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Equal-channel angular pressing of an Al-6061 metal matrix composite

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An Al-6061 metal matrix composite, reinforced with 10 vol % Al_2O_3 particulates, was subjected to equal-channel angular (ECA) pressing at room temperature to a total strain of ~5. It is shown that the intense plastic straining introduced by ECA pressing reduces the grain size from ~35 μm to ~1 μm and this leads to an increase in the microhardness measured at room temperature. Inspection revealed some limit cracking of the larger Al_2O_3 particulates as a consequence of the ECA pressing. Tensile testing after ECA pressing gave a maximum ductility of ~235% at a temperature of 853 K when testing at strain rates from $\sim 10^{-4}$ to $\sim 10^{-3}$ s^{-1}. It is suggested that high strain rate superplasticity is not achieved in this material after ECA pressing due to the presence of relatively large Al_2O_3 particulates.

1. Introduction

Equal-channel angular (ECA) pressing is a processing procedure which may be used to introduce an intense plastic strain without any corresponding change in the cross-sectional dimensions of the sample [1]. This procedure provides the potential for substantially refining the grain sizes of polycrystalline materials down to the submicrometer or nanometer level [2–4]. Several recent reports have described the ECA pressing of cast aluminum-based alloys and they have demonstrated the capability for using these ECA-pressed materials to achieve high superplastic elongations at very rapid strain rates [5–8].

High strain rate superplasticity (HSR SP) has been widely reported in a number of aluminum-based composites fabricated using powder metallurgy methods and having grain sizes close to ~1 μm [9–11] but there have been no similar reports of HSR SP in metal matrix composites fabricated by ingot metallurgy procedures because the grain sizes are generally too large for superplastic flow. The present investigation examines the possibility of achieving HSR SP in a cast aluminum-based composite by using ECA pressing to reduce the grain size.

An earlier report described a series of experiments in which an Al-6061 metal matrix composite, reinforced with 10 vol % Al_2O_3 particulates, was subjected to ECA pressing at elevated temperatures using a pressing procedure of 8 passes at 673 K and 2 passes at 473 K, equivalent to a total strain of ~10 [12]. This work demonstrated a reduction in grain size by ECA pressing down to the submicrometer level but HSR SP was not achieved and the maximum tensile elongation was only ~150% at a temperature of 853 K when testing with a strain rate of 1×10^{-3} s^{-1}. The failure to achieve HSR SP was attributed to the presence of the relatively large Al_2O_3 particulates which were not broken during the ECA pressing. However, there is a report of the breaking of Al_2O_3 particulates in this composite during extrusion [13] and this suggests the particles may have remained unbroken in the ECA pressing because of the use of a relatively high pressing temperature. Accordingly, this report describes experiments in which the same composite was subjected to ECA pressing at room temperature.

2. Experimental material and procedures

The experiments were conducted using an Al-based metal matrix composite designated Al 6061-10 vol % Al_2O_3(p) where p denotes particulates. The composite was fabricated by Duralcan USA (San Diego, California) using a proprietary casting technique and the material was received in the form of rods with a diameter of 19.1 mm. The composite consisted of an Al-6061 alloy reinforced with irregularly-shaped Al_2O_3 particulates: further information on this material was given earlier [12]. The microstructure of the composite was revealed by mechanical polishing and light etching using Keller's reagent (2% HF, 3% HCl, 5% HNO_3 and 92% H_2O). In the as-received condition, measurements gave an average grain size of ~35 μm and an average particulate size of ~7.5 μm.

The ECA pressing was performed at room temperature by pressing cylindrical samples through a special die using a Dake hydraulic press of 150 tons capacity.

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The samples had diameters of 9.5 mm and lengths of $\sim$60 mm and the die was constructed so that it contained two channels, equal in cross-section, intersecting at an angle of 90° and with an arc of curvature of 90° at the outer point of intersection of the two channels. Using this configuration, it can be shown that the strain accrued on a single passage through the die is $\sim$1 [14] and multiple passes may be undertaken to attain high strains. In the present experiments, all samples were pressed for 5 passes to a strain of $\sim$5 using pressing route B_C in which the samples are rotated in the same direction by 90° between consecutive passes through the die [15].

