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The Influence of Processing Conditions on Hardness Homogeneity Evolution in Commercially Pure Cast Aluminium Processed by Equal Channel Angular Pressing

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Commercially pure cast aluminium was subjected to equal channel angular pressing (ECAP) at room temperature using routes A, B_c and C. Microhardness distribution maps were produced on sections of extruded billets after one, two, three and four passes for each of the processing routes. It was found that the mean hardness increased significantly already after the first pass. With subsequent passes, the hardness increase was smaller but the hardness distribution became narrower, indicating increasing homogeneity. For route B_c, a slight decrease in average hardness was observed after the fourth pass. The mean hardness after four passes was highest for the route C sample, followed by the route A and route B_c samples.

Keywords: Aluminium, equal channel angular pressing, hardness

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Introduction

Over the last two decades, equal channel angular pressing (ECAP) has emerged as a viable procedure for producing ultrafine-grained (UFG) and nanostructured metallic materials in a bulk form [1-4]. During ECAP, severe plastic deformation (SPD) is imposed on a metal billet in the form of a bar or rod by pressing it through two channels, equal in cross section, intersecting at an abrupt angle (90-120°) and constrained within a die. Ideally, the billet experiences simple shear as it passes through the intersecting channels; as the billet dimensions remain unchanged during the passage through the die, it is possible to achieve very high strains by passing the billet repetitively through the die several times [1-4]. Exceptional grain refinement is achieved, resulting in unique structural and functional properties, including significant strengthening at ambient temperatures.

At present, ECAP is beginning to emerge from laboratory scale research and the feasibility of up-scaling to industrial scale has resulted in commercial applications [3,4]. As this trend continues, it becomes important to ascertain that ECAP material displays homogeneity in microstructure and mechanical properties through its bulk. The usual approach of tensile testing of specimens extracted from the centre of an ECAP billet or measuring average microhardness at isolated random points on a cross-section cannot provide information on the degree of homogeneity across the whole sample, particularly near the surface regions where frictional effects from the die wall may have an influence. Recently, some researchers have used microhardness survey in a grid pattern over whole cross-sections both parallel and normal to the extrusion direction of a billet to obtain information on the degree of homogeneity in hardness measurements [5-8]. As a direct correlation has been demonstrated between microhardness measurements and the average grain size determined by transmission electron microscopy, it was anticipated that a homogeneity in hardness will correspond to a reasonable homogeneity in microstructure [6,8].

The information on homogeneity evolution during ECAP has thus far been developed exclusively for billets processed by route B_C, in which the billet is rotated by 90° in the same direction after each pass [5-8] and there appears to be scant information on the other processing routes. Accordingly, in this paper, we present the results of a systematic investigation into the evolution of hardness homogeneity in the longitudinal planes of ECAP samples of a commercially pure cast aluminium processed by three processing routes, namely, route A (no rotation between passes), route B_C and route C (180° rotation in the same direction a fter each pass).

Experimental Program

The material used in this study was 99.95% pure aluminium, obtained in the form of a cast ingot. Billets, 70 mm × 10 mm ×10 mm in dimension, were machined from the ingot. No homogenisation heat treatment was conducted. The ECAP processing was carried out using a sharp cornered 90° die at a mbient temperature, at an extrusion speed of 5 mm.min^{-1}. The billets and the die surfaces were coated with a lubricant containing MoS_2 to minimise frictional effects. Processing routes A, B_C and C were used to produce samples that had been subjected to 4 passes. In the case of route B_C, samples that had undergone 5 and 8 passes were also produced. Fig. 1(a) which shows a sample within the die after pressing but prior to extraction, also

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indicates the coordinates used to describe the sample geometry: longitudinal or extrusion direction (LD, X), normal direction (ND, Y) and transverse direction (TD, Z).

