Characteristics of Commercially Pure Aluminum 1020 Deformed by Equal Channel Angular through Routes A and C

S. T. Adedokun, T. A. Fashanu, S. Oyebanji

Abstract— Large uniform plastic strain has been effectively introduced in bulk materials using Equal Channel Angular Extrusion (ECAE) process. This work uses a 90^o ECAE die to deform commercially pure aluminum 1050 at room temperature through routes A and C. Scanning Electron Microscope-Electron Back Scattered Diffractometer (SEM-EBSD) and shear tests were used to characterize the microstructural development and mechanical properties of the alloy respectively.

Index Terms: Microstructural development; Shear tests; Equal Channel Angular Extrusion; Hall–Petch equation.

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1 INTRODUCTION

Recently due to their remarkable physical and mechanical properties, ultrafine-grained (UFG) materials produced by severe plastic deformation (SPD) have been the subject of many research works (Valiev et al., 1993; Horita et al., 2001; Huang et al., 2001; Horita et al., 2001; Shan et al., 2002 and Ferrasse et al., 1997). SPD processes can be defined as metal forming process in which a very high level of strain is applied to the material during processing. Among the various SPD processes, Equal Channel Angular Extrusion (ECAE) can effectively introduce large uniform plastic strain to bulk materials. This process is useful for the grain refinement of bulk materials (Segal V. M., 1995; Segal V. M.,1999; Iwahashi et al., 1998; Iwahashi et al., 1996; Nakashima et al., 2000; Iwahashi et al., 1997; Sun et al., 2000 and Gholinia et al., 2000). During the ECAE process, a workpiece is pressed through a die in which two channels with equal cross-sections intersect at an angle *Φ* and an additional angle *Ψ*, which defines the arc of curvature at the outer point of intersection of the two channels. The characteristics and geometry of the ECAE die used for this work is shown in Fig. 1.

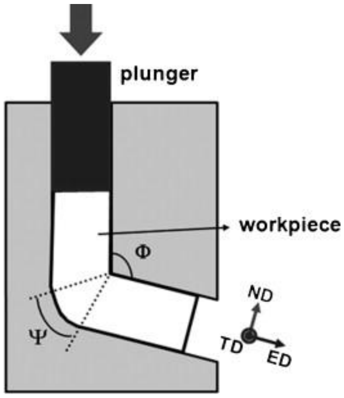

Fig. 1: Characteristics and Geometry of the ECAE die Used.

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The three orthogonal axes of ECAE samples are also shown in Fig. 1. ED is the extrusion direction; TD is the transverse direction normal to both channels; and ND is an additional axis that is normal to both ED and TD. The main advantages of ECAE are that the strain per pass can be very large and that the dimensions of the cross-section in the sample extruded through the die remain nearly constant during the process. Therefore, repeated extrusion is possible, and the strain can accumulate to a high level. The intersecting angle Φ determines the strain level of ECAE. Assuming there is no friction between the die and the workpiece, the total effective strain, ε_N, accumulated by passage through the die, is given by (Iwahashi et al., 1996).

$$\varepsilon_N=N[2\cot(\varphi/2+\psi/2)+\psi\operatorname{cosec}(\varphi/2+\psi/2)]/\sqrt{3} \qquad (1)$$

where N is the number of passages through the die.

There are four different routes (A, B_a, B_c, and C) in ECAE. Route A involves no rotation, route B_a involves ±90° rotation alternatively, route B_c involves 90° rotation always in the same direction, and route C involves 180° rotation (Nakashima et al., 2000). Detailed definitions of routes used in ECAE have been well reported by [Adedokun, 2011].

The present study focuses on processing commercially pure aluminum by ECAE via the two routes A and C. The evolution of the microstructure during ECAE was investigated using SEM-EBSD measurements, and shear tests were performed to determine the influence of ECAE on the mechanical properties of ECAE-processed material.

