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AGING BEHAVIOUR AND MECHANICAL PROPERTIES OF AL ALLOY DEFORMED BY ECAE

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ABSTRACT

Equal Channel Angular Extrusion (ECAE) is a Severe Plastic Deformation (SPD) technique, used to obtain ultrafine-grained microstructures. In the present investigation, specimens of aluminium alloy 6101 were subjected to ECAE and conventional cold extrusion. Differences in mechanical behaviour were investigated as a function of processing routes. Aging behaviour was studied at a constant temperature of 175 ^{o} C for various time periods. Microstructural studies and hardness measurements were carried out in the extruded condition. Hardness results showed that both conventionally extruded ECAE subjected samples and processing route A of ECAE exhibits a similar behaviour attaining peak hardness value at lower aging time.

Keywords: Aging, Equal Channel Angular Extrusion (ECAE), Aluminium alloy.

1. INTRODUCTION

Recently, Nano and near-nano sized materials has occupied a major role in materials science due to their high tensile properties at room temperatures without much loss in ductility and their potential for superplastic behaviour. SPD is an approach in which a material is subjected to very large plastic strain to refine grains and other microstructural features. The most widely used deformation methods are: Equal Channel Angular Extrusion (ECAE), Multi-Step Forging (MSF) and Torsion Under Compression (TUC).

ECAE as a "near ideal" deformation method due to simple shear[1-3] is capable of reducing the grain size of materials to, typically the sub micrometer level.[4] Figure 1 shows the schematic diagram of an ECAE die .In the figure, 2ϕ represents the channel or die angle and χ represents the outer corner angle. The work piece is pushed down from one channel to the other with the help of a plunger and the cross sectional area of the specimen remains the same before and after a processing step. Thus it is possible to subject one specimen several times to ECAE in order to reach highest degrees of plastic deformation. Typical values of channel angle are from 90° to 135°.

Different processing routes are commonly employed in ECAE.[5], based on billet rotation about the extrusion axis: no rotation gives rise to route-A, 180° rotation leads to route-C while an alternative 90° rotation leads to route- B_A and clockwise 90° rotation leads to route- B_C. Selection of proper route is vital to refine grain size and to obtain improved mechanical properties.[6-9] Evolution of microstructure occurs more rapidly with route B_C, less rapidly with route C, and it is slowest when using routes A or B_A[10] due to the reversal of shear plane direction between consecutive passes or constant strain path in different passes.[8]

Several studies have shown that during ECAP deformation, misorientation angle ranges from low to high angles (>15°), and the deformed structure can vary from dislocation wall (DW), partially transformed boundary (PTB) to grain boundary (GB) [11]. Similarly, the dislocation cell size and the average misorientation angle across the dislocation cells increase with the accumulated strain[12-14]. In this study, the effect of processing route on mechanical properties and the aging behaviour has been investigated.

2. EXPERIMENTAL PROCEDURE

In the present study, aluminium 6101 alloy, which has a chemical composition (in wt.%) of 0.39 Si, 0.44 Mg, 0.49 Fe, 0.002 Cu, 0.004 Mn, 0.007 Zn and rest Al was selected. The alloy was solution annealed at 510°C for 1h and immediately quenched in water. Specimens of 20mm diameter and 105mm height with a taper of 10° at one end (to facilitate easy start of ECAE) were prepared from the solutionized aluminium alloy. A 120° channel angle die was designed for the present study, which imparts 0.67 equivalent plastic strain per pass to the sample. Specimens were equal channel angular extruded for 3 passes using two different routes A (no rotation of sample between consecutive passes) and route B (180° rotation about its longitudinal axis between consecutive passes) with mutton tallow as the lubricant. Similarly, specimens of 20mm diameter and 40mm height were conventionally cold extruded (CE) in a die with a strain of 0.65, which is almost equivalent to strain imparted by ECAE in one pass. In order to study the deformation behaviour of ECAE processed materials when processed further through conventional technique, specimens of Pass 1,Pass 2A and Pass 2B of ECAE were cold extruded using a conventional forward extrusion die.

