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Fatigue Behavior of Al-Cu Alloy Subjected to Different Numbers of ECAP Passes**

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Equal channel angular pressing (ECAP) technique has attracted much attention as one of the most prominent methods of severe plastic deformation, and has been widely applied to various metals and alloys.[1–8] To date, many investigations have focused on the static mechanical properties of the ECAP-processed materials such as uniaxial tensile or compressive tests, however, the study on fatigue properties is relatively rare, and only few reports can be found, mainly on pure Cu,[9–15] Al alloys,[16–19] as well as some other metals and alloys.[20–23]

The ultrafine-grained (UFG) materials processed by ECAP often exhibit an enhanced high cycle fatigue life, but a deteriorated low cycle fatigue life.[12,16,17,24] It is believed that fatigue damage and fatigue life strongly depend on the formation of shear bands on surface. As a dominant surface deformation feature, shear bands in cyclically deformed UFG Cu were first reported by Agnew and Weertman,[9] after that further results were obtained.[7,10,11,15,25–33] Some of these researches have shown that the shear bands often orient at about 45° with respect to the cyclic load axis, and the fatigue cracks always initiate and propagate along the shear bands.[7] Shear bands were often found in the form of surface extrusions/intrusions. Wu *et al*. reported the existence of two types of shear bands.[30] They found that most of the shear bands appeared in the form of extrusions/intrusions, while some other shear bands behaved in step form. In addition, some researchers[9,10,25,32] found coarsened cells and recrystallized grains in cyclically deformed specimens, but Wu *et al*.[11] and Vinogradov *et al*.[29] reported that no change in microstructure of UFG Cu was associated with the shear bands. The latest study shows that a shear band is only a thin sheet of tangled dislocations having different burgers vectors.[33] However, so far the understanding of the formation of the shear bands and fatigue damage is still not very clear. The popular viewpoint urged that the orientation of shear bands coincides with the orientation of the shear plane in the last ECAP pass, and that the formation of shear bands is attributed to oriented distributions of defects along the shear plane in the last ECAP pass.

It is known that there is always obvious streamline owing to the shear deformation in the materials subjected to ECAP. When the materials are subjected to tensile or compressive load, deformation or fracture sometimes occurs along the streamline plane, which was regarded as a weak plane to resist shear deformation.[34,35] But, during the fatigue test, it is not clear whether the streamline plane will influence the formation of shear bands or not. Moreover, with increasing the number of ECAP passes, different streamlines will form. The effect of the variation of microstructure on the formation of shear bands should also be further studied.

In the present work, strain-controlled fatigue tests on Al-0.63 wt.%Cu alloy subjected to different number of ECAP passes were performed. One of the aims is to further study fatigue properties and damage mechanism of the ECAPed materials. Another aim is to investigate the variation of shape parameter of hysteresis loops with the number of ECAP passes, as well as Bauschinger effect, which was rarely mentioned in the fatigued UFG materials.

Experimental Procedure

The materials used are cast Al-0.63 wt.%Cu ingots. Firstly, rods of 10 mm in diameter and 80 mm in length were made from ingots by spark cutting technique. Secondly, equal channel angular pressing (ECAP) was conducted at room temperature using a solid die having an angle of 90° between the two channels. The samples subjected to repetitive pressing were rotated by 90° in the same direction between each pass in the procedure designated as route B_C.[36] Before pressing,

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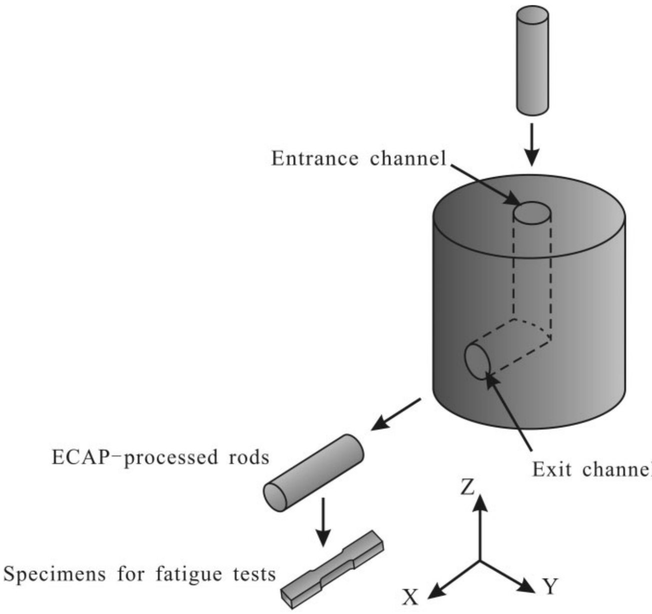

Fig. 1. Illustration of ECAP die and orientation of fatigue specimens relative of the pressing direction.

the rods were coated with MoS_2 as lubricant. The number of ECAP passes for the current study is 1, 2 and 4, respectively.

