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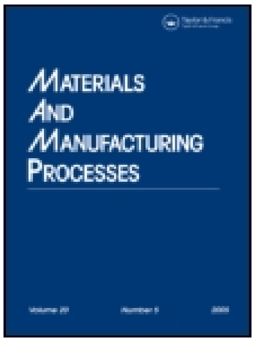

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Forming of Tubular Commercial Purity Aluminum by ECAP

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The equal channel angular pressing (ECAP) process is a promising technique for imparting a large plastic deformation to materials without a resultant decrease in cross-sectional area. In the present study, the suitability of this technique for the processing of tubular specimens has been investigated. Commercially pure aluminum was selected for the study. Tubular specimens were extruded to three passes using four processing routes through an ECAP die with an angle of 150° between the two intersecting channels. Sand was used as a mandrel during the pressing. Analysis of force–stroke diagram was carried out. The mechanical properties were also investigated. Improvement in mechanical properties was observed in all the routes. These investigations demonstrate that ECAP is a promising technique for improving properties of tubular materials while ensuring retention of shape (with the possibility of imparting further deformation to the specimen using the same die) and with low pressing pressures.

Keywords Aluminum; Aluminum tube; ECAP; SPD.

Introduction

Plastic deformation is an effective method of structure alteration and properties improvement of different materials. Among the recently developed severe plastic deformation (SPD) techniques, equal channel angular pressing (ECAP) is a novel deformation process capable of introducing large amount of plastic strain to bulk material by application of uniform simple shear [1]. A schematic diagram of ECAP die with round corner intersections is shown in Fig. 1. The die used for ECAP consists of two channels of equal cross-section that meet at an angle of 2 φ. A well-lubricated billet of almost the same cross-section is placed in the top channel and extruded into the intersecting channel by a punch [2, 3]. The main advantage of the ECAP process is that materials can be deformed to very high strains without any decrease in cross-sectional area. ECAP process has the ability to obtain ultrafine-grained material with submicron or nanometer sized grains with enhanced mechanical properties [4–10]. Most of the published research has dealt with fundamental issues in materials science such as development of subgrain structures, grain refinement, formation of shear bands, and development of texture in solid materials. Limited articles related to property enhancement of tubular specimens using ECAP have been reported [11, 12].

The aim of the present work is to study the candidature of the ECAP process for processing of materials in tubular form. Commercially pure (CP) aluminum was used for the study. Force–stroke data were recorded. Parameter that characterizes the resistance to flow during extrusion is the surface area/volume ratio of the specimens (referred to as the shape difficulty factor, SDF). As the shape difficulty factor is high in tubular specimen geometries compared to solid shapes, significant differences are expected as far as extrusion/pressing pressures, microstructures, and mechanical properties are concerned. In general, the higher the value of SDF, the higher the pressure needed for extrusion. In extrusion of tubes, an addition to the extrusion pressure arises due to the presence of the mandrel. In the present study, sand was used as mandrel for maintaining tube concentricity and form. The use of sand as a mandrel transforms the pressing process into a friction aided process and this is expected to result in a reduction in the pressing pressure. Therefore, the influence of ECAP on tubular specimen in enhancing the properties with respect to conventional extrusion was considered to be of interest to study.

Experimental procedure

CP aluminum was chosen for this study. All the specimens were annealed at 300°C for 2 h and then furnace cooled. Specimens were tested at room temperature in a 250 T hydraulic press with a velocity of 13 mm/sec. The die used for ECAP consisted of two intersecting channels 20 mm in diameter intersecting at a die angle of 150° and outer corner angle 30° (as shown in Fig. 1). Tubular specimens of CP aluminum with outer diameter 20 mm, inner diameter 13 mm, and length 60 mm were used for the extrusions (shown in Fig. 2). The end thickness (t) of 3 mm was provided to support the mandrel (sand in this study). A 30° taper was made at one end of specimen to facilitate easy start of ECAP (as shown in Fig. 2). Three passes of ECAP were carried out with four different routes (Routes A, B_a, B_C, and C) with molybdenum disulfide as lubricant. In Route A processing, the specimen orientation was kept constant between passes, Route B_a the specimen orientation was kept 90° in clockwise and anticlockwise direction between passes,

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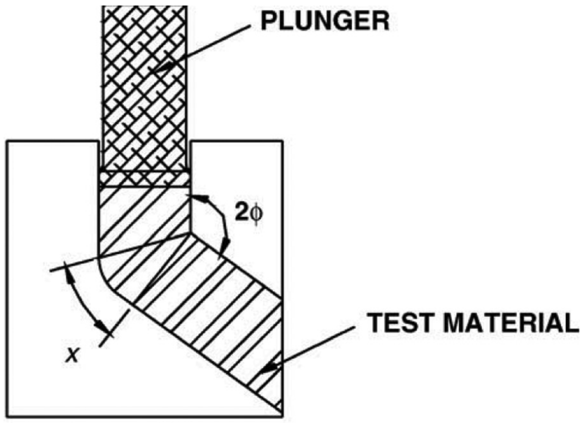

FIGURE 1.—Schematic diagram of equal channel angular pressing (ECAP) die with round corner.

