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Nature of shear flow lines in equal-channel angular-pressed metals and alloys

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The nature of shear flow lines in equal-channel angular-pressed (ECAPed) metals has been investigated experimentally and theoretically. Experimental results indicate that, for metals pressed in a right-angle die, the shear flow lines often have an angle of ~27° with respect to the extrusion direction. It is suggested that the shear flow lines are composed of a group of elongated grains with an elongation direction that deviates slightly from that of the shear flow lines.

1. Introduction

Equal-channel-angular-pressing (ECAP) is an exciting prospect in the field of material science and engineering owing to its potential application in the fabrication of ultrafine-grained materials [1–3]. Significant progress has been made in understanding the fundamental properties and microstructures of ECAPed materials via theoretical and experimental methods [4–10]. However, insufficient attention has been paid to the nature of shear flow lines, which are parallel plastic flow traces always formed after single-pass ECAP, as reported and listed in table 1 [7–17]. Recently, we investigated the influence of shear flow lines on the anisotropic compressive properties of iron subjected to single-pass ECAP [15]. The experimental results show that the plane parallel to the shear flow lines is mechanically weaker and has the lowest critical shear stress in resisting shear deformation during compressive testing. Fang *et al*. [14] found that the tensile fracture surface is also approximately parallel to the shear flow lines in ECAPed Al–Cu alloys. These results provide clear evidence that shear flow lines play an important role in shear deformation and fracture of ECAPed materials. However, there is ambiguity between the stretching direction of shear flow lines reported in the literature and our previous works [7, 14, 15]. The main objective of this paper is to further investigate the nature of shear flow lines, including the formation process, microstructural features and stretching direction during ECAP processes.

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Table 1. Comparison of shear flow line angle, θ, for different materials subjected to single-pass ECAP.

Material	Die angle (ϕ/ψ)	Shear flow line angle θ (°)	Reference
Ni	90/0	22.5	[7]
Al	90/0	26.5	[8]
Al	90/0	26 or 27	[9]
Al–1% Mg–0.2% Sc	90/30	16	[10]
Fe	90/0	27.6	[11]
Low-carbon steel	90/0	30	[12]
Low-carbon steel	90/20	30	[13]
Al–3.9% Cu	90/0	27	[14]
Fe	90/0	27	[15]
Stainless steel	90/0	30	[16]

2. Experimental procedures

Samples of commercial Armco iron (99.3% purity), austenitic stainless steel and Al–3.9% Cu alloy with an average grain size of about 100 μm were employed as model materials due to their good ductility and suitability for illustrating the formation process of shear flow lines during ECAP. Initially, they were extruded for a single pass only in a right-angle ECAP die at room temperature at an extrusion rate of 5 mm/min. The cross-section of the working piece was 10 mm in diameter. Surface observations were made on the *y*-plane (at right angles to the *y*-axis, as shown in figure 2a, via scanning electron microscopy (SEM) and optical microscopy (OM). Microstructural features were also examined by electron backscattered diffraction (EBSD), using a LEO SUPRA 35-FEG-SEM with a map step-size of 2 μm.

3. Results and discussion

Figure 1 shows the surface morphology on the three model specimens subjected to single-pass ECAP. It can be seen that there is a group of plastic flow traces formed on the surface of each of the three specimens. Hereafter, we define these traces as shear flow lines, as indicated in figure 1. It is apparent that the shear flow lines make an angle of about 27° with respect to the extrusion direction for the Al–3.9% Cu alloy and iron samples, as shown in figures 1a and c, which is consistent with the results in table 1 [8, 9, 14, 15]. For the stainless-steel sample, the shear flow lines have an angle of about 30° with respect to the extrusion direction, as shown in figure 1b. The small difference in the angles is caused by the intrinsic nature of steel during pressing, i.e. the corner of the right-channel die is not fully filled by the steel and a dead metal zone is formed. The steel appears to be processed in an ECAP die with a circular angle; therefore, the shear-flow-line angle is slightly larger for hard materials, such as steel and other alloys [3, 4]. Figure 1d shows the result of an EBSD experiment conducted on the *y*-plane of the iron billet. It is clearly seen that all the grains are generally elongated along the direction of the shear flow lines.

