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Abstract

A study is presented on the behaviour of an AA6082 aluminium alloy during ECAP. The pressing curves were analysed in terms of billet flow path along the cornered die. Analyses on samples taken from interrupted tests showed that a complex strain path system was active. Evidence of curvature of the original grain structure suggested that bending around the corner of channel intersection occurred and superimposed to shear deformation.

From comparisons between experimental pressing loads and numerical estimates based on simplified conditions, it was suggested that that frictional effects are of large importance and it was confirmed that other strain components differing from pure shear markedly affect the billet flow in the ECAP die.

Riassunto

Viene presentato uno studio sul comportamento della lega AA6082 processata mediante tecnica Equal Channel Angular Pressing (ECAP). Sono state analizzate le curve di pressatura considerando il flusso plastico della billetta all'interno dello stampo.

Analisi dedotte dalla struttura di campioni prelevati da prove interrotte hanno evidenziato la curvatura dei grani cristallini a cavallo della zona di intersezione dei canali dello stampo, dimostrando l'esistenza di un complesso stato di deformazione che si sovrappone allo stato di deformazione tangenziale ipotizzabile teoricamente.

Dal confronto tra i dati sperimentali sul carico di pressatura e le stime teoriche desumibili da condizioni di deformazione semplificate, si deduce che gli effetti dell'attrito assumono una rilevante importanza, confermando come le componenti di deformazione diverse dal taglio puro influenzino il processo di deformazione ECAP del materiale.

INTRODUCTION

One of the emerging and most effective routes to generate ultrafine structures in the nano- or submicrometer range of bulk metals is severe plastic deformation by equal channel angular pressing (ECAP). This technique is particularly promising for industrial applications since it is scalable to large billet sizes and leads to very fine and homogeneous microstructures [1-5].
The ECAP devices commonly used in research laboratories consist of a die containing two channels having the same cross-section and intersecting at an angle Φ. A second angle Ψ is commonly set to define the curvature at the outer intersection of the two channels. Machined samples are used having a section that exactly fits that of the channels. The samples are pressed through the die by a plunger and the process is repeatedly carried out on the same sample to attain the desired amount of deformation.
The theoretical deformation accumulated by passing through the die can be estimated by the Iwahashi equation considering ideal conditions of simple shear and homogeneous deformation over the cross section [6], being N the number of passes and Φ and Ψ the above defined angles.

$$\varepsilon_N = \frac{N}{\sqrt{3}}\left(2\cot\left(\frac{\Phi}{2}+\frac{\Psi}{2}\right)+\Psi\,\mathrm{cosec}\left(\frac{\Phi}{2}+\frac{\Psi}{2}\right)\right) \qquad (1)$$

However, detailed studies on actual deformation path showed that when the outer corner angle Ψ becomes large, a bendinglike deformation near the curvature is introduced [7-10]. Frictional effects can also play an important role in defining the homogeneity of strain distribution close to the surface of the billet [7,11,12].
Data and interpretation of the loading curve (load vs. ram position during pressing) are available from several experimental and finite element analysis works [4,9,11]. Segal [13] showed that the theoretical pressing load under simple shear deformation and in absence of friction condition can be calculated from:

$$\frac{P}{Y} = \Delta\varepsilon_i \qquad (2)$$

being P the working pressure, Y the flow stress of the processed material and $\Delta\varepsilon_i$ the strain imparted during one single pass. This equation revealed to be reasonably accurate especially when testing pure aluminium with a low friction die [11]. Indeed, experimental tests confirmed that friction is of secondary importance in defining the applied

load, the main parameter being material strength [4].
From the analysis of the current literature, it appears that relatively little attention was paid on the effects of material behaviour, process condition and tooling design on metal flow during ECAP. It is the aim of the present paper to share the experience gained on laboratory processing an Al 6082 alloy and to supply data about the material behaviour during pressing.