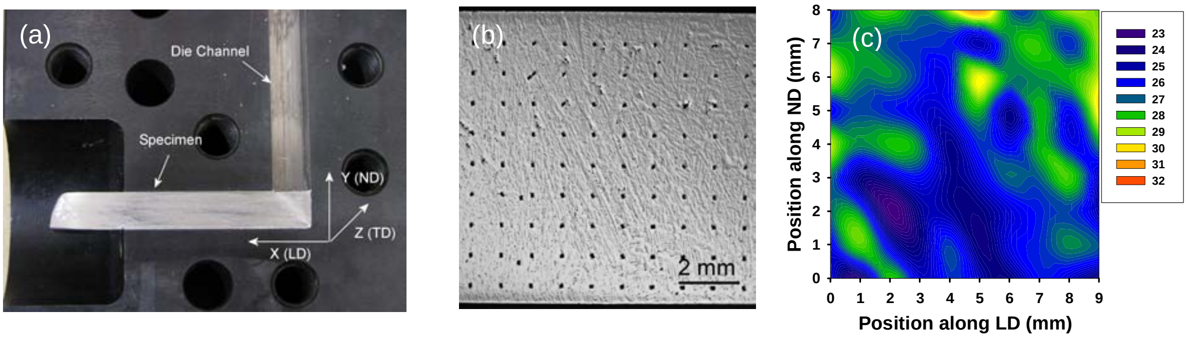

Figure 1 (a) An extruded billet within the ECAP die, prior to extraction; (b) Low magnification macrograph of the as received material; (c) Hardness contour map for the as received material. (Note the array of hardness indentations in (b)).

The extruded samples were mounted in epoxy and the sample faces parallel to the plane defined by LD and ND (shown in Fig. 1(a), also referred to as the Y plane in the literature) were polished using standard metallographic techniques. In the process, ~ 1 mm of the material was removed from the surface. Vickers microhardness survey of the polished surface was carried out at a load of 0.98 N with 15 s dwell. A 10 mm $\times$ 10 mm area, at a distance of 26 mm from the leading end of the extruded bar, was traversed at increments of 0.5 mm in each direction, resulting in at least 400 measurements from which colour coded hardness contour maps were plotted. A similar survey was also conducted on the as-received cast material, but here the step size was 1 mm: Fig. 1(b) and 1(c) present a macrograph of the area surveyed and the resulting hardness map, respectively. The slight variation in microhardness over the area is consistent with the as-cast nature of the starting material.

Results and Discussion

Fig. 2 presents the hardness contour maps developed for the ECAP aluminium samples produced using the three different processing routes, A, B_C and C, after 1, 2, 3 and 4 passes. Comparison with the hardness map for the as received material (Fig. 1(c)) shows that significant hardening occurred already after the first pass over the entire area sampled. The representative macrograph in Fig. 2 shows that after the first pass, the primary and second phase constituents present in the cast material served as tracers delineating the state of strain in the sample. It is interesting to note that the corresponding hardness contour map shows a similar pattern; similar results were obtained for the other samples in the study. As seen in Fig. 2, for all three processing routes the hardness continued to increase slightly with subsequent passes, but more significantly, the hardness distribution became more uniform, indicating an increasing homogeneity.