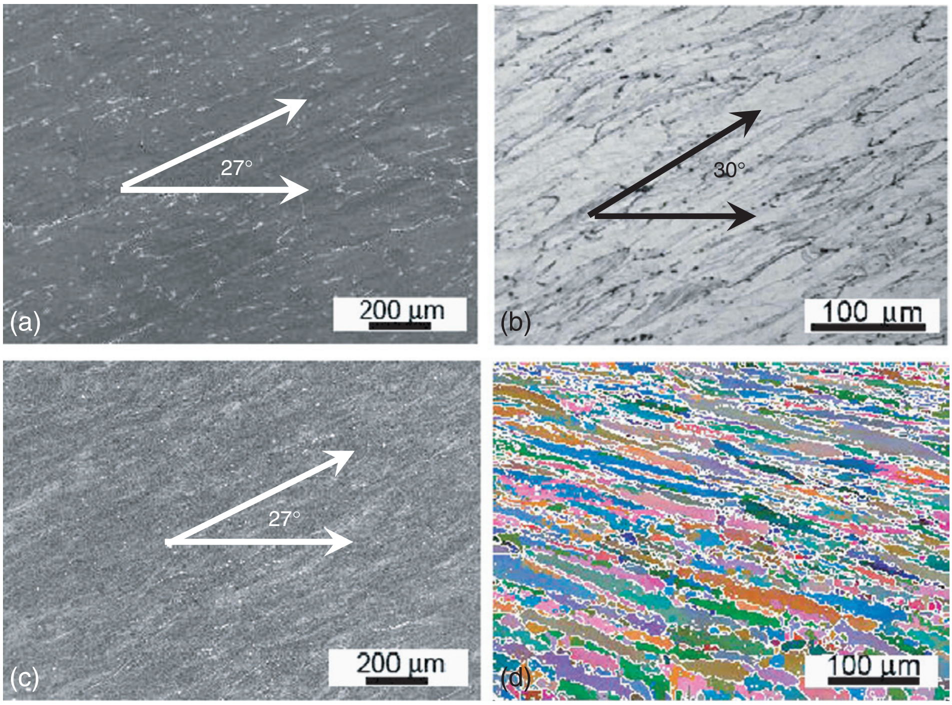

Figure 1. Shear flow lines in different materials subjected to single-pass ECAP. (a) Al–3.9% Cu alloy, (b) austenitic stainless steel, (c) iron, (d) EBSD image on *y*-plane of iron in (c). (d) Figure has been rotated approximately 180° around a vertical axis compared to (c).

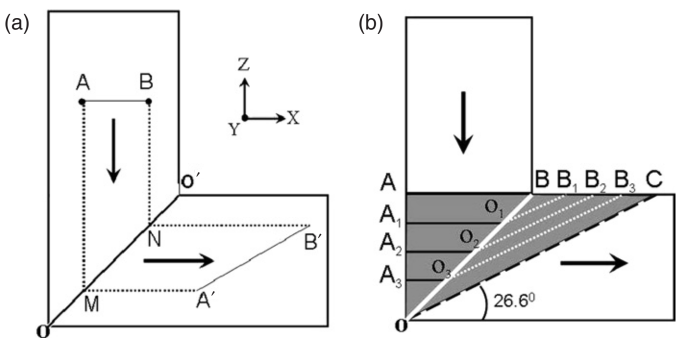

Figure 2. (a) The three principles and (b) the evolution of a horizontal line during ECAP.