Following ECA pressing, small tensile specimens were machined parallel to the pressing direction with gauge lengths of 4 mm and gauge widths and thicknesses of 3 and 2 mm, respectively. These samples were pulled to failure at elevated temperatures using an Instron testing machine operating at a constant rate of cross-head displacement. In order to investigate the effect of static annealing, small samples, with thicknesses of $\sim$3 mm, were cut from the as-pressed material, annealed in air for 1 hour at selected temperatures within the range from 373 to 773 K and then quenched into water. The hardness of these samples, Hv, was measured by mechanically polishing and then using a Future-Tech digital microhardness tester (model FM-1e) equipped with a Vickers diamond indenter. For each measurement, a load of 50 g was applied for 15 s and care was taken to ensure that the measurements were recorded at positions remote from any visible Al_2O_3 reinforcement. The values reported for Hv represent the average of 5 separate measurements on each sample.

To check whether there was any breaking of the Al_2O_3 particulates during the ECA pressing, polished samples were prepared in both the as-received and the ECA-pressed conditions and these samples were examined using a quantitative image analyzing facility attached to an optical microscope. A linear traverse was made across each sample parallel to the direction of pressing and the dimension of each particle was recorded in this direction. For each sample, measurements were taken on $\sim$300 particles to permit the construction of distribution histograms.

3. Experimental results and discussion

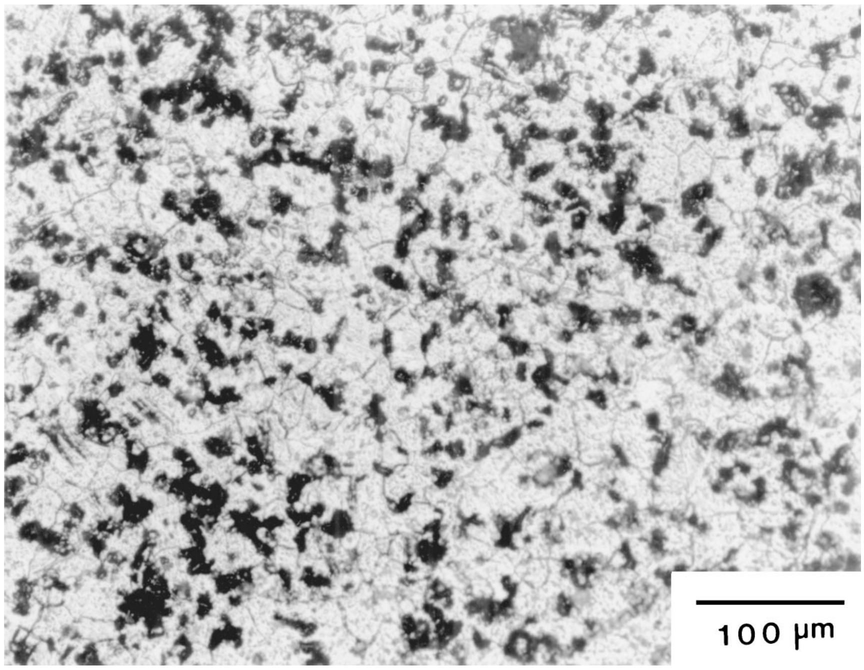
Typical microstructures are shown in Fig. 1 for (a) the as-received and unpressed composite and (b) the composite in the ECA-pressed condition. It is apparent from these photomicrographs that the grain size is very much reduced by the ECA pressing although the size and distribution of the Al_2O_3 particulates appears to be relatively unaffected. Detailed measurements gave an average grain size of $\sim$1 μm after ECA pressing which compares with a value of $\sim$35 μm in the unpressed condition.