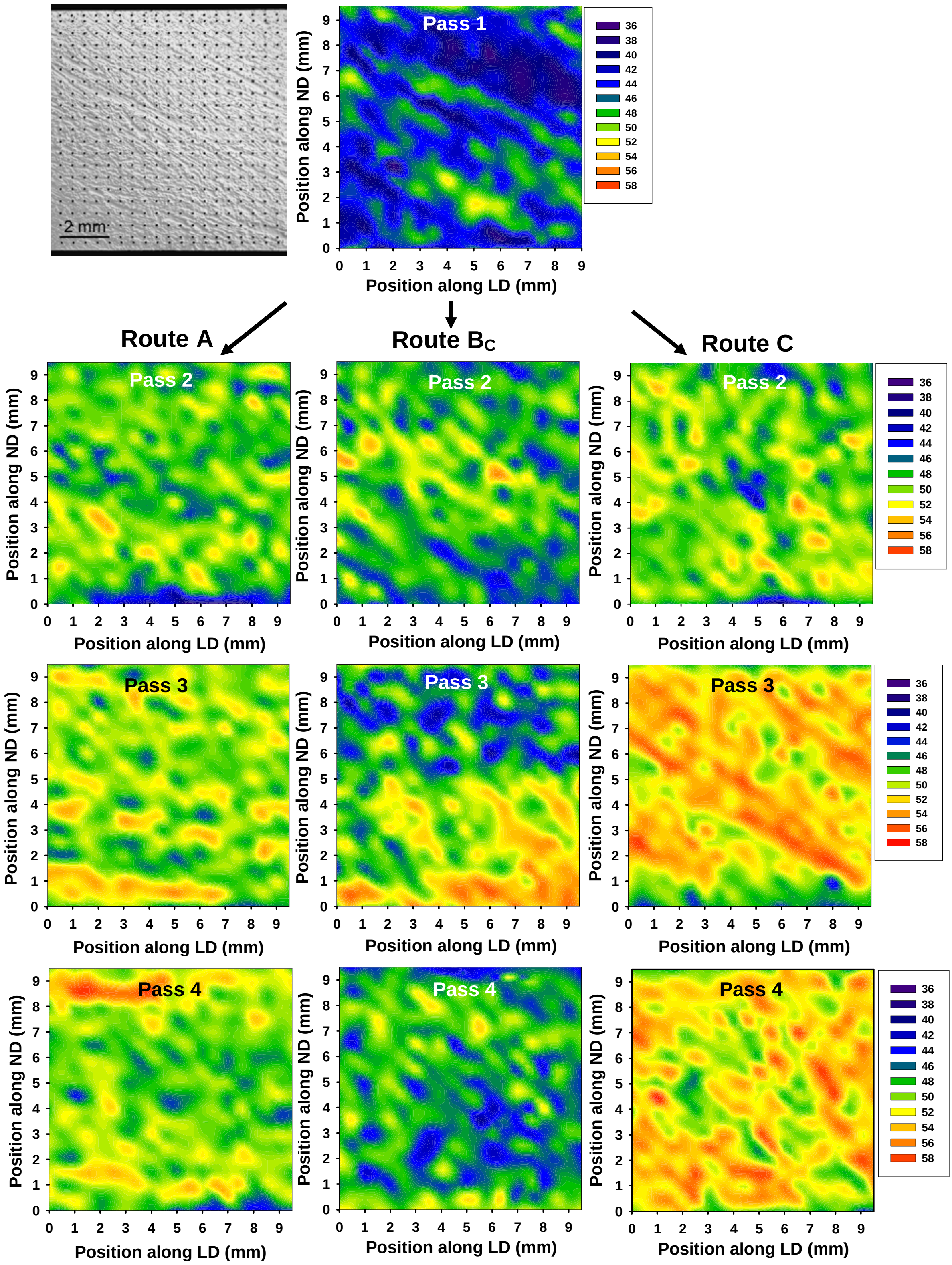

Figure 2 Contour maps showing the distribution of microhardness on the longitudinal planes of ECAP samples after one pass, and after two, three and four passes by routes A, B_C and C, respectively. The scales on the right provide information on the hardness levels. The macrograph shows the area scanned for the Pass 1 sample.

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Visual examination of the hardness contour maps reveals a trend in the degree of hardening achieved by the three processing routes: after each pass, the route C sample showed the highest hardness, followed by the route A sample; the route B_C sample showed the lowest hardness. This influence of the processing route on hardening is also evident in Fig.3(a)-(c) in which we have plotted the mean hardness calculated from the data obtained for each sample processed by the three routes. It is evident that the mean hardness almost doubled after the first pass, but increased less slowly for the subsequent passes and appeared to reach a plateau after the fourth pass. Fig. 3(d) compares the mean hardness obtained for samples subjected to 4 passes by each of the three routes. Statistical analysis of the more than 400 data points from each map confirms that the observed hardness differences are statistically significant. As noted earlier, a direct correlation has been demonstrated between microhardness measurements and the average grain size determined by transmission electron microscopy for samples processed by ECAP [6,8]. Taking this into consideration, our results in Fig. 2 suggest that route C has effected higher grain refinement than both routes A and B_C.