Tensile specimens with a gauge diameter of 4mm were made as per the ASTM sub-size standards and were tested for all the ECAE processed, conventionally extruded samples. Ultimate Tensile strength and % Elongation to failure were measured. Vickers Hardness measurements were made in both directions perpendicular and parallel to extrusion at a load of 2 Kg in an Otto-Wolpert machine. Ten readings were taken for calculating mean hardness. Transmission electron microscope (TEM, Philips CM 200) was used to examine the microstructure and specimens were cut using a diamond wheel cutter, then subjected to twin jet electro polish. Grain size was measured by intercept method at different places of photos taken from the different regions of the sample and the average value of these measurements was reported.

Aging treatment was done at a constant temperature of 175° C for a time period of 1.5,3,4.5,6,7 and 8h for all the ECAE processed and conventionally extruded samples. For the aging treatment, specimens were cut in the extrusion direction and aged. Hardness measurements were taken and were compared with that of the starting condition.

3. RESULTS AND DISCUSSION

3.1 Mechanical properties of the as deformed material

3.1.1 Tensile strength

Ultimate tensile strength and % elongation to failure for different processing routes of ECAE, conventional cold extrusion with respect to strain imparted is given in Figures 2 and 3 respectively. In both the figures, 0 strain corresponds to the initial solutionized material. The tensile strength of the ECA extruded samples increased up to 2 passes for both the routes, but the difference is more in route B rather than route A, which may be due to the reversal of strain path [8]. The strength decreased in the 3rd pass for both the routes, which may be due to the reduction in work hardening after 2nd pass. Tensile strength depends on the strength of the dislocation walls generated in the previous deformation step rather than only the grain size. The reason is the disruption and partial dissolution of the original dislocation substructure that operated in the previous deformation step[15]. The % elongation to failure exhibits drastic decrease after the 1st pass of ECAE, however it remains the same or increases slightly on further passes. Similarly, conventionally extruded pass 2 ECAE subjected samples showed improved strength compared to ECAE specimens, with little decrease in % elongation to failure. This may be due to the activation of inactive slip plane that were present in the prior deformation step.

3.1.2 Hardness

The average values of Vickers hardness number taken in the longitudinal direction of the extrusion for different processing conditions of ECAE and conventional extrusion with strain is provided in the Figure 4. The changes in hardness was almost same for all the passes of route A, but was more for pass 2 of route B and decreased drastically further in the 3rd pass. The increase in hardness of the pass 2B ECAE samples may be due to the reversal of strain path[8]. Similarly, the decrease in hardness of pass 3B ECAE samples may be due to the reduction in work hardening[15]. Likewise, there is not that much of variation in hardness of the conventionally extruded ECAE subjected samples with that of the prior deformed condition. The reason may be due to the stabilisation of grain size in the sub micron range with increasing deformation for aluminium and its alloys.

3.1.3 Microstructural evolution of the ECAE deformed material

The microstructure of the as deformed ECAE processed material for various routes is shown in Figures 5a-d. The average grain size of the initial solutionized sample is ~150 μm and the grain size was refined to 0.46 μm and 0.55 μm respectively for routes A and B after 3 passes.

3.2 Hardness of the aged material

Hardness variations with aging time for all the ECAE processed and ECAE processed samples subjected to conventional extrusion are given in the Figures 6a and b respectively. . Similarly, Table 1 shows the values of peak hardness and the peak aging time of the ECAE processed and ECAE processed samples subjected to conventional extrusion. Samples of solutionized, pass 3B of ECAE, conventional extrusion of solutionized, pass 1 and pass 2A ECAE subjected samples showed normal aging behaviour with time period due to continuous coarsening of grains, while remaining samples showed variations in hardness with time period. The difference in the average misorientation angle between the grains and the average cell size increased with increasing deformation. During aging of this deformed structure, at some places there will be gradual reduction in dislocation density both at the grain boundaries and inside the grains that results in the coarsening of the grains. But some of the dislocations arrange to form equi-axed sub-boundaries and these newly formed sub-boundaries will not undergo any further grain coarsening. Due to this, the structure consists of mixed equi-axed and coarsened structure and this may be attributed for this variation in aging behaviour.[16-17]

4. CONCLUSIONS

1. Equal channel angular extrusion through route B (180° rotation about the longitudinal axis of extrusion) leads to better strength and hardness values without significant loss in ductility when compared to route A. This may be due to the reversal of strain path that leads to different dislocation configurations.

2. For initial strain $\varepsilon \approx 0.66$, both conventionally extruded and equal channel angular extruded samples gives same hardness but conventional extrusion showed increase in strength value

with reduction in ductility. The reason may be due to the weakening of texture with the development of low angle grain boundaries. To understand the clear phenomena, further texture studies has to be done on both conventionally extruded and equal channel angular extruded material.

