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A characterization of microstructure and microhardness on longitudinal planes of an Al–Mg–Si alloy processed by ECAP

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ABSTRACT

An AA6005 Al–Mg–Si alloy was used to investigate the evolution of microhardness and microstructure on the longitudinal or Z planes after processing by ECAP where these planes lie parallel to the upper and lower surfaces of the billet. The processing was conducted at a temperature of 423 K using an ECAP die with a channel angle of 90°. Samples were pressed for up to 8 passes and observations were undertaken on the top and bottom planes and on a parallel plane located at approximately the center of the billet. The results show that the grain size is reduced from ~50 μm in the initial condition to ~200 nm after 8 passes with similar grain sizes recorded on all three planes of observation. Measurements of the microhardness show the values increase by a little more than two times after 8 passes. The results from this investigation demonstrate that excellent microstructural homogeneity may be achieved throughout the Al–Mg–Si billet after processing through a total of 8 passes.

1. Introduction

The processing of bulk metals by equal-channel angular pressing (ECAP) has now become important for the production of materials with exceptionally small grain sizes [1]. In ECAP, a material in the form of a rod or bar is pressed through a die constrained within a channel which is bent through a sharp angle near the center of the die. Since the cross-sectional area remains unchanged during a single pass through the die, repetitive pressings may be performed to impose high strains on the material. This type of processing produces significant grain refinement and gives materials having average grain sizes that lie typically within the submicrometer range.

The microstructural evolution taking place in ECAP is generally evaluated by taking a series of hardness measurements along linear traverses on or within the specimen after processing. It is convenient to define three orthogonal axes and the associated planes of ECAP as illustrated in Fig. 1 [2]. Specifically, the X or transverse plane lies perpendicular to the pressing direction, the Y or flow plane lies parallel to the side face at the point of exit from the die and the Z or longitudinal plane lies parallel to the top surface at the point of exit from the die.

In early studies of microhardness evolution in ECAP, measurements of the individual hardness values were generally taken on the X or cross-sectional plane to provide an overview of the variations in hardness between the top and bottom surfaces [3–9]. There are also some reports of microhardness measurements on other planes including on the Y plane of an AA6082 aluminum alloy after one pass [10],

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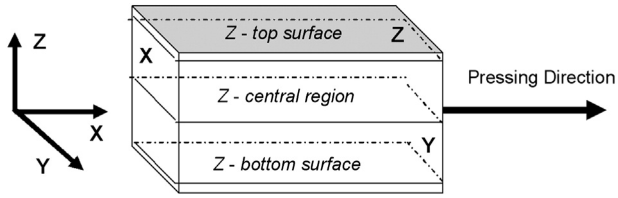

Fig. 1 – Schematic illustration of the ECAP billet with three orthogonal axes X, Y and Z: microhardness measurements and microstructural observations were undertaken on the Z planes at the top surface, on a plane at approximately the central position within the billet and on the bottom surface.

on the four outer surfaces corresponding to the Y and Z planes for pure Cu after one pass [11] and on the Y planes of a magnesium ZK60 alloy [12], aluminum Al-1050 [7] and Al-6061 alloys [13], commercial purity grade 2 Ti [14] an a Cu-0.1% Zr alloy [9]. An examination of these data shows that relatively little attention has been paid to the evolution of hardness on the Z or longitudinal planes during processing by ECAP although this information is important if the pressed billets will be used in industrial applications. Accordingly, the present investigation was initiated to examine both the values of the microhardness and the appearance of the microstructure on the Z plane after ECAP.

The tests were conducted using a commercial AA6005 Al–Mg–Si alloy and, as indicated in Fig. 1, measurements and observations were recorded on three separate surfaces: on the top surfaces, in the central regions on planes cut parallel to the upper surfaces at approximately the mid-sections of the samples and on the bottom surfaces of the ECAP billets. The AA6005 alloy was selected because numerous reports are now available documenting the successful processing of Al–Mg–Si alloys to high strains by ECAP [13,15–42] but nevertheless there has been no study of the evolution of microstructure and microhardness on the longitudinal planes of an Al–Mg–Si alloy, or any other alloy, with increasing numbers of passes.

