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The Evolution of Homogeneity during Processing of Commercial Purity Aluminium by ECAP

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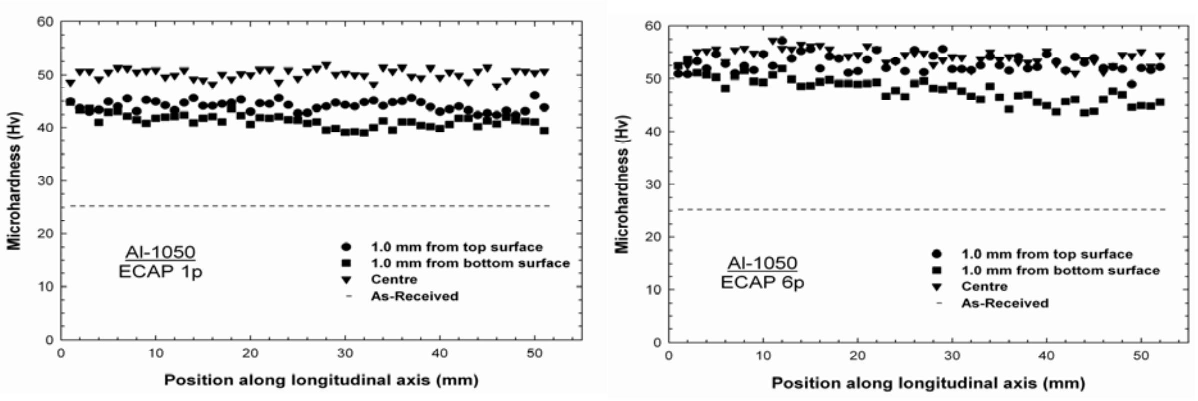
Abstract. Billets of a commercial purity aluminium Al-1050 alloy were processed by equal-channel angular pressing (ECAP) for up to a maximum of 6 passes. Following processing, the billets were sectioned and hardness measurements were recorded on both longitudinal and transverse sections. These measurements showed the hardness increases significantly in the first pass and continues to increase by small amounts in subsequent passes. Initially, there are regions of lower hardness running in bands near the top and bottom surface of each billet. The region of lower hardness near the upper surface disappears with increasing numbers of passes but near the bottom surface the lower hardness remains even after 6 passes. The results show that, neglecting the small region near the bottom of the billet, there is an excellent potential for achieving microstructural homogeneity within the Al-1050 alloy after pressing through a sufficient number of passes in ECAP.

Introduction

It is now well established that the processing of bulk solids through the application of severe plastic deformation (SPD) is an excellent procedure for introducing very significant grain refinement [1]. Although several SPD processing techniques are available, most attention is generally directed towards the procedure of equal-channel angular pressing (ECAP) [2]. In ECAP a billet, in the form of a bar or rod, is pressed through a die constrained within a channel that is bent through an abrupt angle within the die. High strains may be imposed on the sample using this type of processing. For example, if the internal angle between the two parts of the channel is 90°, the imposed strain on a single pass is ~1 [3]. Furthermore, since the billet emerges from the ECAP die with the same cross-sectional area, repetitive pressings may be conducted to impose very high total strains. Since processing by ECAP leads to a very significant grain refinement, the strength of the material after pressing is increased substantially by comparison with the unpressed material.

An important question in ECAP concerns the consequent homogeneity of the microhardness, and therefore of the microstructure, within the billets processed by ECAP. In early investigations the microhardness was usually determined by taking several measurements at randomly selected points on the cross-sectional planes of the pressed billets but later it was recognized that it was important to evaluate the distribution of hardness measurements over the entire cross-sections of the billets. Accordingly, a procedure was adopted in which microhardness measurements were taken following regular rectilinear grid patterns on the transverse sections [4-7]. Only limited information is available at present for the hardness distributions on longitudinal sections [8-11] although this information is needed to evaluate the extent of any end effects within the billets. Accordingly, the present investigation was initiated to evaluate the potential for achieving reasonable hardness homogeneity within a commercial Al-1050 alloy processed by ECAP.



