graphs in Figure 6 show that this varies little with heating procedure; for example, the results show that there were no significant differences in these parameters after the specimens were heated up to the semisolid state to achieve a solid fraction 60%, indicating that the microstructure is highly stable, a characteristic that is in fact essential to ensure the thixoforming process can be controlled. Thus, among all the samples, the best combination of GS, GLS, and SF was achieved by the ECAP samples.

4. Conclusions

ECAP process is a promising route for production of semisolid raw material for thixoforming. Structure of the Al-4.0wt%Si-2.5wt%Cu alloy presented excellent response to the recovery and recrystallization mechanisms that lead to a refined microstructure ideal for thixoforming. Small globule sizes of about 45 μm and small grain sizes of about 75 μm and circularity shape factor higher than 0.60 were obtained. The alloy presented good morphological stability at the semisolid state without presenting significant changes in size and shape that should lead to homogeneous apparent viscosity and consequently homogeneous die filling. Comparing the two processing routes tested, the ECAP process yielded the most suitable thixotropic raw material, presenting the best results.

Additional Points

Highlights. The paper introduces new Al-Si-Cu alloys for thixoforming and morphological comparison of Al-Si-Cu alloys by electromagnetic stirring and ECAP.

Competing Interests

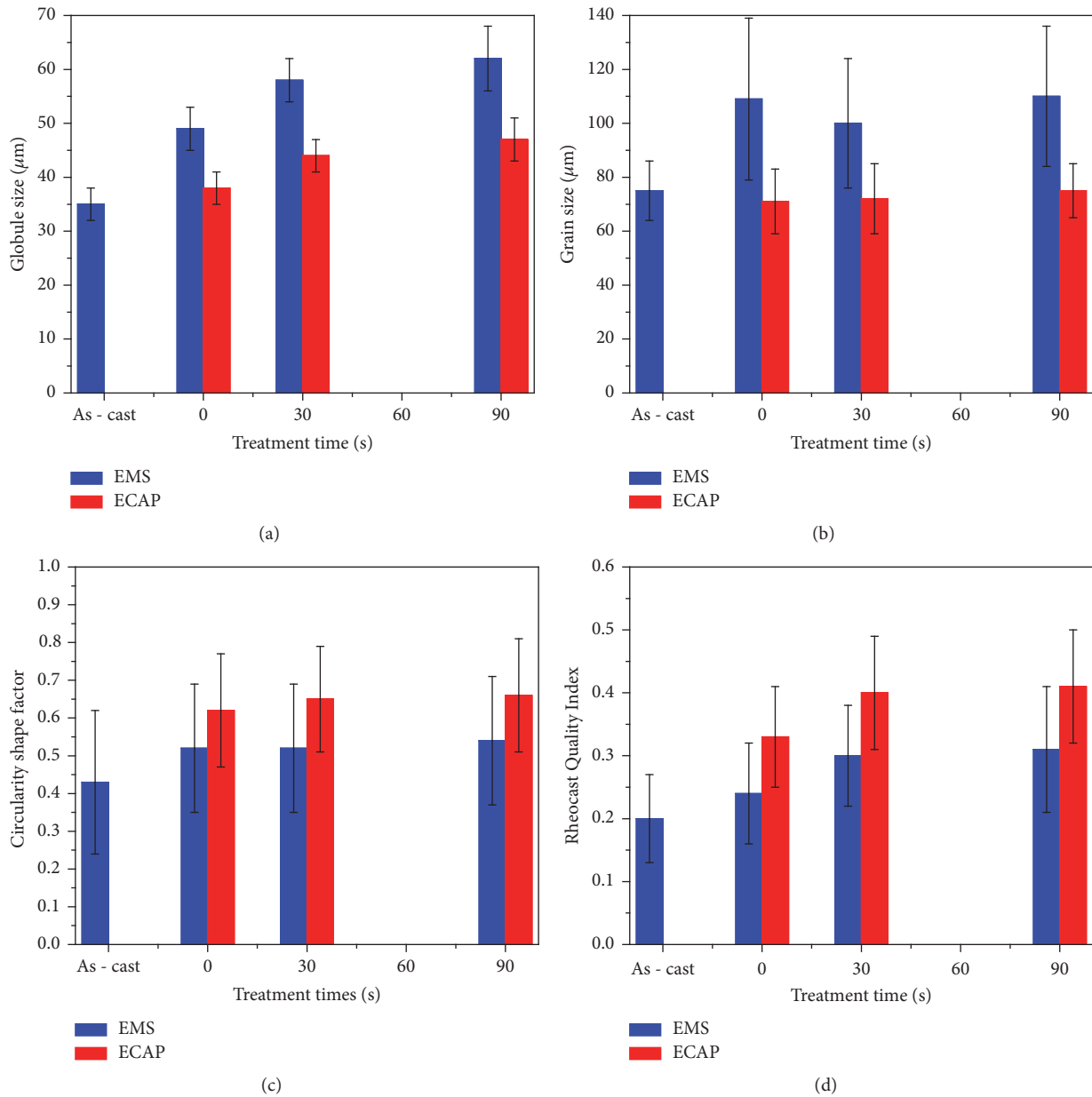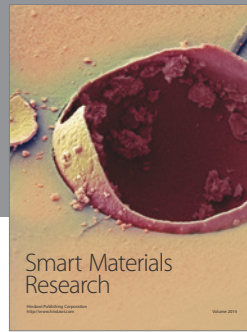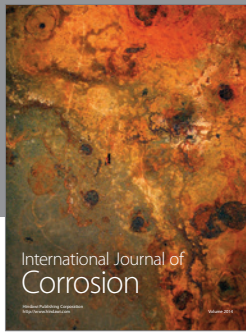The authors declare that they have no competing interests.

Acknowledgments

FIGURE 6: Globule size, grain size, circularity shape factor, and RQI of the Al-4.0wt%Si-2.5wt%Cu samples alloy heat-treated (584°C) at 60% of solid fraction in 0, 30, and 90 s.

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