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Effect of the deformation path on the ductility of a hypoeutectic Al–Si casting alloy subjected to equal-channel angular pressing by routes A, B_A, B_C and C

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An Al–7%Si casting alloy has been subjected to equal-channel angular pressing up to eight passes by routes A, B_A, B_C and C. Microstructural and mechanical characterization by tensile testing was performed. No significant differences in tensile strength were found between the processed samples. However, there are strong differences in ductility, which are attributed to the dependence of the fracture propagation path on the processing route due to different geometric redistribution of the eutectic constituent.

Keywords: Aluminium alloys; Equal-channel angular pressing (ECAP); Ductility; Fracture propagation

Al–Si casting alloys are extensively used in the automotive and aerospace industries. An economic processing as a result of their good castability, linked to a moderate strength at room temperature, stability at high temperatures and good wear resistance, gives this family of alloys a wide range of possibilities for industrial applications [1]. The weak point of the Al–Si casting alloys is their poor ductility and toughness. The importance of microstructural parameters such as dendrite sizes and Si particles shapes and sizes on the mechanical properties has been studied extensively [2–7]. A great number of solutions have been given for controlling these parameters and improving their mechanical behavior, such as additions of modifying elements, variations of solidification rates and performing different heat treatments.

Application of severe plastic deformation for processing of Al–Si alloy has been performed showing how microstructural homogenization and refinement leads to improvement of the mechanical properties [8–10]. Equal-channel angular pressing (ECAP) is a severe plastic deformation process which has been widely applied to many metals and alloys, increasing their resistance at room temperature due to grain refinement [11]. Nevertheless, not all the potential of ECAP processing has been studied systematically in Al–Si alloys since only limited processing paths have been performed so far.

In a previous work it was shown how the dendritic microstructure of the same Al–7%Si alloy selected for this study evolves differently depending on the ECAP processing route [12]. The aim of the present work is to study the ductility of these different microstructures developed by ECAP, or concretely, the effect of the deformation path on ductility of the alloy. Tensile testing results and micrographs showing the fracture path suggest a close dependence of the ductility on the ECAP processing route.

A $400 \times 250 \times 40$ mm^3 plate of an Al–7 wt.%Si alloy was prepared by casting pure Al (99.95 wt.%) and Al–12.3 wt.%Si ingots in adequate proportions. To the melt was added 0.02 wt.% Na to modify the solidification and obtain a fine Si particle morphology in the eutectic constituent. The chemical analysis composition of the resulting plate measured by emission spectroscopy was (in wt.%) 7% Si, 0.3% Fe, and balance aluminum.

ECAP billets with dimensions $90 \times 10 \times 10$ mm^3 were machined along the largest dimension of the as-cast ingot in such a way that three rows of samples were obtained across the thickness of the casting plate. ECAP samples were processed in a sharp ECAP die with an intersection channel angle of 90°. The samples were pressed at room temperature up to eight passes by four

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deformation paths: routes A, B_A, B_C and C at a pressing speed of 10 mm min^{-1}.

Planar dog-bone tensile samples of $10 \times 3 \times 1.5$ mm^3 gage dimensions with a radius of 3 mm were machined out of the ECAP samples parallel to the flow plane (FP) in such a way that the gage length coincided with the middle region of the ECAP samples. Monotonic tensile tests were performed using a universal hydraulic Instron testing machine at room temperature with a constant strain rate of 10^{-3} s^{-1}.

Optical microscopy (OM) was used for microstructural characterization of the as-cast alloy and the samples pressed by the processing routes mentioned. The characterization of the fracture propagation path of the tensile samples was also performed by OM. The sample preparation for OM consisted of mechanical grinding, polishing up to 1 μm diamond paste and a final polishing with a 0.05 μm colloidal silica suspension.