MATERIALS AND EXPERIMENTAL PROCEDURES

Commercially available extruded bars of an AA6082 Al alloy having a diameter of 10 mm were considered for this study. Samples of 100 mm length were cut from the bars and subjected to thermal treatments. Two different tempers were selected for the present investigation. A first set of samples was solution treated (530°C for 2 hours and water quenching) whereas a second set of samples was studied in the annealed condition (530°C for 2 hours and slow furnace cooling).
The facility for ECAP processing the samples was based on a system of two symmetrical half dies machined from two blocks of H11 tool steel, heat treated to achieve a nominal hardness of 45 HRC. Cylindrical channels having a diameter of 10 mm were machined with a configuration characterised by angle values of $\Phi = 90°$ and $\Psi = 20°$. In Figure 1 the geometry of a single half die is depicted. Previous practical experiences had shown that a calibrated length of 10 mm after the corner followed by an enlargement of the exit channel could reduce friction and thus lower the pressing load. With the aim of further reducing friction and increasing wear properties, once the channels had been machined and heat treated, the two half die were ion nitrided. The two half dies were assembled and held together with 6 bolts having a diameter of 20 mm. The outer dimensions of the assembled die were approximately 160x160x185 mm^3. A plunger was obtained by the design of a dedicated fixturing device to be installed on the load cell, so as to record plunger load and displacement during pressing. A centering device was also used to precisely centering the die with respect to the plunger, before each testing session.

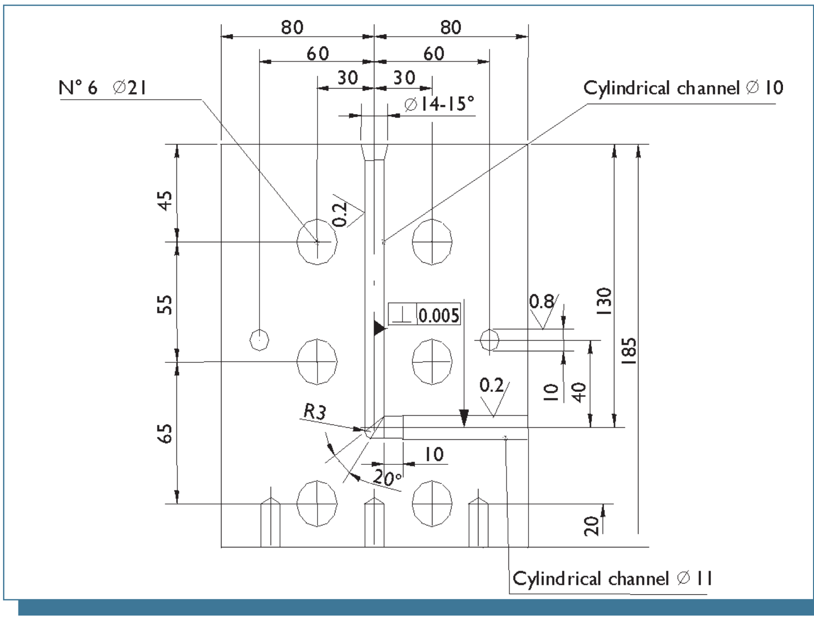


Fig. 1: Geometry of a half die used for ECAP processing the materials

ECAP testing was carried out at room temperature. The samples were coated with a lubricant based on molybdenum disulphide. Several specimens were pressed consecutively and repeatedly to accumulate the desired plastic deformation. Samples processed with either route B_C (rotation of 90° in the same sense between each pass) or C (rotation by 180° of the sample between each pressing) were produced. Up to 4 and 6 repeated passes were carried out by route B_C and C, respectively. Finally, a limited number of interrupted tests was also carried out to collect samples processed only along half of their length.
After processing, the samples were longitudinally sectioned for optical microscopy and microhardness analyses. Transmission electron microscope (TEM) samples were also prepared starting from 1 mm thick disks transversally cut from the samples.
Mechanical testing was carried out at room temperature at a engineering strain rate of $1{,}5 \cdot 10^{-3}$ s^{-1} on specimens with a gauge length of 30 mm and a diameter of 6 mm.