The white lines in figure 1d represent grain boundaries with misorientations larger than 15°. A large number of subgrain boundaries were also formed during ECAP deformation and can be seen within each elongated grain. With continuous pressing, these sub-grain boundaries would evolve into high-angle grain boundaries [1]. EBSD experimental data demonstrate that the average aspect ratio of the elongated grains is about 2.77, indicating that ECAP can effectively elongate the grains to form

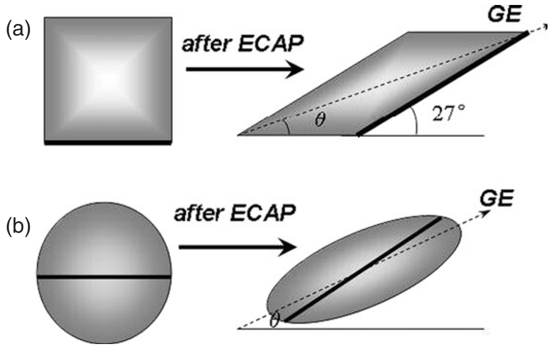

Figure 3. Evolution of a square and sphere during ECAP.

different microstructures. These findings imply that the formation of shear flow lines during ECAP is a common phenomenon in ECAPed metals or alloys.

According to numerous studies on the deformation mechanism [4, 5, 7, 18, 19], it is possible to decipher the formation processes of shear flow lines. Considering the ECAP deformation processes in a right-angle die, the materials must follow three principles, as illustrated in figure 2a: (a) the material must move straight down in a vertical channel before reaching the intersection plane OO′ and move parallel to the extrusion direction in a horizontal channel after passing the intersection plane; (b) the moving direction of the material must change suddenly at the intersection plane; (c) the total moving distance of any point must be identical within the same time, i.e. $AM + MA' = BN + NB'$.

Figure 2b shows a simple model of the deformation process of a sample along a horizontal line AB. According to the three principles above, the right side of line AB initially deforms and is directly changed into an oblique line parallel to the final line OC, as shown in figure 2b. Then, the horizontal line AB changes gradually into OC, i.e. $AB \rightarrow A_1O_1B_1 \rightarrow A_2O_2B_2 \rightarrow \cdots \rightarrow OC$. As a result, the final line OC is stretched compared to line AB along the direction of OC. Therefore, the line AB is rotated and turned into an oblique line in the area ABCO.

For a better understanding of microstructural evolution and shear flow lines, two types of grains with spherical and square shapes are considered. After deformation, their shapes are changed, as shown in figures 3a and b. Marking the lower edge of the square, as with analysis of the horizontal line, it is found that the square is rotated and turned into a diamond-shape with the grain being elongated along the direction of the diagonal line. The angle between the diagonal line and the extrusion direction is $<26.6^\circ$, the exact value being decided by the length:width ratio, as shown in figure 3a. Using the same method, the horizontal diameter of the sphere was marked and similar principles to the deformation of the square applied, as demonstrated in figure 3b. It was found that the sphere is turned into an ellipse after deformation and, accordingly, the angle between the long axis and the extrusion direction is also $<26.6^\circ$. The exact value will be calculated in the next section.

Consider the evolution of a spherical grain with a diameter R_0 during ECAP. By establishing the coordinate system within the centre of the sphere grain, as shown in

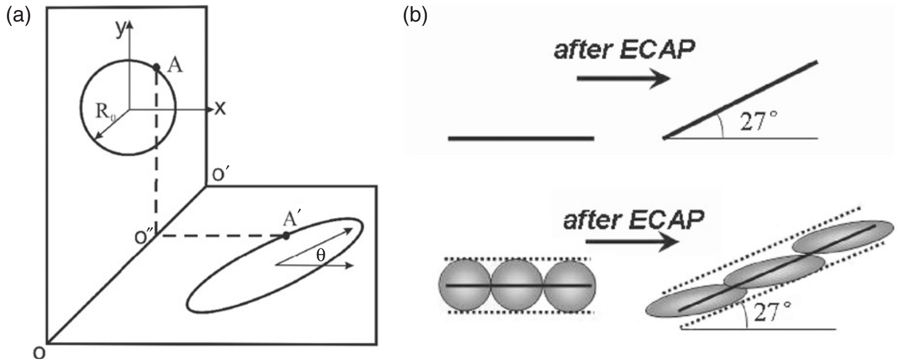

Figure 4. (a) Sphere evolution in an ECAP die following the three principles and (b) the relationship between the shear flow line and elongated grain.