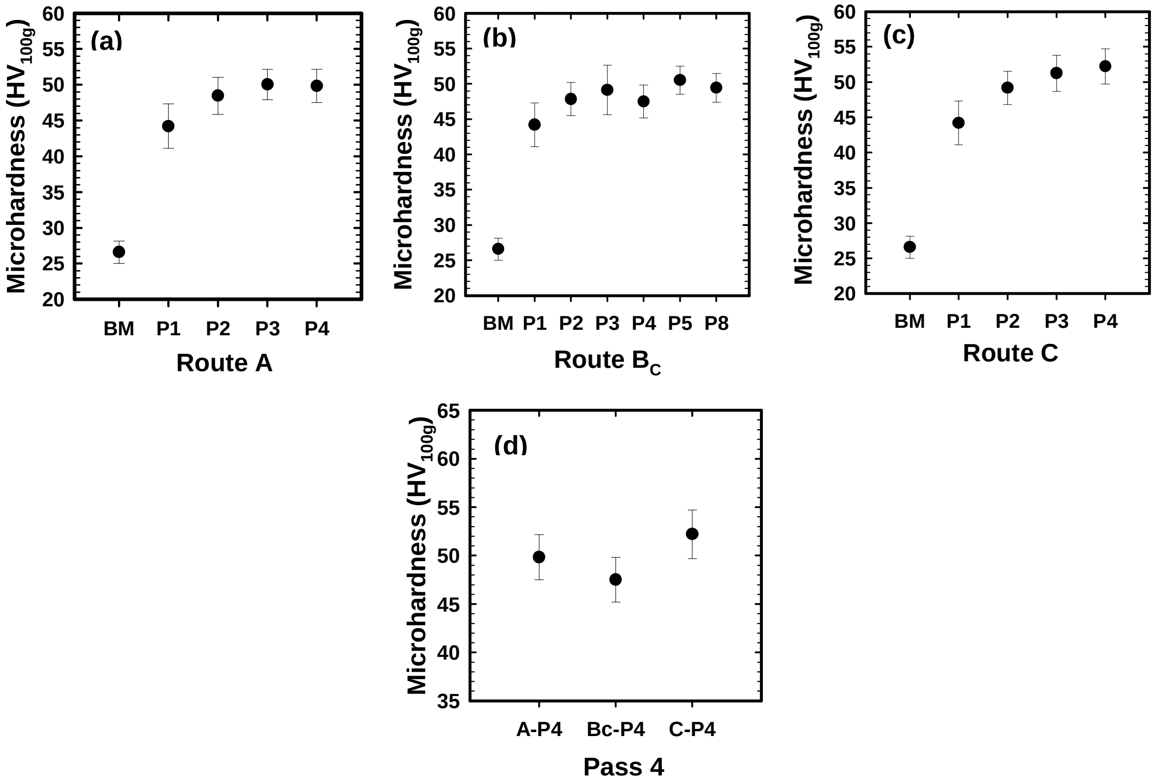

Figure 3 (a)-(c) Plots showing the variation in mean hardness with number of passes for ECAP samples produced by routes A, B_C and C; the mean hardness for the as-received base material is shown for comparison; (d) Comparison of hardness data for pass 4 samples produced by routes A, B_C, C.

There is a general consensus in the literature that route B_C leads most expeditiously to an array of reasonably equiaxed ultrafine grains whereas elongated grains are visible after four passes when processing through routes A and C, and also that route B_C causes the most rapid development of high angle grain boundaries, leading to the conclusion that this route is the optimal processing route, particularly for pure aluminium [2,3]. In light of these observations, the results reported here are unexpected. Investigations are underway, including further hardness surveys on both longitudinal and transverse planes to confirm the observed trend and detailed microstructural examination to verify the degree of grain refinement obtained for each processing route.

Summary and conclusions

1. Microhardness scans were made on the longitudinal faces of billets subjected to ECAP by processing routes A, B_C and C, after one, two, three and four passes; a further two samples were subjected to five and eight passes by B_C.
2. The mean hardness over the sampled area increased significantly after the first pass. Additional, smaller increases were observed for the subsequent passes for all three processing routes.
3. Route C resulted in the highest degree of hardening after each pass, followed by routes A and B_C. After four passes, this trend was clearly evident; indeed the mean hardness of the route C sample after four passes was slightly higher than those of route B_C samples after five and eight passes.
4. As a direct correlation between microhardness and microstructure has been demonstrated in the literature, the results suggest the route C might be a more effective route than the other two routes; further research is required to ascertain if this is the case.

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