RESULTS AND DISCUSSION

In Figure 2 representative curves recorded during processing of the materials are reported. The annealed AA6082 alloy revealed to be well suitable to room temperature pressing according to both route B_C and C. By slowly pressing at a plunger displacement rate of 10 mm/min, 4 and 6 pressing cycles were carried out for route B_C and C, respectively, without evidence of material damage. On the contrary, in the solution treated condition, only ECAP pressing under route C could be performed satisfactorily. Diffused shear cracking formed starting from the third pass of route B_C pressing and evidence of sample damage was also inferred from the serrated shape of the loading curves, as shown in figure 3.

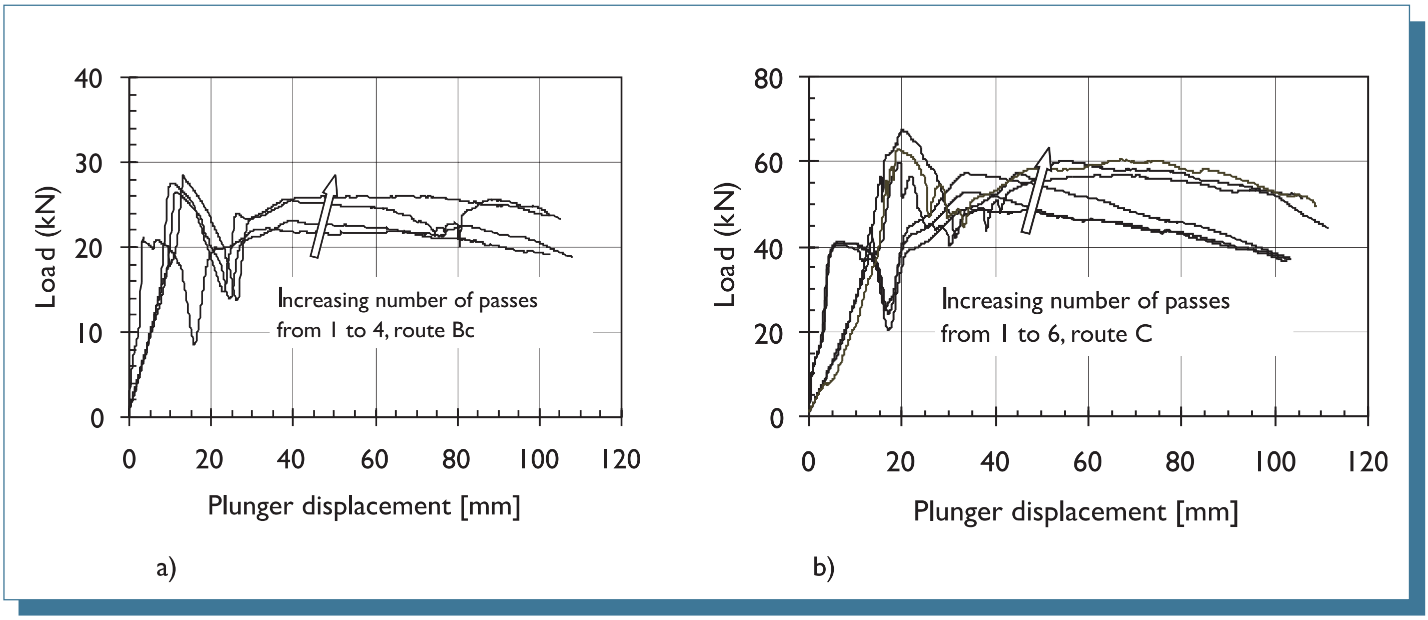


Fig. 2: Pressing load vs. plunger displacement recorded during ECAP tests of the samples; (a) route B_C, annealed alloy(b) route C, solution treated alloy.