(a) (b)

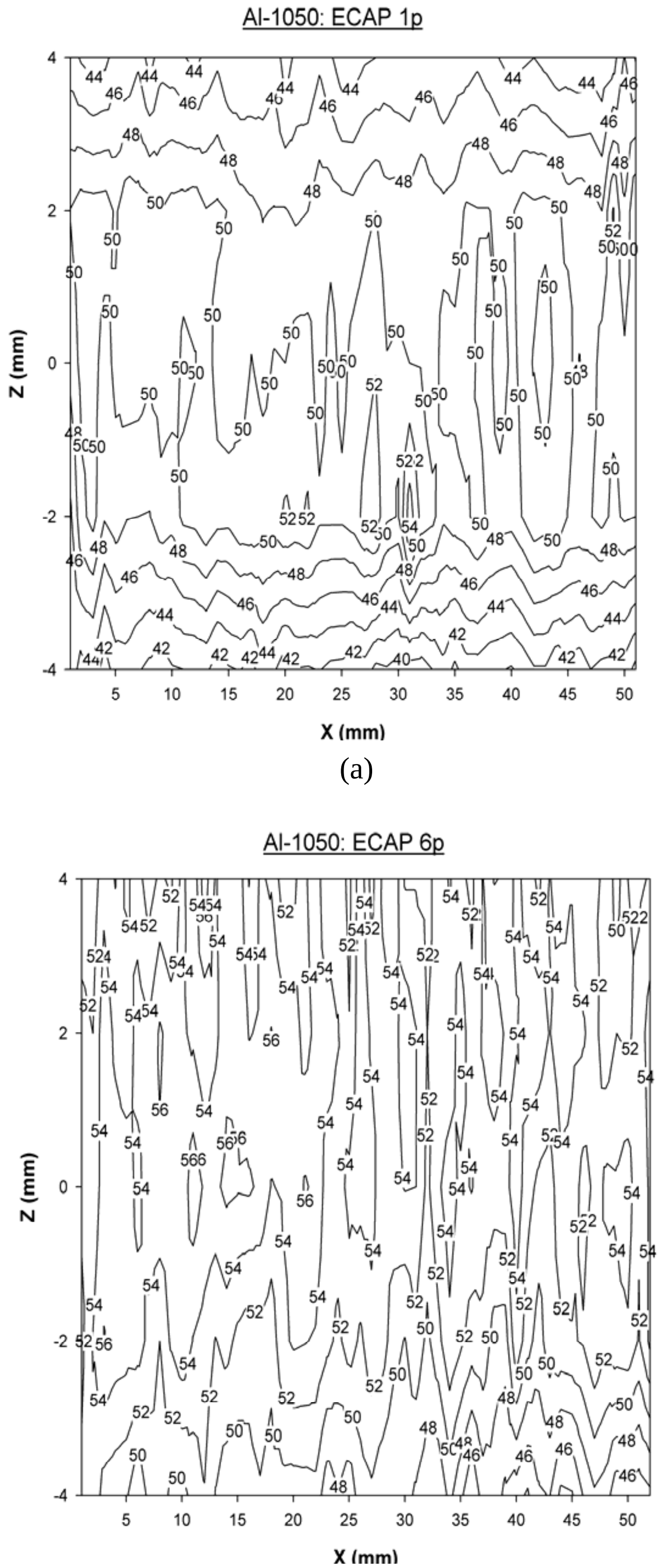
Fig. 1 Values of the Vickers microhardness, Hv, recorded on longitudinal sections of the Al-1050 alloy after processing by ECAP through (a) 1 pass and (b) 6 passes, respectively: the front edge of the billet is located on the right and the lower broken lines denote the value of the microhardness in the as-received unpressed condition.