3. For strain $\varepsilon \approx 1.33$, specimens processed through route B of equal channel angular extrusion showed improved mechanical properties rather than specimens processed through route A of equal channel angular extrusion and conventional extrusion of ECAE subjected samples.

4. For strain $\varepsilon \approx 2.01$, samples processed through both routes A and B of pass 2 ECAE subjected to conventional extrusion showed improved strength and hardness values with little reduction in ductility.

5. In ECAE processed materials, samples processed through route A attained peak hardness value at lower aging time than samples processed through route B. Similarly, conventionally extruded ECAE subjected samples attained peak hardness values at lower aging time when compared to ECAE processed samples. \

6. In general, samples processed through route B of ECAE attained high hardness value than samples processed through route A of ECAE irrespective of aging time. Similarly, conventional extrusion of solutionized and ECAE processed samples attained high hardness value than ECAE processed samples.

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TABLES

Table 1: Values of peak Vickers hardness number and peak aging time of the ECAE processed and ECAE processed samples subjected to conventional extrusion.

Condition	Peak aging time in hrs	Peak Vickers hardness number
Solutionized sample	7	39
Pass 1 ECAE sample	4.5	81
Pass 2A ECAE sample	4.5	79
Pass 2B ECAE sample	6	99
Pass 3A ECAE sample	5	76
Pass 3B ECAE sample	7	99
CE of solutionized sample	7	100
CE of Pass 1 ECAE subjected sample	4.5	88
CE of pass 2A ECAE subjected sample	7	98
CE of Pass 2B ECAE subjected sample	4.5	97

FIGURES

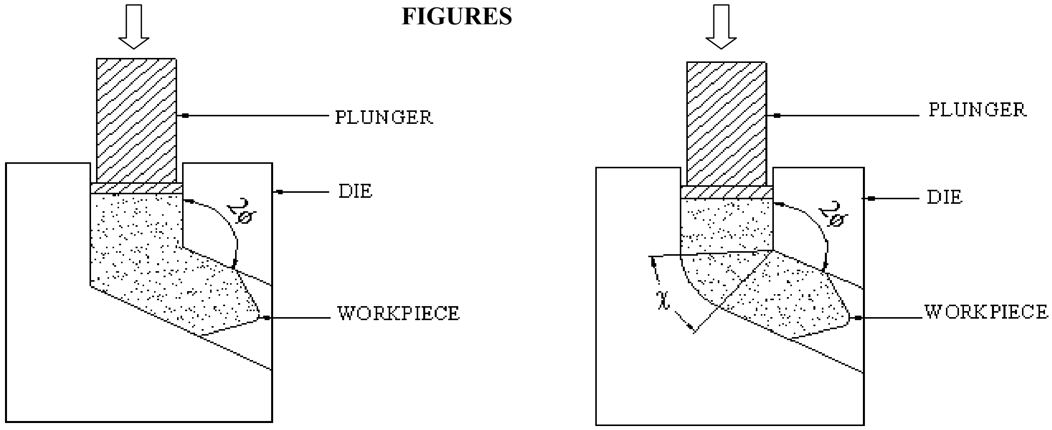


Figure 1 Schematic diagram of an ECAE die with a) sharp corner b) round corner.

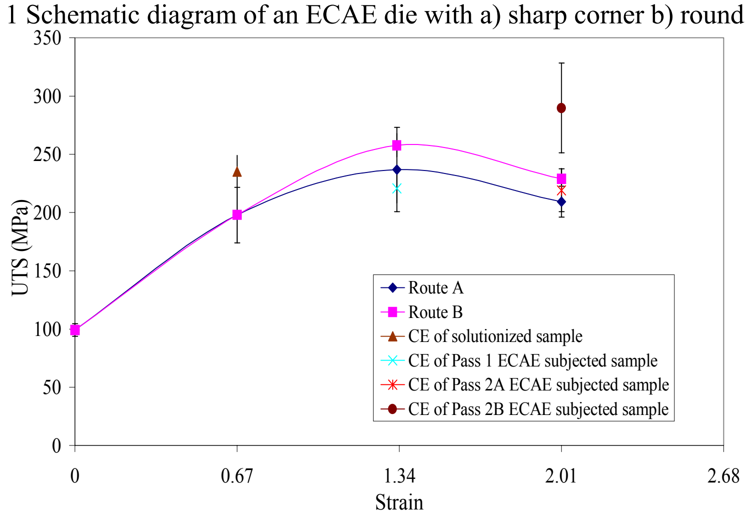


Figure 2. Variation of Ultimate tensile strength with strain imparted for various processing routes of ECAE and conventional extrusion (Error bar shows the std deviation from the mean value).