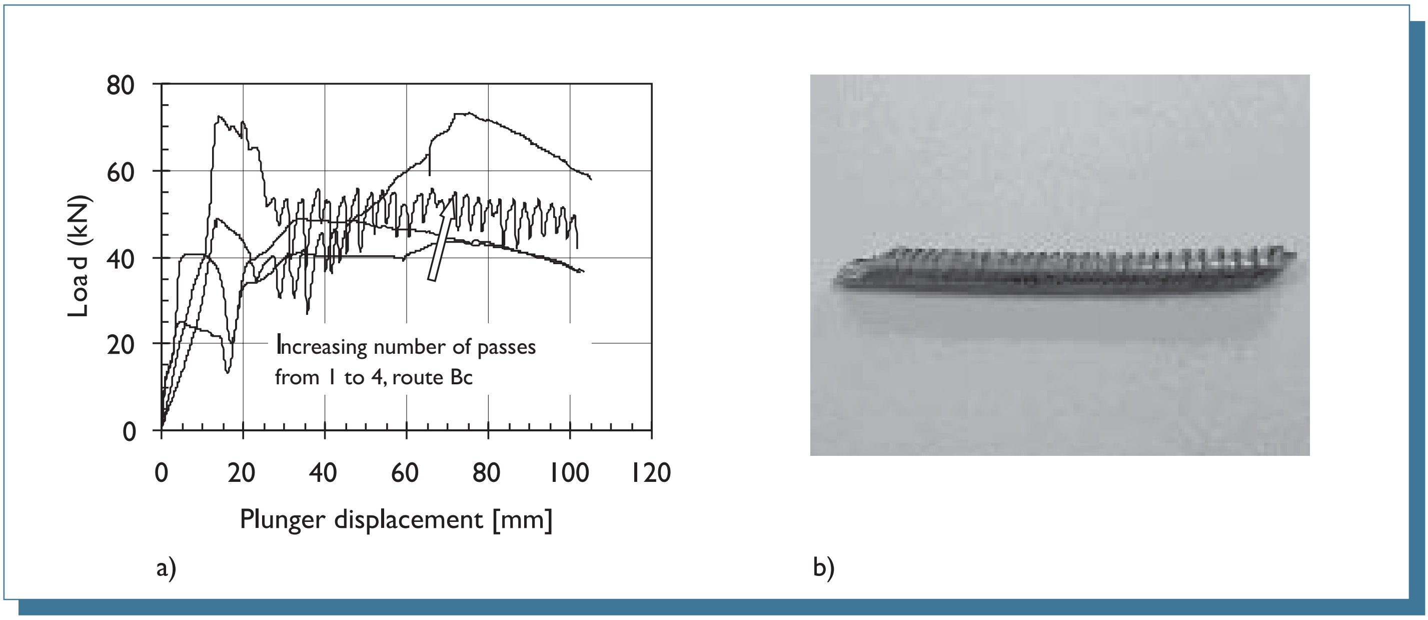


Fig. 3: Loading curves of the solution treated samples pressed according to route B_C (a) and corresponding sample aspect after 4 passes (b).

The reported load vs. plunger displacement curves for a single test are apparently composed by two loading ramps. Explanation to this apparently inconsistent behaviour can be found considering that the expulsion of a partially pressed sample can be achieved only by inserting a new sample in the upper channel of the die. Therefore, the first sector of the loading curve, consisting of a rapid rise up to a relative peak and a steep decrease of the load, are to be viewed as the expulsion phase of a previously pressed sample.