Experimental material and procedures

The experiments were conducted using a commercial purity (99.5%) Al-1050 aluminium alloy. The alloy was received in the form of a long bar with a diameter of 10.0 mm. Billets for ECAP were cut from the bar with lengths of 65.0 mm and they were processed by ECAP at room temperature using a pressing speed of 0.5 mm s^{-1} and with a die having a channel angle of $\Phi = 90°$ and an outer arc of curvature at the intersection of the two parts of the channel of $\Psi = 20°$. Each billet was processed through a selected number of passes using processing route B_C in which the billet is rotated about the longitudinal axis by 90° in the same sense between each pass [12]. After pressing, billets were sectioned either longitudinally, perpendicular to the top surfaces, or on transverse sections perpendicular to the longitudinal axes. As in the earlier notation [2], the three orthogonal planes within the billet are designated the *X* plane perpendicular to the flow direction, the *Y* plane parallel to the side face at the point of exit from the die and the *Z* plane parallel to the top surface at the point of exit from the die, respectively. Thus, the individual hardness measurements were taken on the *Y* plane and the *X* plane, respectively. These sections were carefully polished and then the Vickers microhardness, Hv, was measured using a Matsuzawa Seiki MHT-1 microhardness tester equipped with a Vickers indenter. Each hardness measurement was taken using a load of 300 gf and a dwell time of 15 s. On the longitudinal sections, measurements were taken along longitudinal traverses for distances of 52 mm following lines located at selected distances from the top and bottom surfaces. Each measurement was taken with a separation of 1.0 mm giving a total of 52 separate measurements for each traverse on the *Y* plane. Similar measurements were taken on the *X* plane again using increments of 1.0 mm between each position.

Experimental results and discussion

Figures 1 and 2 show representative results obtained on longitudinal sections, where Fig. 1 denotes the individual points measured along traverses either in the centre or at distances of 1 mm from the top and bottom surfaces for (a) 1 and (b) 6 passes and Fig. 2 shows datum points plotted as contour maps after (a) 1 and (b) 6 passes, respectively.



(a)

(b)

Fig. 2 Distributions of hardness contours along longitudinal sections of billets processed by ECAP through (a) 1 pass and (b) 6 passes, respectively.