2 EXPERIMENTAL PROCEDURES

2.1 ECAE Process

The die for ECAE consists of two blocks that are held together using several large bolts. The die has an intersecting angle (Φ) of 90° and an outer arc angle (Ψ) of 10°. The magnitude of the strain in one ECAE pass is 1.05 according to Eq. (1). Specimens were subjected to two passes using two different processing routes, route A and route C, in order to change the shearing conditions by rotation of the specimen between successive extrusions. In route A, the orientation of the specimen is kept between the two extrusion passes, whereas in route C the specimen is rotated 180° about its longitudinal axis between each pressing. All ECAE processes were conducted in air at room temperature using a hydraulic 450-ton press. Several specimens were pressed consecutively to avoid any difficulties in removing the samples from the ECAE die. The ECAE processes were conducted under pressures ranging from ~15 to ~25 tons at an extrusion speed of 8 mm/s. The specimen and plunger were well lubricated before pressing. The material used in this study was 99.5% commercially pure aluminum which was homogenized at 343 °C for seven hours and then cooled in a furnace to room temperature. Specimens for the ECAE process were machined to dimensions of 20 (ND) × 60 (TD) × 70 (RD) mm^3. An average grain size of 160 μm was revealed before extrusion.

2.2 Shear Test

Shear tests that utilized a V-notched beam method (ASTM D 5379/D 5379M – 05) were conducted with the ECAE-processed commercially pure aluminum samples. In this test, a specimen with symmetrical centrally located V-notches was loaded into a testing machine using a special fixture. The specimens for the shear test were extracted from the ECAE-processed materials and inserted into the fixture with the notch located along the line of action of the loading. The two halves of the fixture were then compressed by the testing machine. The dimensions of the specimen and the fixture are shown schematically in Fig. 2. The testing was performed with the shear in the transverse direction (TD). In order to measure the shear strain, two strain gauges oriented at ±45° to the loading axis were attached to the middle of the specimen (away from the notches). The tests were carried out using an Instron testing machine with cross head speed of 2.0 mm/min at room temperature.

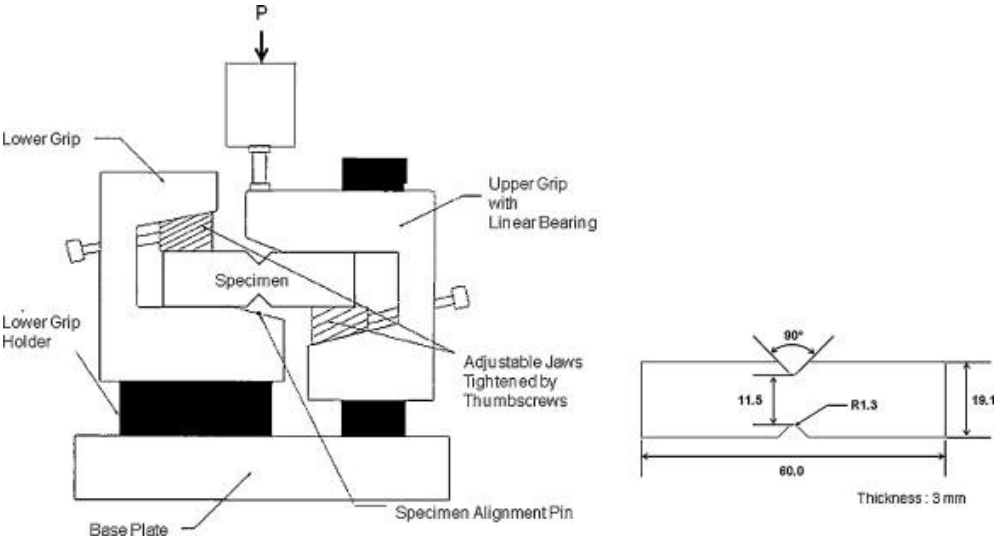

Fig. 2: Shear test V-notched beam set up and shear test specimen dimensions.

The shear strain was determined from the normal strains at +45° and −45° using Eq. (2)

$$\gamma = \left|\varepsilon_{+45}\right| + \left|\varepsilon_{-45}\right| \qquad (2)$$

2.3 Microstructural Examination

Following the ECAE process, small samples were cut from the middle of the ECAE-processed specimens. EBSD measurements were made on the plane normal to the TD. Good surface preparation is crucial; hence, the sample surface was mechanically polished with SiC paper with grit sizes of 800, 1200, 2000 and 4000 progressively. It was then electropolished to remove surface damage and to guarantee a sharp Kikuchi pattern. The solution for the electropolishing process was a mixture of 380 ml ethanol and 40 ml 70% perchloric acid. The electropolishing was carried out at room temperature with an applied voltage of 20 V. OIM analysis was carried out using a high-resolution EBSD system attached to a scanning electron microscope (SEM) with a field emission gun.