Analysis of the curves will be limited to the loading ramp following the minimum at the end of the expulsion phase. The general shape of the loading curves given in Figure 2 is in good agreement to that reported by Shan and co-workers referred to a low-friction rectangular-section channel die [11] and to finite element method (FEM) simulations published in [9]. The starting rapid increase in load is supposed to be due to the initial accommodation of the sample along the channel curve and to progressive increase of deformed material volume. After this phase, a marked decrease in slope of the curves or even the formation of a relative minimum of the load was recorded (see for instance fig 2a). This behaviour was also encountered in several published loading curves of ECAP processed materials [9,11,14]. According to FEM analysis carried out by Kim [9], the relative minimum peak could be related to onset of a regular and continuous flow across the main deformation zone of the die corner. The following rise of the pressing load is believed to be due to the establishment of full contact and constraint between the initial part of the sample and the exit channel surface. Eventually, a plateau or steady state flow condition is encountered, possibly related to entrance of the sample in the final portion of the exit channel, where a gap exists between the die and the sample (see Figure 1 for details).

When considering the expulsion phase of the samples, emphasis should be made to the different sets of initial loading ramps that can be identified for both route B_C and route C. Figure 2a reveals that the loading profile corresponding to the first pass features an initial steep rise followed by a rapid decrease down to a low minimum value. On the contrary, in the second to fourth passes, the load increases less rapidly but generally reaches higher values before decreasing to the minimum peak. Similar observations can also be drawn from Figure 2b, when considering the behaviour of the first three passes as opposed to that of the fourth to sixth passes. An explanation to this trend can be suggested by considering that expulsion of a partially pressed sample could be achieved only by inserting a new sample in the upper channel of the die. It is suggested that the degree of matching of the edge regions of a pair of samples (the tail of the processed sample contacts the head of a new sample inserted in the entry channel) would strongly affect the loading curve. When pressing according to route B_C, each sample is rotated by 90° before being inserted for further passes. During second pass, a sample head, whose edge was sheared by approximately 45° during the first pass, would contact the tail of the previously pressed sample with a high degree of mismatch, inducing an extensively localised plastic strain before the plunger displacement is fully transferred to force out the first sample. This would result in a lower slope of the initial curve and in higher friction in the entry channel, leading to a higher peak load. On the contrary, during route C processing, the samples are rotated by 180°. During the second pass, the tail of a first-pass processed sample would contact the head of a sample to be processed for the second pass with a theoretically ideal matching, the two contacting edges being both sheared by 45° in the same direction. Eventually, repeated pressings by route C generated localised edge cracking (after about four passes in the present investigation) and irregularities on sample edges. Correspondingly a modification of the loading curves was observed, similarly to what found for route B_C after the first pass.

Observations on structure deformation during ECAP were conducted by sectioning samples that had been subjected to interrupted tests and collected by separating the two die halves. In Figure 4 the microstructure of a solution treated AA6082 alloy sample during processing is depicted. In particular, Figure 4b shows the samples microstructure at a region close to the line bisecting the two channels. It is inferred that with the present die angles ($\Phi = 90°$ and $\Psi = 20°$) and friction conditions, alternative deformation systems are acting on the sample in addition to the expected pure shear. The marked grain curvature highlighted in the micrograph demonstrates that gradual bending along the corner occurs and superimposes to the shear deformation.