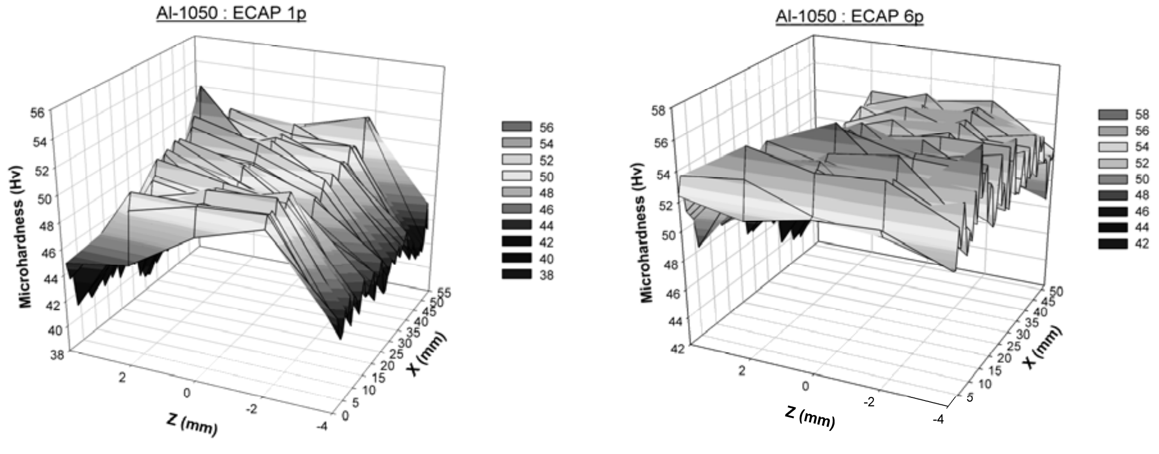
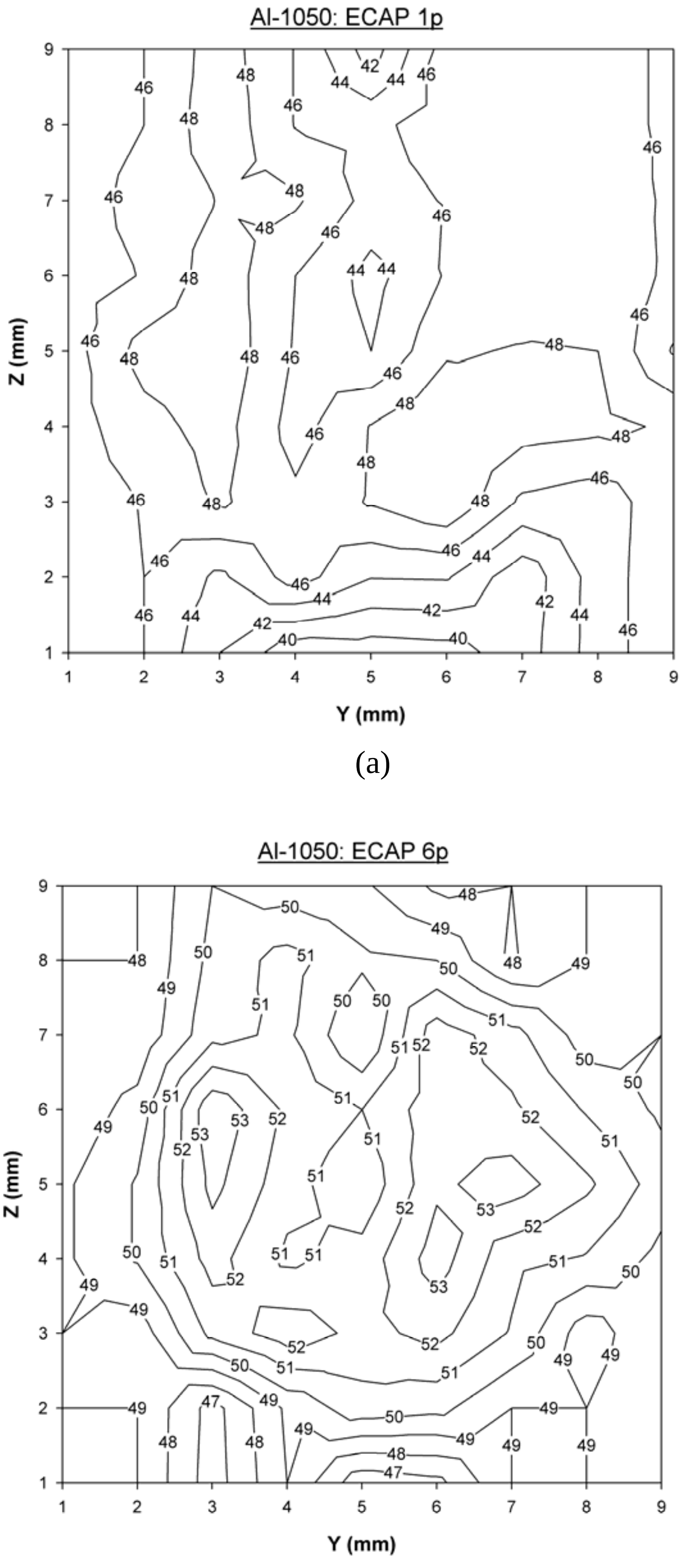


Fig. 3 Three-dimensional representations of the hardness distributions on the *Y* plane after processing by ECAP through 1 pass on the left and 6 passes on the right.