Fatigue specimens with gauge length and cross-section of 14 mm and 4 × 5 mm^2 were machined from the ECAP-processed rods with their tensile axis lying parallel to the extrusion direction. The vertical plane parallel to extrusion direction is defined as XZ-plane, and the horizontal plane is XY-plane, as shown in Figure 1. Besides, some fatigue specimens were also cut from the rolled pure Al plate for comparison. The RD, TD, and ND correspond to X, Y, and Z, respectively.

The specimens were mechanically polished followed by electropolishing in a solution of $HClO_4$ and C_2H_5OH. Symmetrical push-pull fatigue tests were carried out using a Shimadzu servo-hydraulic testing machine under a constant plastic strain amplitude of 10^{-3} at a frequency of 5 Hz at room temperature. In order to study the formation of shear bands and crack initiation, fatigue tests were stopped after 1000 cycles. The surfaces of the fatigued specimens were observed using a Cambridge S360 or a LEO Supra 35 scanning electron microscope (SEM).

TEM observations were performed using a JEM-2000FX ||TEM. The thin foils for TEM observations were cut from the center of the pressed rods on XZ-plane, then mechanically ground to about 50 μm and finally thinned by twin-jet electropolishing method with a solution of 33 % nitric acid-methanol.

Results and Discussion

Microstructures and Tensile Properties Before and After ECAP

The microstructure of the as-cast alloy, as shown in Figure 2(a), consists of Al solution and few of dot-like θ phase (Al_2Cu) distributing in the matrix, and the average grain size is about 400 μm. With multipass ECAP, a remarkable grain refinement occured by repeated shear deformation, as shown in Figure 2(b), and the grains were refined to submicron level after four passes. The θ phase is invisible in the TEM micrograph because the amount of θ phase in the alloy is very little.

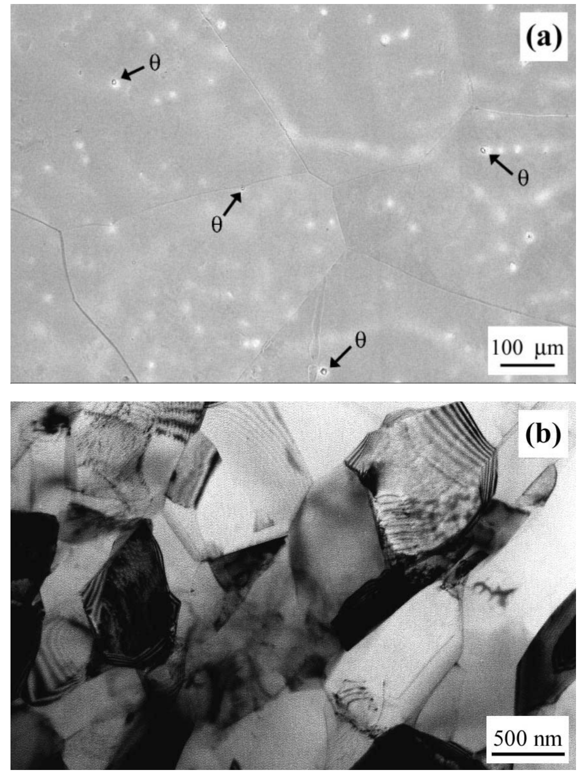

Fig. 2. Microstructure of cast alloy Al-0.63 %Cu, (a) and TEM images showing the microstructure of Al-0.63 %Cu alloy ECAPed for four passes (XZ-plane), (b).

The tensile properties of the present Al-Cu alloy are summarized in Table 1 according to the reference.[34] The ultimate tensile strength (UTS) of the as-cast alloy is 83.2 MPa, while after four passes the UTS increases to 216.2 MPa. However, the elongation to failure decreases drastically after one pass, from 47.8 % to 17.3 %. With further increasing the number of passes, the elongation almost maintains constant.

Cyclic Stress Response Curves

Figure 3 shows the cyclic stress response curves of the Al-0.63 %Cu alloy subjected to different numbers of ECAP passes. As can be seen, the as-cast Al-Cu alloy only displays slight cyclic hardening, while the Al-Cu sample subjected to

Table 1. Tensile properties of Al-0.63 %Cu alloys subjected to different number of ECAP passes.

Number of ECAP passes	0 (as-cast)	1	2	4
UTS / MPa	83.2	145.6	182.1	216.2
Elongation to failure / %	47.8	19.4	17.8	17.3

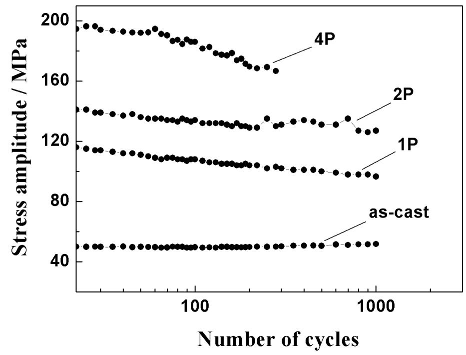

Fig. 3. Cyclic stress response of Al-0.63 %Cu alloy subjected to different numbers of ECAP passes indicated as "1P, 2P, 4P", fatigued under a constant plastic strain amplitude of 10^{-3}.