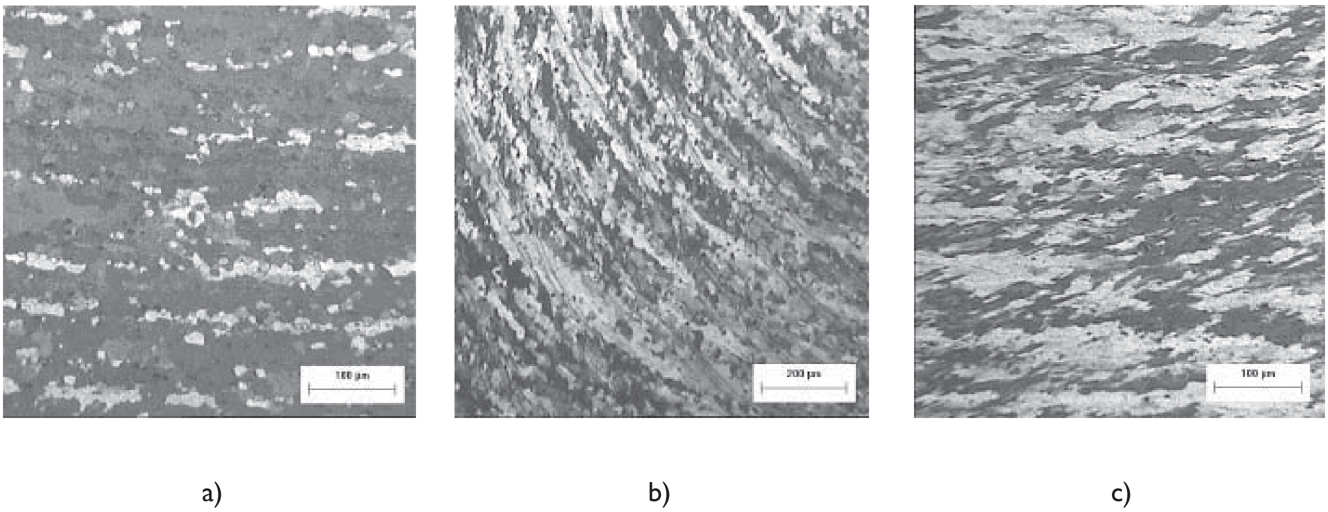


Fig. 4: Evolution of microstructure during first pass of ECAP processing. (a) as solution treated; (b) at channels intersection during first pressing; (c) at end of first pressing.

This conclusion is indeed in good agreement with FEM analyses and experimental works [7,9,12] showing that, although almost pure shear can be produced in sharp cornered dies and under no friction conditions, the actual strain path often found in experimental laboratory conditions (i.e. Ψ greater than zero and significant contact friction) induces additional strain components (e.g. tension and compression strains) and irregularities of the shear path due to friction, especially in the material regions close to free surfaces of the billet.

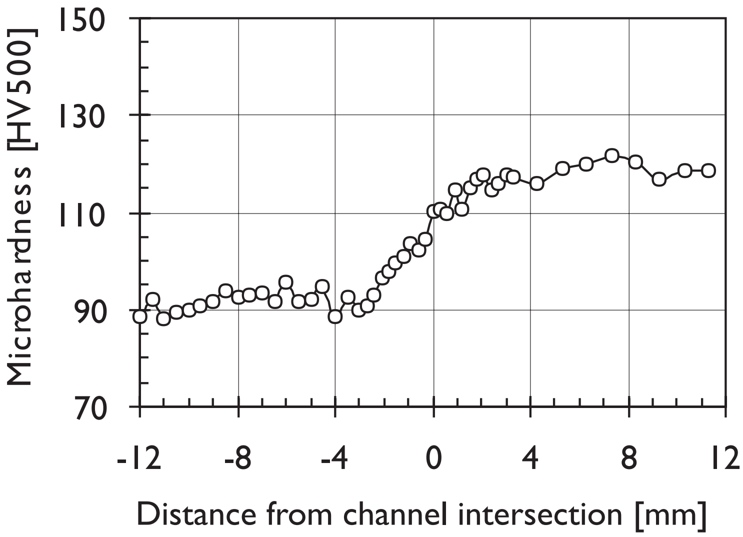
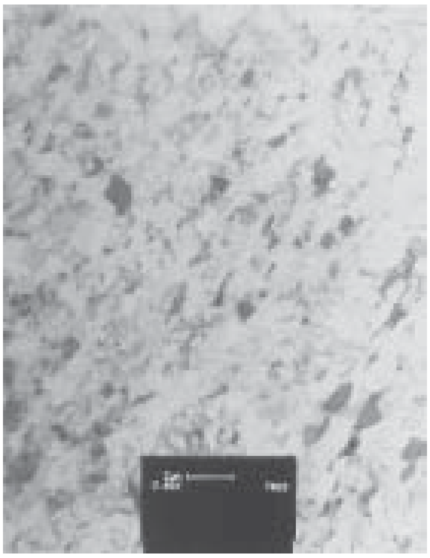