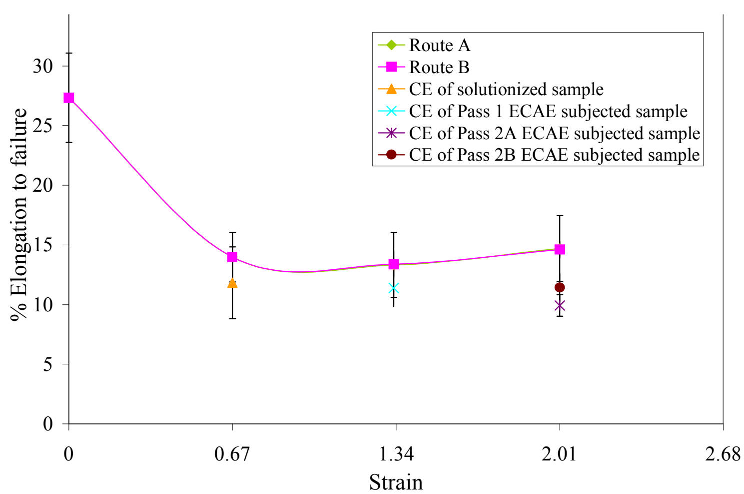


Figure 3 Variation of % elongation to failure with strain imparted for various processing routes of ECAE and conventional extrusion (Error bar shows the Std deviation from the mean value).

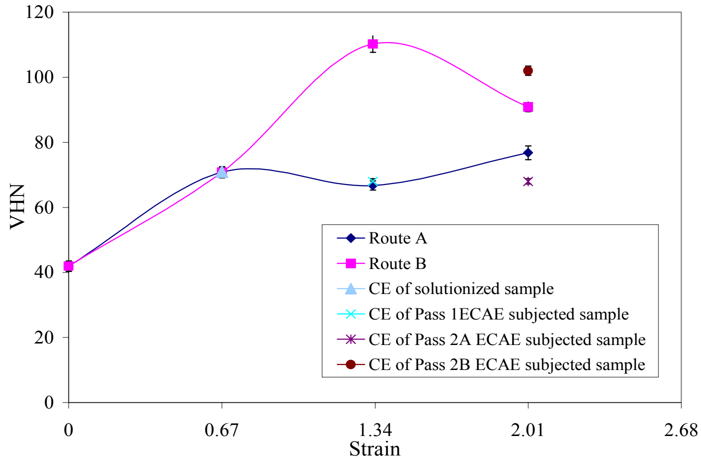


Figure 4. Average values of Vickers hardness number in the longitudinal direction of extrusion for different processing conditions of ECAE and conventional extrusion with strain (Error bar shows the std deviation from the mean value).