Route B_C the specimen orientation was kept 90° in clockwise direction, while in Route C processing the specimen was rotated by 180° about its longitudinal axis between passes. After each pass, the specimen ends (the unextruded portion) were made straight, faced in a lathe, and the sample surface made smooth by using polishing papers. The specimens were then subjected to further pressing. The force–stroke diagram was recorded during the pressing and used in further analysis. Vickers microhardness measurements were carried out on specimens cut from each of transverse direction (perpendicular to ECAP direction) of the ECA pressed tubular specimens of different passes and using 300 gmf load. Figure 3 gives the schematic diagram showing direction of punch travel, mandrel, deformation zone, exit direction of extrusion, of the tubular specimen used for ECAP.

RESULTS AND DISCUSSION

After each pass, the Von Mises equivalent true strain (ϵ) that is imparted to the billet by shear through the die in plain strain is dependent upon the channel or die angle '2φ' and outer corner angle 'χ' and is given by Segal et al. [1] as the equivalent plastic strain

$$\varepsilon = \frac{2\cot(\varphi + (\chi/2)) + \chi \operatorname{cosec}(\varphi + (\chi/2))}{\sqrt{3},} \quad (1)$$

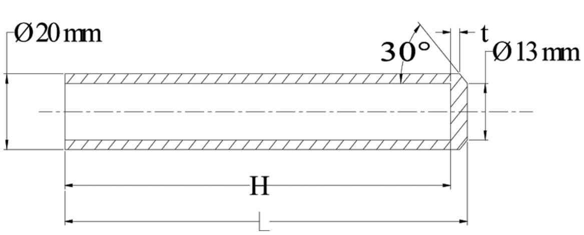

FIGURE 2.—Dimensions of the tubular specimen used for equal channel angular pressing ($L = 60$ mm, $H = 57$ mm, $t = 3$ mm). Inner and outer diameters of the tubes are 13 and 20 mm, respectively.

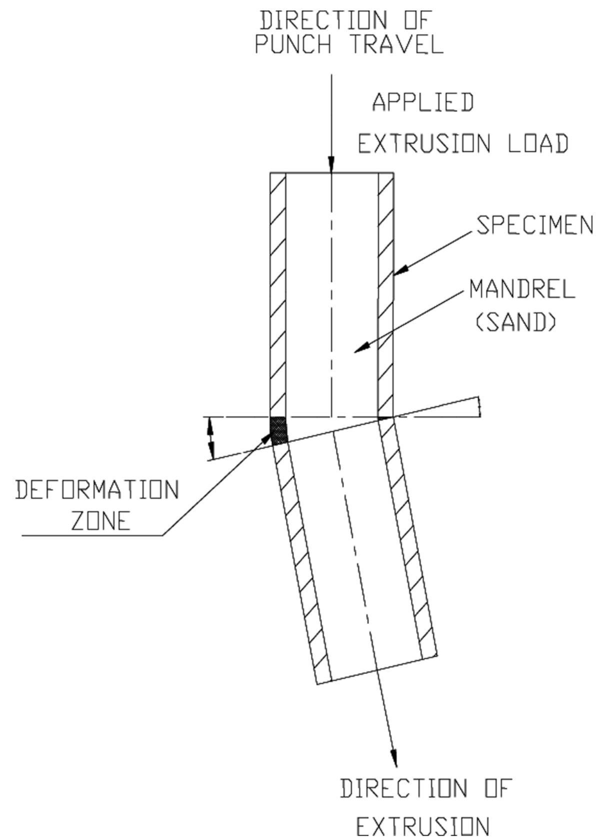

FIGURE 3.—Schematic diagram showing direction of punch travel, mandrel, deformation zone, exit direction of extrusion, of the tubular specimen used for ECAP.

where $2\varphi = 150°$and $\chi = 30°$ for the die configuration used in the present study. The equivalent true strain imparted to the sample after one pass is, therefore, 0.3.

Mechanical Property Evaluation

Vickers hardness number (VHN) for different number of passes and routes are shown in Fig. 4. The mechanical properties were improved.