3 RESULTS AND DISCUSSION

The initial microstructure and distribution of the grain size as measured by the EBSD analysis are shown in Fig. 3. Most of the grains in the initial specimen are equiaxed, and the average grain size is 160 µm. The size of the grain is expressed as the diameter of a circle of equivalent area.

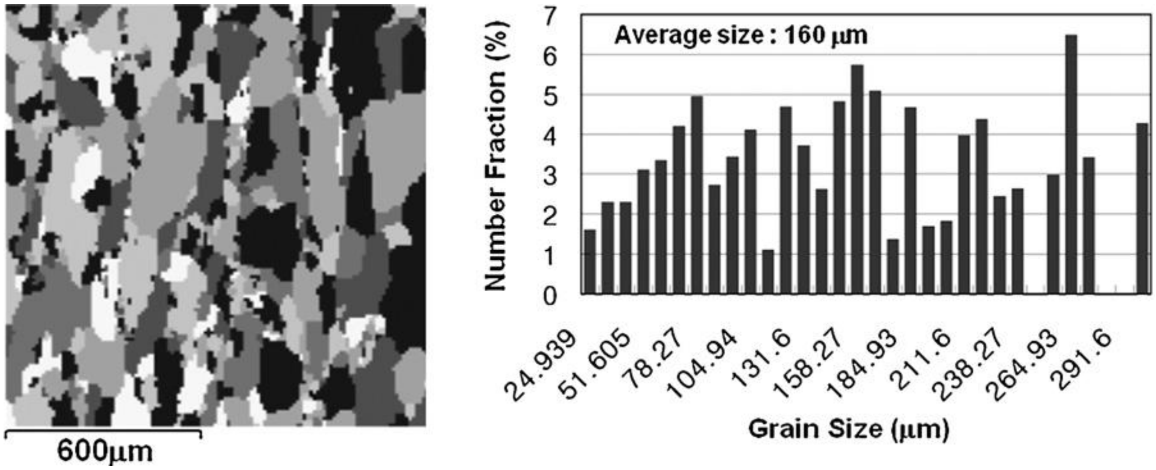

Fig. 3: Initial microstructure and distribution of grain size measured by EBSD.

The microstructural evolution of the specimens deformed by the ECAE die with $\Phi = 90°$ after one pass and two passes in routes A and C are shown in Fig. 4 (a)–(c), respectively. As shown in Fig. 4, the microstructure after one ECAE pass is a mainly banded structure consisting of elongated grains. The deformation microstructure of the specimen after two ECAE passes with route A is more uniform than that after one pass and is a clearly banded structure. The main feature is elongated grains with a large aspect ratio. In the microstructure of the specimens after two ECAE passes with route C, the elongated grains in the banded structure are diminished.

Some equiaxed grains appear again, and wavy or curved grain boundaries can be observed. The grain size of the ECAE-processed material is dramatically reduced in the first pass; this was followed by a gradual decrease in the second pass. After one pass, the average grain size is reduced from 160 µm to 10 µm. It was subsequently reduced to 5 µm after two passes in route A and was reduced to 4 µm in route C. The deformed shape of the grains shows clear differences between route A and C; however, the processing route has little influence on the average grain size. The distribution of the grain size shows that a single pass is not enough to produce a uniform strain in which all of the grains in the material can be refined uniformly. Further pressings through an ECAE die increased the introduced strain and caused a gradual decrease in the grain size. Comparing samples produced by routes A and C, the shearing pattern and deformation modes are different. In the ECAE process with route A, the shear strain of each following pass is identical to that of the first pass. For specimens after two passes with route A, the grains become elongated and the grain boundaries become parallel to each other. The ECAE process with route A is a uni-directional strain process; hence, the original grain boundaries are extended by the shear deformation. In the ECAE process with route C, the shear strain is fully reversed macroscopically during the second pass (Furukawa et al., 1998). However, the reversibility of the micro-deformation is not perfect. If the reverse process occurs with perfect reversibility, all dislocations and substructures would be lost from the material during every second extrusion cycle. However, a new set of grain structures with wavy or curved boundaries is produced in the second pass instead of the sample's deforming back to the original microstructure of before the first pass. It therefore appears that deformation does not follow the same slip system as activated during the first pass. This will likely cause a breakup of the previous grains.