2. Experimental Material and Procedures

This investigation used an Al–Mg–Si alloy AA6005 having a composition (in wt.%) of 0.65 Si, 0.40 Mg, 0.35 Fe and 0.01 Mn. The material was received in the form of extruded cylindrical bars having diameters of 10 mm. The alloy was solution treated and homogenized at 723 K for 5 h and then furnace cooled. For processing by ECAP, bars were cut having lengths of ~60 mm.

The ECAP was conducted using a hydraulic press with a maximum capacity of 150 kN operating with a linear speed of ~4 mm s^{-1}. The ECAP processing used a solid die with a channel bent internally through an abrupt angle of $\Phi = 90°$ and an outer arc of curvature of $\Psi \approx 20°$ at the intersection of the two parts of the channel. The channel had a cylindrical cross-section throughout the die with a diameter of 10 mm. Using this die configuration, the imposed strain in a single pass is given by $\varepsilon = 1.08$ [43]. The processing was performed at a temperature of 423 K and samples were pressed repetitively for up to a total of eight passes corresponding to a maximum strain level of $\varepsilon \approx 8.64$. Each billet was pressed using route B_C where the sample is rotated in the same sense by 90° around the longitudinal axis between each pass [44].

The undeformed material was observed using a Reichert Jung MeF3 polarized light optical microscope. The material surface was chemically etched using a Barker solution (200 ml H_2O and 12 ml fluoro-boric acid) at 18 V at room temperature. The mean grain size was determined using the linear intercept method.

Specimens were prepared for transmission electron microscopy (TEM) by cutting thin sections, grinding these sections to plates with thicknesses of ~170 μm and then etching for a few minutes in a solution of perchloric acid ($HClO_4$) in methanol at room temperature in order to eliminate all surface mechanical damage. Finally, discs were prepared by electro-polishing at −40 °C with a solution of 25% nitric acid and 75% methanol.

All microstructures were examined using a Philips CM200 TEM operating at 200 kV and equipped with a double-tilt specimen holder. A copper grid with parallel lines was aligned to the long axis of the holder and mounted under each disc. All discs were then aligned so that the pressing direction was parallel to the copper lines. This copper grid served to keep track of the pressing direction throughout the TEM inspections. Sections were examined at three different depths within each sample: specifically, examinations were conducted adjacent to the top surface, in the vicinity of the central longitudinal plane and adjacent to the bottom surface of the cylindrical specimens as illustrated in Fig. 1. Thus, all of the TEM observations were performed on the Z plane.

Microhardness measurements were taken using a Metalloplan microhardness tester equipped with a Vickers indenter and using an applied load of 25 gf with a dwell time of 30 s. Values of the Vickers microhardness, Hv, were measured on the longitudinal Z plane after 2, 4 and 8 passes corresponding to imposed strains of 2.16, 4.32 and 8.64, respectively. The microhardness values were recorded at regular steps of 0.3 mm from one end of the sample to the opposite end. Each reported hardness value represents the average from 5 different measurements.

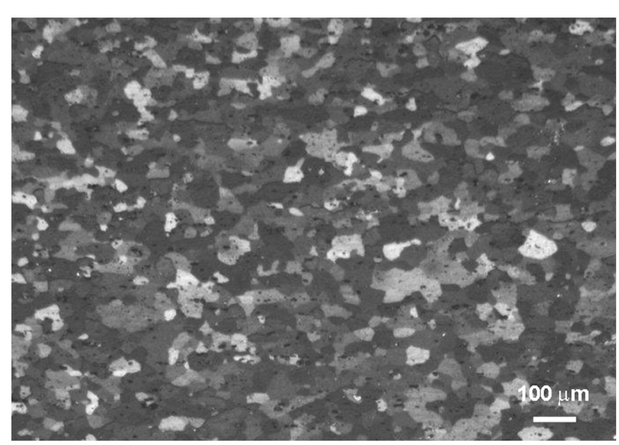

Fig. 2 – Microstructure of the extruded and homogenized material prior to processing by ECAP.