Fig. 5: Microhardness profile along sample longitudinal axis in the region close to intersection of channels [15]

It is also known from FEM studies that when round cornered dies are used (large values of Ψ), the theoretically narrow zone of shear deformation located at a plane bisecting the channels spreads over a larger area [7]. Experimental evidence of this behaviour was also found in the present study by microhardness measurements of interrupted ECAP samples. Figure 5 shows a microhardness profile along the sample longitudinal axis clearly demonstrating the extension of the region subjected to straining at the moment of test interruption. Considering that the origin of the X axis was taken at the point of interception of the two channels, it is possible to estimate that the deformation zone approximately extended 3 mm in the entry channel and 2 mm in the exit channel with respect to the theoretical shear plane [15].
A detailed microstructural investigation on grain and subgrain evolution during ECAP processing by TEM analyses is beyond the scope of the present paper. However, representative micrographs of the submicrometer high-angle grain structure achieved after four ECAP pressings is given in figure 6 for sake of completeness. The observations showed that a elongated subgrain structure formed during the first pass of ECAP processing. These elongated subgrains were then sheared and fragmented into small equiaxed grains separated by low-angle boundaries, precursors of high-angle grains formed after four passes [16].

a)



b)

Fig. 6: TEM micrographs of the AA6082 alloy after (a) 4 and (b) 6 passes according to route C.

Finally, the mechanical properties of the processed samples were evaluated by tensile tests on the samples subjected to ECAP [15]. The typical stress vs. strain curves are reported in figure 7 while relevant tensile data are summarised in Table 1.
From tensile curves it is clearly inferred that the ECAP processed materials underwent a dramatic workhardening after the first pressing. For the present alloy and processing route, tensile and yield strength continuously improved up to the fourth pass. Further passes apparently generated a saturation in alloy properties. As expected, fracture elongation significantly reduced after the first pressing. However further ECAP processing did not induce significant depletion in ductility, typical final elongation values ranging from about 6 to 9%.

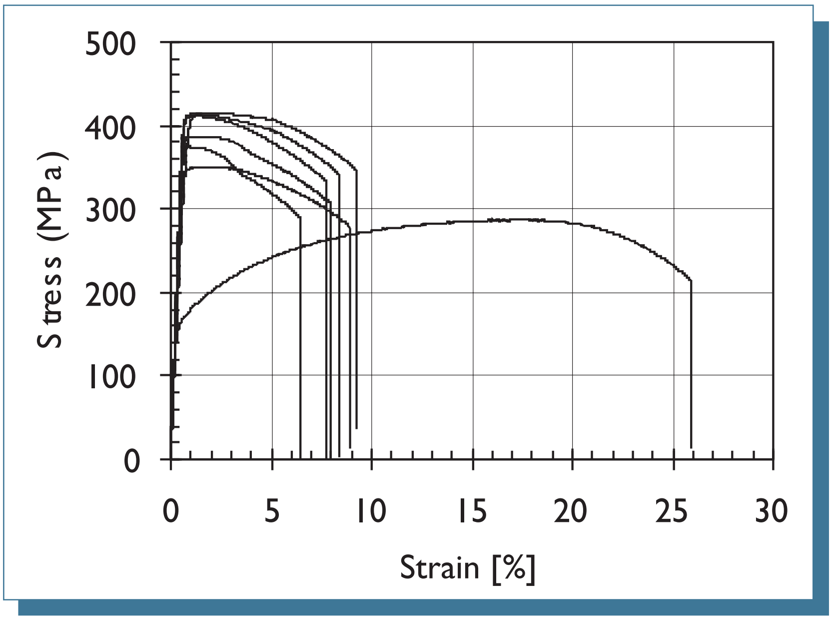


Fig. 7: Tensile curves of the solution treated alloy ECAP processed for passes 1 to 6, according to route C.