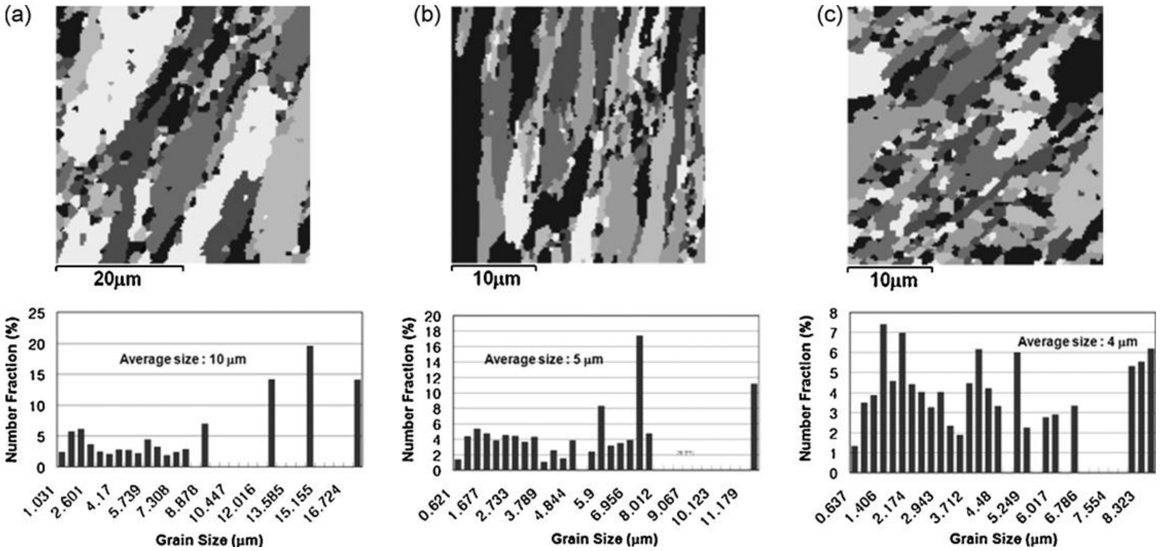

Fig. 4: Microstructural evolution of the specimens deformed by ECAE with (a) one pass, (b) two passes in route A and (c) two passes in route C.

Fig. 5 shows the shear stress–shear strain curves of the specimens subjected to 1–2 passes for both processing routes. For comparison, the shear stress–shear strain curve of the initial material is also shown. From the results of the shear tests, the shear yield strength at 0.2% shear strain of ECAE-processed specimens was obtained. The materials processed by ECAE show much higher strength than the initial material. This increase in strength is attributed to the build up of high dislocation density in the grains that generate subgrain walls. The rate of strain hardening of the ECAE-processed material is very low compared to that of the initial material. This discrepancy arises because the absorption of dislocations into the grain boundaries leads to an absence of strain hardening (Reihanian et al., 2008). Fig. 6 shows the variation of the shear yield strength with the number of passes for both processing routes. The shear yield strength for the initial material was approximately 18 MPa. The shear yield strength increased to nearly 61 MPa after one ECAE pass and then improved to about 70 MPa and 72 MPa after two passes using routes A and C, respectively. The shear yield strength increases with a decrease in the grain size, but the increase is significant only after the first pass. The shear yield strength increased gradually with the second pass. It can be seen that the shear yield strength of commercially pure aluminum after two ECAE passes is four times greater than that before ECAE passes. During the ECAE passes, a high density of dislocation is built up and numerous low angle boundaries are created and all of these can influence the shear yield strength. The improvement in the shear yield strength is mostly independent of the processing route, which means that the size of the grains in the material processed by ECAE plays a dominant role in increasing the shear yield strength; the shape of the grains has only little effect on the shear yield strength.

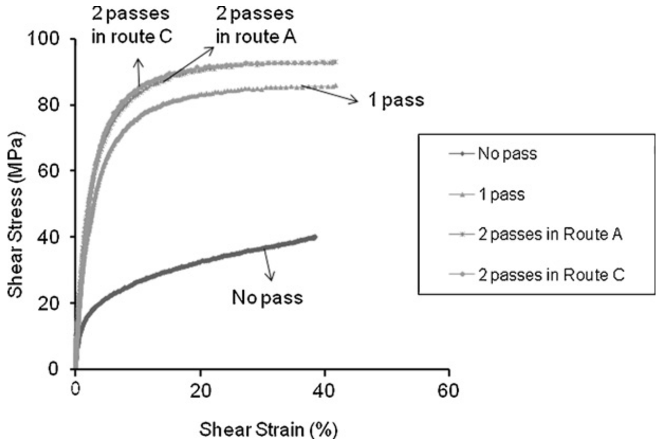

Fig. 5: Shear stress–shear strain curves of the specimens subjected to 1-2 passes for routes A and C.