It is apparent from Fig. 1(a) that processing through a single pass introduces a significant hardening into the alloy. This can be seen by comparing the experimental datum points and the lower broken line which denotes the as-received and unpressed condition. Furthermore, the individual hardness values are reasonably constant along each linear traverse, thereby demonstrating there is a good longitudinal homogeneity over a central length of at least 52 mm within the billets having initial lengths of 65 mm. This result therefore confirms earlier similar longitudinal measurements on an Al-6061 alloy [11]. However, there are differences in the average values of Hv which depend upon the precise location of the linear traverse on the longitudinal face. Thus, the hardness values are highest, with an average value of Hv ≈ 50, along the centre line of the billet, whereas the lowest hardness values of Hv ≈ 40-45 are recorded along a traverse at 1.0 mm from the bottom surface. For the traverse at 1.0 mm from the top surface, the hardness values are also low but they are higher than in the vicinity of the bottom surface. By contrast, Fig. 1(b) shows the development of good hardness homogeneity along the central line and at the upper surface after a total of 6 passes, with an average value of Hv ≈ 53-55, but with lower values of Hv recorded in the vicinity of the lower surface. Furthermore, the values of Hv along the lowest traverse are especially low towards the front of the ECAP billet.

More detailed information is given in Fig. 2 by plotting hardness data taken over the longitudinal faces in the form of contour maps for (a) 1 pass and (b) 6 passes, respectively. Again the lower hardness values at the upper and lower surfaces are clearly visible in Fig. 2(a) and in Fig. 2(b) the lower values of Hv occur adjacent to the bottom surface and especially near the front of the billet. Following the procedure introduced in plotting hardness data for the Al-6061 alloy [11], these various hardness values may be presented in a clear pictorial way by constructing three-dimensional representations as shown in Fig. 3 for 1 and 6 passes, respectively. These representations provide a clear illustration of the lower hardness values occurring at the edges in the early stages of processing and the more uniform hardness ditributions that develop with further pressing.

Contour hardness maps for the transverse sections are shown in Fig. 4 for (a) 1 pass and (b) 6 passes, respectively. It is apparent from Fig. 4(a) that there are lower values of hardness near the bottom surface, thereby supporting the results obtained on the longitudinal sections. However, in Fig. 4(b) after 6 passes the average hardness values are higher and there is more homogeneity throughout the cross-section.



(a)

(b)

Fig. 4 Distributions of hardness contours along transverse sections of billets processed by ECAP through (a) 1 pass and (b) 6 passes, respectively.

The results obtained in this investigation demonstrate the gradual evolution towards a reasonably homogeneous structure in the Al-1050 alloy after processing by ECAP, except possibly in a small area immediately adjacent to the lower surface. Within this lower region, the values of the Vickers microhardness recorded after 6 passes remain slightly lower than in the bulk of the billet. Nevertheless, it is concluded that good homogeneity is generally attained in processing by ECAP provided the pressings are continued through a sufficient number of passes. This conclusion is important because of the recognized potential for using SPD processing in industrial applications as, for example, in the fabrication of high-strength micro-products such as gear wheels [13] and in the manufacture of ultrafine-grained wires [14] or parts for micro electro-mechanical systems (MEMS) [15]. The development of good homogeneity confirms the capability of processing these and other parts with a high degree of reproducibility.

Summary and conclusions

1. Hardness measurements were taken on a commercial purity aluminium alloy after processing by ECAP through either 1 or 6 passes at room temperature.
2. The results demonstrate a significant hardness increase in the first pass and some further increase in subsequent passes. The hardness values are lower near the top and bottom surfaces in the first pass but there is reasonable homogeneity after 6 passes except in a narrow region adjacent to the bottom surface.
3. It is concluded that good homogeneity may be obtained in the Al-1050 alloy after 6 passes of ECAP except for a narrow region along the bottom edge of the billet.

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