Table 1. Tensile properties of the ECAP processed materials

Temper	Route	Passes	UTS (MPa)	0,2 YS (MPa)	Fracture elong. (%)
Solution treated	-	-	283,3	158,2	25,6
Solution treated	C	1	350,3	345,0	8,9
Solution treated	C	2	374,5	374,1	6,5
Solution treated	C	3	386,7	383,3	8,0
Solution treated	C	4	411,6	407,5	7,7
Solution treated	C	5	413,7	410,1	8,4
Solution treated	C	6	416,0	392,4	9,3
Annealed	-	-	137,9	77,4	22,8
Annealed	B_C	4	236,7	211,4	9,4

Table 2. Pressing loads of the solution treated materials processed according to route C

Passes	Maximum load (kN)	Load at deflection (kN)	Predicted load (kN)*
-	-	-	-
1	48,8	39,5	23,4
2	52,9	42,9	29,0
3	57,2	46,1	31,0
4	57,0	50,4	32,0
5	60,3	49,2	34,1
6	60,5	52,3	34,3

* Predicted values calculated according to equation 2

Table 2 supplies further information on pressing loads that were required to produce the billets. The data are useful to draw a comparison between the experimentally recorded pressing load and the estimated load given by equation (2) implying simple shear deformation and absence of friction. As suggested by Shan et al. [11], in addition to the highest load recorded during the test, also the load at flexus corresponding to above described decrease in slope of the curves or at the formation of a relative minimum was considered. The predicted pressing loads given in the last column of table 2 were calculated by assuming a flow stress Y equal to the ultimate tensile stress value. The strain $\Delta\varepsilon_i$ given at each pass was assumed to be 1,055 for the present die geometry, in accordance to equation (1).
The theoretical prediction revealed to be systematically lower than the recoded loads by 30 to 40%, thus suggesting that frictional effects are of large importance and that other strain components differing from pure shear markedly affect the billet flow in the ECAP die. The above suggestions are indeed in good agreement with several research studies based on numerical and/or experimental modelling of the process that stressed the complex strain path of the billets severely deformed by ECAP [7,9,10,14].

CONCLUSIONS

A laboratory ECAP test rig was used to study the behaviour of an AA6082 commercial alloy under different starting tempers (solution treated and annealed) and pressing conditions (route B_C and route C). The investigation allowed to draw the following conclusions.

- Route C revealed to be less critical for sample integrity during ECAP processing. Six passes could be easily performed on solution treated samples whereas extensive cracking occurred just after three passes in samples processed according to route B_C. As expected, the annealed alloy featured an improved workability and four passes could be performed according to route B_C.
- The recorded pressing load vs. plunger displacement curves suggested that a regular flow of the billet could be achieved by the present experimental conditions. Analysis of the shape of the curves was interpreted in terms of billet flow along the cornered die. It was shown that the expulsion of a partially pressed sample by inserting a new sample in the upper channel of the die is ruled by the degree of matching of the edge regions of the pair of samples. The different conditions encountered as a function of the route adopted and of the amount of passes experienced by the billets strongly affected the loading curve.
- Analyses on structure deformation and of microhardness carried out on samples subjected to interrupted ECAP pressing showed that a complex strain path systems was active in the samples in addition to pure shear. Evidence of curvature of the original grain structure suggested that bending around the corner of channel intersection occurred and superimposed to shear deformation. The extension of the ECAP deformation zone was estimated to be of the order of 5 mm (3 mm in the entry channel and 2 mm in the exit channel) from microhardness profiles.
- The availability of the tensile strength data and of the pressing loads required to process the samples allowed to check the predictions obtainable from a simple equation assuming pure shear deformation during ECAP. The theoretical prediction revealed to be significantly lower than the recoded loads, thus suggesting that frictional effects cannot be neglected and confirming that other strain components differing from pure shear markedly affect the billet flow in the ECAP die.

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