The variation of the Vickers microhardness with annealing temperature is shown in Fig. 2 up to a temperature of 773 K: for comparison, the value of Hv was measured as $\sim$78 in the as-received and unpressed material. Thus, as with the samples of this composite pressed earlier at a higher temperature [12], ECA pressing increases the strength of the material at room temperature by a factor of $\sim$2. The slight initial increase in Hv with increasing annealing temperature, and the subsequent drop in Hv at even higher temperatures, are both consistent with the results presented earlier for the samples subjected to ECA pressing at a high temperature [12] and these trends are associated with an initial equilibration of the microstructure at the lower temperatures and the subsequent advent of grain growth at the higher temperatures. Thus, in terms of grain size refinement and microhardness, the present results reveal no clear distinction between the samples pressed to a strain of $\sim$10 at high temperatures and those pressed to a strain of $\sim$ 5 at room temperature.

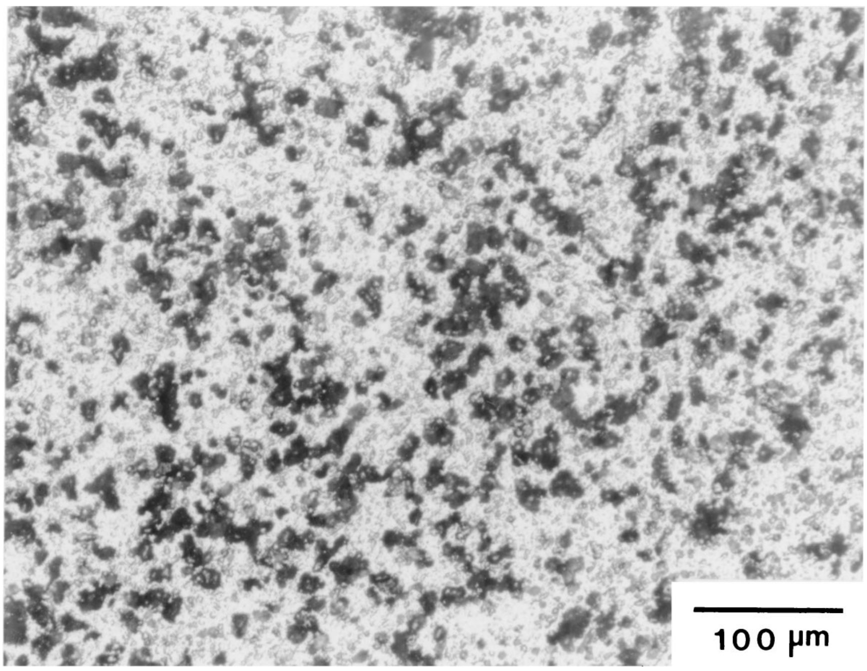
It was reported earlier that a maximum elongation to failure of $\sim$150% was recorded for the samples pressed at the high temperature when testing at 853 K with an initial strain rate of 1×10^{-3} s^{-1} [12]. Similar tests were conducted on the present samples at 853 K and the elongations to failure were recorded as $\sim$235%, $\sim$235%, $\sim$115% and $\sim$90% for initial strain rates of 1×10^{-4}, 1×10^{-3}, 1×10^{-2} and 1×10^{-1} s^{-1}, respectively. These results again fail to reveal any evidence of HSR SP but, nevertheless, the maximum elongations of $\sim$235% are significantly higher than the elongations achieved in the samples subjected to ECA pressing at the high temperature.

Fig. 3 shows the distributions of sizes for the Al_2O_3 particulates in (a) the as-received and unpressed condition and (b) after ECA pressing at room temperature through 5 passes. These two histograms are reasonably similar but the average particulate size was reduced from $\sim$7.5 μm in the unpressed condition to $\sim$7.2 μm after ECA pressing and close inspection revealed some limited breaking of the larger particulates during the ECA pressing procedure. This breaking of the larger particulates may account for the higher tensile elongations observed in these samples since the presence of large particles would tend to inhibit the occurrence of easy grain boundary sliding. However, it appears that the reduction in particle size is not sufficient to permit the development of high tensile elongations and significant superplasticity.