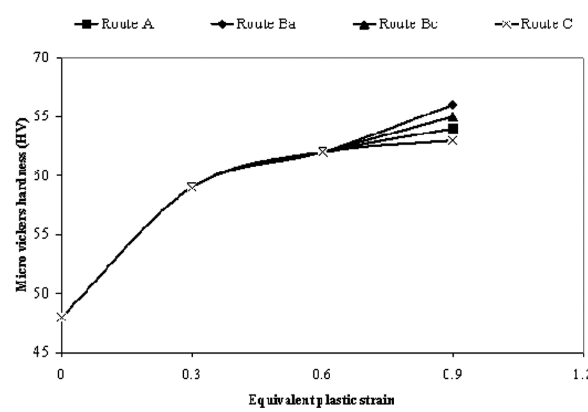

FIGURE 4.—Comparison of Vickers hardness of tubular CP aluminum processed by various routes of ECAP.

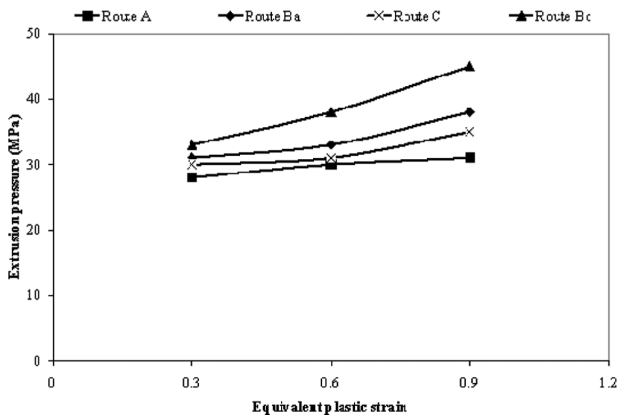

FIGURE 5.—Comparison of forming pressures during processing through ECAP by various routes.

The force–stroke diagram for extruding a 60-mm length tubular CP aluminum was found. After each pass of ECAP, the end of sample, i.e., unextruded portion of 5 mm sample was cut off. This causes a reduction in length of the specimen after each pass. Therefore, to compare the three different passes (for the purpose of calculations and comparison between passes) calculations were carried out for a stroke of 60, 55, and 50 mm, in each case. The observed peak force value is shown in Table 1 for each pass obtained from the force–stroke plots of several ECAP.

The comparison of extrusion pressure for various routes is shown in Fig. 5. It can be observed that extrusion pressure for ECAP increased from one pass to the next when processed through all routes. The magnitude of the increase in load was reported to be higher in Route B_C and least in Route A. The rate of increase is not significant except for Route B_C. This is may be due to the insignificant increase in SDF from one pass to the next.

Influence of SDF

To determine the influence of shape difficulty factor (which is defined as the ratio of the surface area to volume of the extruded specimens), data for the ECAP specimens from the current study were considered. In general, the higher the shape difficulty factor, the higher forming pressures are required. The comparison shown in Table 1 reveals that even though the ECAP specimens have high SDF, the peak pressing pressures recorded were very low compared to conventional extrusions of CP aluminum [13]. The hardness values are higher at

TABLE 1.— Comparison of peak extrusion pressure at comparable strains for specimens with various shape difficulty factors

Equivalent plastic strain	Surface area/volume ratio (SDF)	Peak extrusion pressure (MPa)			
		Route A	Route B_a	Route B_c	Route C
0.3	0.604	28	31	33	30
0.6	0.608	30	33	38	31
0.9	0.611	31	38	45	35

TABLE 2.— Comparison of Vickers hardness number at comparable strains for different routes

Equivalent plastic strain	Micro Vickers Hardness (HV)			
	Route A	Route B_a	Route B_c	Route C
0	48	48	48	48
0.3	59	59	59	59
0.6	62	62	62	62
0.9	64	66	65	63

higher strains when processed through ECAP. Even though the hardness of the material was improved when processed though ECAP (as shown in Table 2), the forming pressures required were lower when compared to conventional extrusion. This demonstrates that the ECAP process is advantageous in improving the properties for higher SDF specimens compared to conventional extrusion.

CONCLUSIONS

Tubular specimens of CP aluminum were subjected to three ECAP passes using four different processing routes. The force analysis shows that the force needed to process material along Route B_C are higher compared to other Routes. The increase in forming pressures for three passes required for CP aluminum (tubular specimen with high shape difficulty factor) processed by ECAP were insignificant except for Route B_C. The VHN of ECAP processed material increased for 0.3 and 0.6 strain but didn't show pronounced difference between various routes, but at 0.9 strain, Route B_a showed maximum hardness, and Route C showed the minimum hardness. The low pressing pressures during ECAP of tubular materials are due to the high heat retention capacity of sand and the movement of mandrel (sand) along with the specimen (hence the drag friction acts in the same direction as the main punch force). From these results it can be concluded that ECAP is a promising technique for improving properties of tubular specimens of CP aluminum and can be commercialized since global markets for SPD products are expected to triple between 2010 and 2015

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