figure 4a, the equations of the sphere and the line OO′ are:

$$x^2 + y^2 = R_0^2 \tag{1}$$

and

$$y = x - a \tag{2}$$

where a is the intercept of line OO' on the y-axis. Assuming that, after deformation, the total distance of the movement for any mass point is L_0 (i.e. for an arbitrary point A, $L_0 = \text{AO}'' + \text{A}'\text{O}''$), the coordinate transformation can be established. Considering the arbitrary point A(x, y), the coordinate will be changed to A′(x', y') after deformation. According to the three principles above, point A will firstly move parallel to the y-axis by a distance AO″ and will move parallel to the x-axis by a distance A′O″ ($= L_0 - \text{AO}''$). Then, the changes of coordinates are:

$$\begin{cases} \Delta y = y - (x - a) = y - x + a \\ \Delta x = L_0 - \Delta y = L_0 - y + x - a \end{cases} \tag{3}$$

Therefore, the original (x, y) and the new coordinates (x', y') will have the following relationship:

$$\begin{cases} x = y' + a \\ y = 2y' + L_0 + a - x' \end{cases} \tag{4}$$

By substituting the coordinate transformation into equation (1), one finds:

$$x'^2 - 4x'y' + 5y'^2 + Bx' + Ay' + C = 0 \tag{5}$$

This is the equation of an ellipse and the tilt angle θ between the grain elongation (GE) and extrusion direction is:

$$\theta = \frac{1}{2} ar\cot\left(\frac{1-5}{-4}\right) = 22.5^\circ \tag{6}$$

After deformation, the sphere is changed into an ellipse and its long axis has an angle of 22.5° with respect to the extrusion direction, which is consistent with the calculations of Xia *et al*. (obtained by different methods) [20]. Therefore, the elongation direction is tilted 22.5° after deformation for grains with a spherical shape. However, after deformation, a horizontal line becomes an oblique line and makes an angle of 26.6° with respect to the extrusion direction, which is the same direction as the shear flow lines. This appears to contradict the analysis using linear, square or spherical models.

Figure 4b shows the relationship, from EBSD experiments, between shear flow lines and GE during ECAP. It is clearly seen that the shear flow lines only describe the surface morphology on a macroscale, while the grain shape reflects the evolution of the structures on a microscale. The shear flow lines on the macroscale are composed of a group of elongated grains on the microscale. The GE processes bear most of the plastic strain during deformation via dislocation activities within each grain and interaction between elongated grains. Accordingly, the shear flow lines often have an angle of 26.6° with respect to the extrusion direction although they are composed of a group of elongated grains with an elongation direction deviating slightly from that of the shear flow lines. Therefore, it is not difficult to understand why the shear flow lines make an approximate angle of 27° with respect to the extrusion direction in many different metals and alloys, as listed in table 1 [7–17].

The above analysis only considered the influence of material flow on the shape of shear flow lines during deformation in an ECAP die at room temperature. The evolution patterns of the shear flow lines could also be influenced by crystallographic orientations, surrounding conditions or crystalline properties of the ECAPed materials. The shear flow lines are often around the 27° direction with respect to the extrusion direction for materials processed by a right-angle ECAP die [8, 9, 11–17]. For a given grain, the elongation direction is not only decided by the ECAP die but also by the initial shape of the grain. In principle, shear flow lines are the result of flow deformation during ECAP. Therefore, it is easier to understand the deformation and formation processes of shear flow lines from the viewpoint of metal flow. Furthermore, a ductile metal can be easily processed by an ECAP die but, for a brittle metal, shear fracture will occur during the pressing. Details will be published shortly [21].

4. Conclusions

The experimental results indicate that, for metals and alloys pressed in a right-angle die, shear flow lines often have an angle of ~27° with respect to the extrusion direction. For a given grain, its elongation direction is decided not only by the parameters of the ECAP die, but also by the initial shape of the grain. It is suggested that shear flow lines are actually composed of a group of elongated grains with an elongation direction deviating slightly from that of the shear flow lines.

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