The particulate sizes in aluminum alloy matrix composites exhibiting HSR SP are typically in the range $\sim$0.2 to 2 μm [9] and these sizes are substantially smaller than the Al_2O_3 particulates employed as the reinforcement in the present composite. Furthermore, detailed evidence from experiments on aluminum-based alloys reinforced with SiC particulates suggests there is generally very little fracture of the smaller SiC particles having sizes below $\sim$10 μm [16, 17]. Since the ECA pressing at room temperature in the present experiments leads to only a very minor reduction in the average particulate size, it is concluded that this material cannot be used to achieve significant HSR SP through ECA pressing. Conversely, it is probable that HSR SP may be achieved in cast aluminum alloy composites through ECA pressing if, as in the powder metallurgy composites, the average size of the initial reinforcement is of the order of $\sim$1 μm.



(a)



(b)

Figure 1 Microstructures for (a) the as-received and unpressed condition and (b) after ECA pressing.

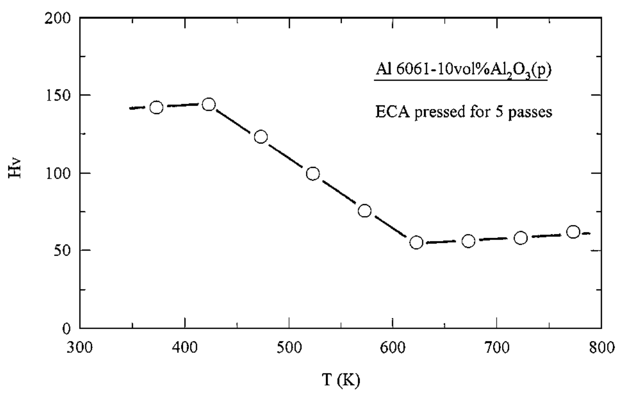


Figure 2 Variation of Vickers microhardness with annealing temperature.

4. Summary and conclusions

1. An Al-6061 metal matrix composite reinforced with 10 vol % Al_2O_3 particulates was subjected to ECA pressing to a total strain of ∼5 at room temperature.

2. The intense plastic straining reduced the grain size to ∼1 μm and there was a corresponding increase, by a factor of ∼2, in the microhardness measured at room temperature. The ECA pressing produced some limited cracking of the larger Al_2O_3 particulates.

3. A maximum tensile ductility of ∼235% was achieved at a temperature of 853 K using strain rates in the range of $\sim 10^{-4}$ to $\sim 10^{-3}$ s^{-1}. The failure to achieve high strain rate superplasticity is attributed to the presence of the relatively large Al_2O_3 particulates.

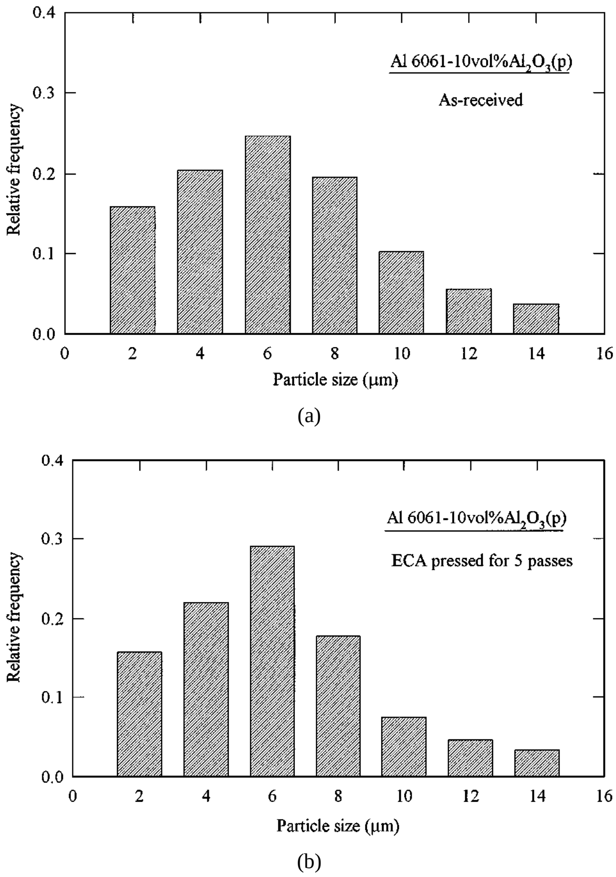


Figure 3 Distributions of Al_2O_3 particulate sizes for (a) the as-received and unpressed condition and (b) after ECA pressing.

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