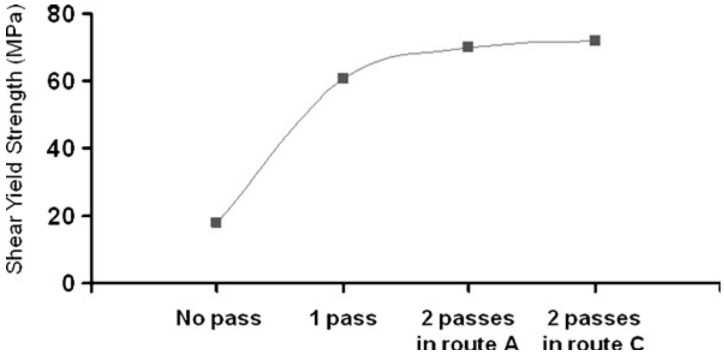

Fig. 6: Variation of the shear yield strength with the number of passes for both processing routes.

The effect of the grain size on the yield strength of metallic materials has been described by the Hall–Petch relationship, which is demonstrated in equation form as (Hall E. O., 1951) and (Petch N. J., 1953):

$$\tau_0 = \tau_i + k\,D^{-1/2} \tag{3}$$

where τ_0 is the yield stress, τ_i is the friction stress, which represents the resistance of the crystal lattice to dislocation movement, k is the Hall–Petch coefficient and D is the grain diameter. In Fig. 7, the shear yield strength of the ECAE-processed material is plotted as a function of $d^{-1/2}$, where d is the average grain size. The shear yield strength changes inversely with the square root of the average grain size. A linear fit of the experimental data, represented as a dashed line in Fig. 7, results in the following Hall–Petch relationship:

$$\tau_0 = 11.3 + 131D^{-1/2} \tag{4}$$

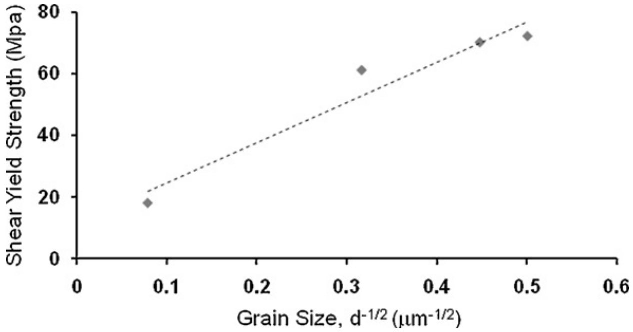

Fig. 7: Shear yield strength of ECAE-processed aluminum versus $d^{-½}$.

The values of τ_i and k are 11.3 MPa and 131 MPa $(\mu m)^{-1/2}$, respectively, in the commercially pure aluminum. This equation can be used to predict the shear yield stress of commercially pure aluminum when grains are refined to the submicron level by SPD processing.

4 CONCLUSIONS

Equal Channel Angular Extrusion was carried out for commercially pure aluminum via routes A and C; the microstructural evolution and its effect on mechanical properties were investigated. The following deductions from the results can be made:

- The microstructure in which most of the grains are equiaxed having average grain size of 160 µm was transformed after two ECAE passes in route A into a structure that was uniformly elongated and had a small grain size of about 5 µm. The materials after two ECAE passes in route C consisted of a fine-grained structure with wavy or curved grain boundaries and an average grain size of 4 µm.
- The shear yield strength increased rapidly with the first ECAE pass, but the second pass resulted in only a slight increase in strength due to the gradual decrease in the grain size. The shear yield strength increased from 18 MPa to 61 MPa after one ECAE pass and was then improved to about 70 MPa and 72 MPa after two passes using routes A and C, respectively.
- The Hall–Petch relationship which can be used to predict the shear yield strength of the ECAE-processed commercially pure aluminum was obtained.

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