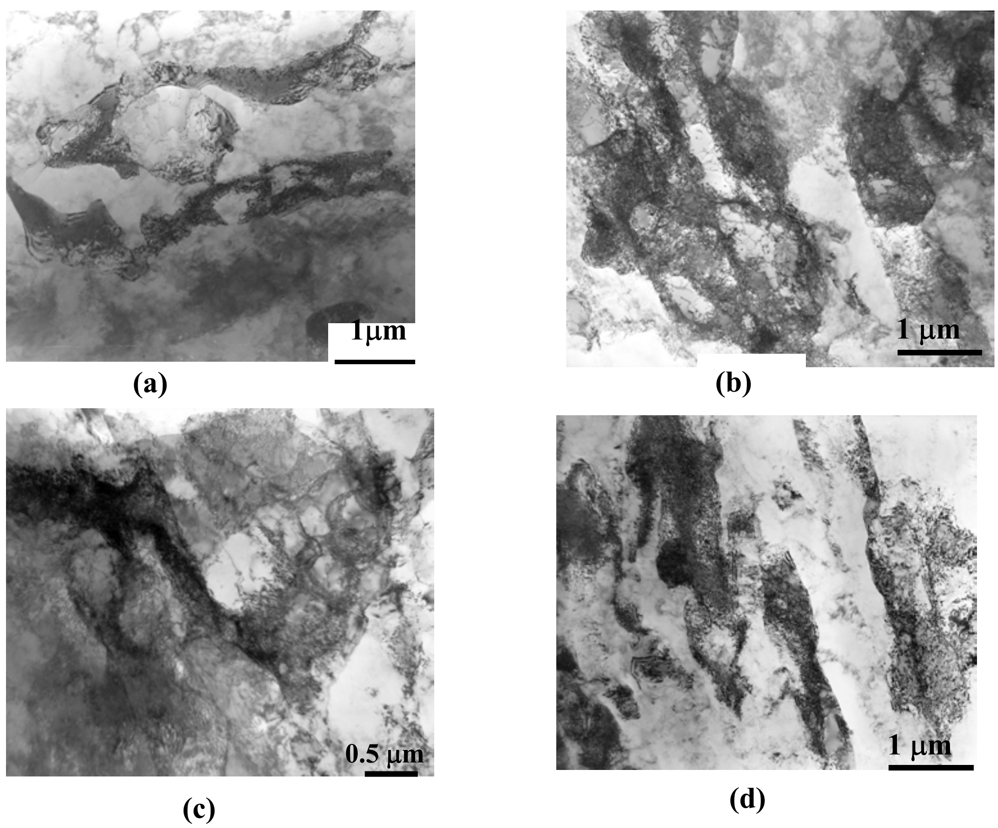
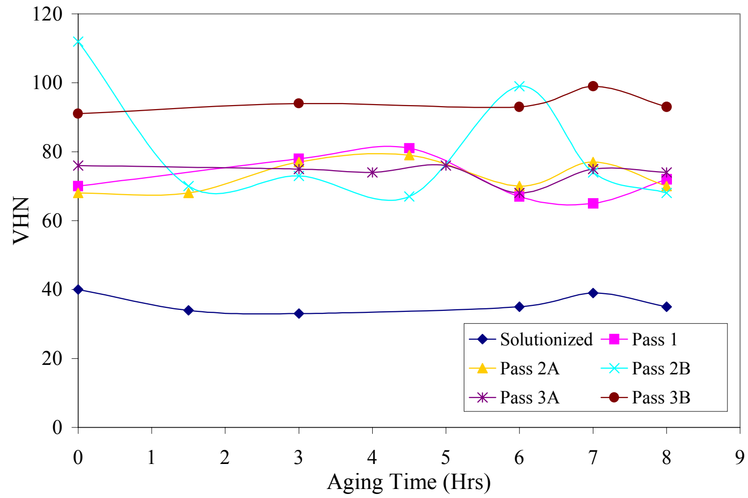
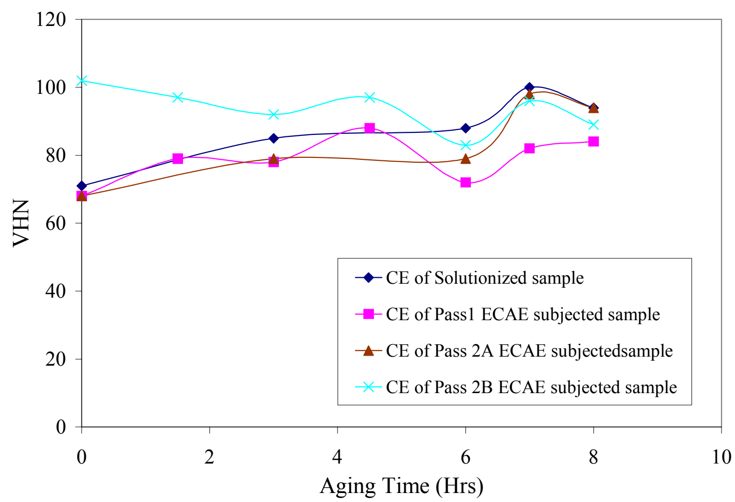


Figure 5 Microstructure of the as deformed material processed through different processing routes of ECAE (a) Pass 1 (b) Pass 2 route A (c) Pass 3 route A (d) Pass 3 route B.



(a)



(b)

Figure 6 Hardness variations of the specimens aged at 175° C for various time periods (a) ECAE processed (b) ECAE processed samples subjected to conventional extrusion.