Figure 1 depicts isometric views in three orthogonal planes – flow plane (FP), top plane (TP) and cross-sectional plane (CP) – defined in the ECAP schematic shown in Figure 1a. Figure 1b represents the initial as-cast microstructure and Figure 1c–e shows the resulting microstructures after eight ECAP passes by routes B_C, A and B_A, respectively. The microstructure corresponding to eight passes by route C is well represented by Figure 1c at this magnification level, since it is identical to that of eight passes by route B_C. The microstructure of the Na-modified Al–7 wt.%Si in the as-cast condition consists of primary Al dendrites surrounded by the eutectic constituent (Al–12 wt.%Si), which contains a distribution of fine Si fibers (1–3 μm in thickness and 5–10 μm in length) as a result of the Na addition, and a small volume fraction of needle-like Al_5FeSi phase. After eight ECAP passes, each processing route provokes a different distribution of the microstructural constituents. Processing up to eight passes by route B_C and C (Fig. 1c) results in the maintenance of the original dendritic microstructure. Processing by route A (Fig. 1d) leads to the progressive elongation of the microstructure. As a consequence, the primary Al is arranged in a pancake structure surrounded by the eutectic constituent. Details of the microstructural evolution of this alloy processed by routes B_C and A has been given elsewhere [12]. Processing by route B_A (Fig. 1e) involves a $\pm 90°$ rotation of the ECAP billet around its extrusion axis between passes, which also results in a pancake arrangement of the original dendrites but oriented differently to those processed by route A. Independently of the dendritic distribution, all processing routes obtain a grain size of about 0.3 μm, which is not visible in the figures.

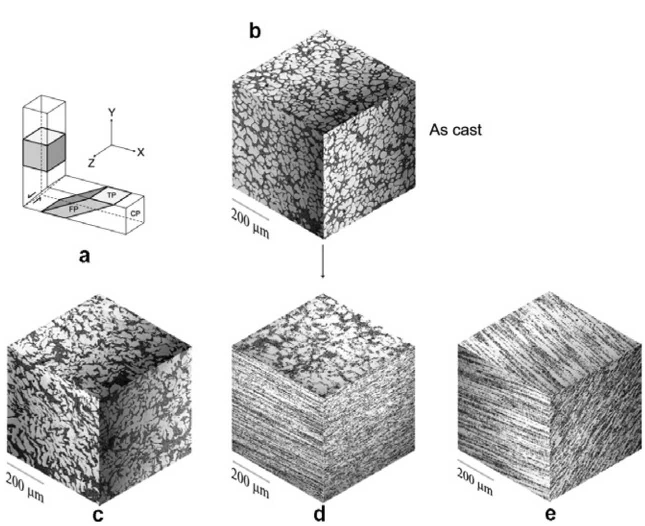

Figure 1. (a) Schematic of ECAP process showing the coordinate axes and defined orthogonal planes for the isometric montages. Isometric OM images of Al–7%Si microstructure after (b) casting; (c) route B_C (also representative of route C); (d) route A; and (e) route B_A.

Figure 2 shows the tensile testing results. The processed samples show an increase in ultimate tensile strength (UTS) of about 60%, from 157 MPa for the as-cast sample to about 245 MPa for the four processed samples. The UTS increase is attributed to the grain refinement of the Al matrix during the severe deformation.

In contrast, the ductility of the ECAP samples processed by the four routes shows very different behavior. The samples processed by routes B_C and C show an elongation to fracture, ε_F, of about 10%, which is lower than that of the as-cast sample ($\varepsilon_F = 14\%$). However, those processed by routes A and B_A present values of 24% and 22%, respectively, which are more than twice those for the samples processed by routes B_C and C. The ductilities shown in Figure 2 are in contrast with the behavior of most metallic materials, i.e. the increase in strength is generally associated with a decrease in elongation to failure as a consequence of cold work during the severe deformation processing, as occurs for samples B_C and C. As shown below, this behavior is based on differences in microstructure affecting the failure mechanisms.

Figure 3 shows the eutectic distribution and the crack path of the tensile tested samples for the as-cast condition (Fig. 3a) and the processed samples in the FP (Fig. 3b–d). These figures show the eutectic distribution in greater detail than in Figure 1. It can be clearly seen that the crack path follows the eutectic constituent exactly whenever possible, i.e. in the as-cast and B_C conditions (Fig. 3b, also representative of route C), whereas for A and B_A routes (Fig. 3c and d) the crack path is forced to pass through the primary Al.

The differences in ductility of the various samples can be explained by two concepts: a different mechanism of damage generation in the processed samples with respect to the as-cast alloy, and a different crack propagation path depending on the processing route.

During tensile testing of the as-cast alloy, damage appears by cracking of the Si and Al_5FeSi particles at small

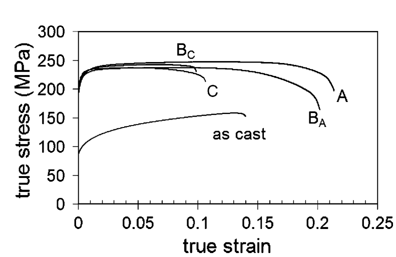

Figure 2. Stress–strain curves for the as-cast and processed material.