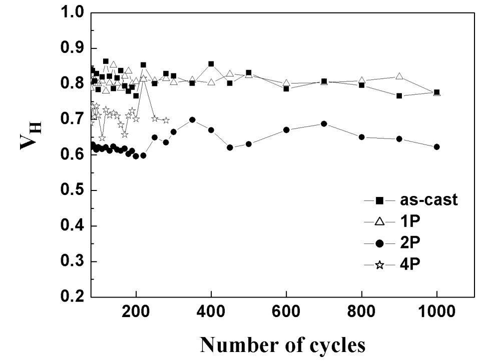

Fig. 5. Variation of shape parameter of the specimens subjected to different numbers of ECAP passes, fatigued under a plastic strain amplitude of 10^{-3}.

ECAP exhibit cyclic softening behavior. The cyclic softening feature is consistent with the reports on many other UFG materials.[7,10,13,17,19,21,22] The mechanisms of cyclic softening are associated with a complex effect of dislocation recovery, dynamic "recrystallization" and grain coarsening.[7,9,10,23,26,28,32,37] Besides, a variation is that fatigue life becomes very short after four passes. The deteriorated strain-controlled fatigue life of UFG materials was attributed to the low ductility of the materials after ECAP.[24,37]

Shape Parameter and Bauschinger Effect

The shape parameter (V_{H}) is an important value to describe the shape variation of hysteresis loops during cyclic deformation[38] and can be expressed as

$$V_H = E/S = \oint \sigma d\varepsilon / 4\sigma_a \varepsilon_{pla}. \quad (1)$$

Where E is hysteresis energy, i.e. the area of the stable hysteresis loop, S is the area of the parallelogram, σ_{a} is stress amplitude and $\varepsilon_{\mathrm{pla}}$ is plastic strain amplitude, as illustrated in Figure 4. From the above equation, V_{H} of the specimens subjected to different number of ECAP passes can be calculated and is shown in Figure 5. It can be seen that V_{H} changes less after one pass, while decreases obviously after two and four passes. It suggests that the shape of hysteresis loops becomes sharper after multipass ECAP treatment.

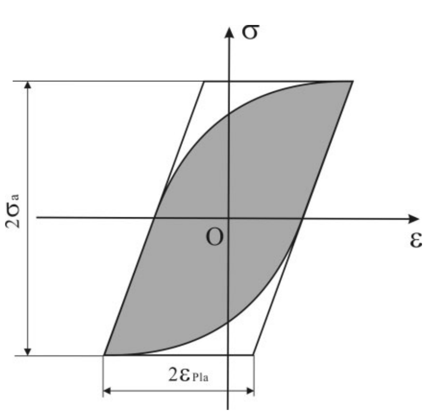

Fig. 4. Illustration of shape parameter of hysteresis loops.

Besides shape parameter, Abel and Muir[39] once proposed that the hysteresis loop shape can be evaluated by the so-called Bauschinger energy parameter

$$\beta_E = \frac{4\sigma_a \varepsilon_{pl} - \int\limits_{loop} \sigma d\varepsilon}{\int\limits_{loop} \sigma d\varepsilon} \quad (2)$$

From Equation 1 and Equation 2, the relationship between shape parameter V_{H} and Bauschinger energy parameter β_{F} can be written in the following form

$$\beta_E = \frac{1}{V_H} - 1. \quad (3)$$

It is obvious that with decreasing V_{H}, β_{E} increases. This indicates that multipass ECAP treatment can effectively increase the Bauschinger effect for the cast alloy Al-0.63 %Cu. But the variation of the Bauschinger effect with the number of ECAP passes is different from that of ECAP-processed ultrafine-grained Cu. It has been found that the Bauschinger effect decreases with increasing the number of ECAP passes in UFG Cu.[40] Furthermore, it is noted that for the Al-0.63 %Cu alloy subjected to multipass ECAP, its fatigue life was shortened, although its Bauschinger energy parameter was increased.

Cyclic Deformation and Shear Bands

The surface morphology of the as-cast Al-Cu alloy after fatigue is shown in Figure 6. Under cyclic stress, there are many slip bands along different directions in coarse grains (see Fig. 6(a)). All the slip bands terminated at the grain boundaries, as seen in Figure 6(b). Figure 7 shows the deformation morphology of the Al-Cu alloy ECAPed for one pass and fatigued for 1000 cycles. It can be seen that there are many shear bands on the surface. The shear bands orient at about 45° with respect to the cyclic load axis on XZ-plane (see Figs. 7(a) and (b)), while make an angle of around 90° with respect to the cyclic load axis on XY-plane (see Figs. 7(c) and (d)). Along the shear bands, there are some obvious extrusions and intrusions, as shown in Figures 7(b) and (d).

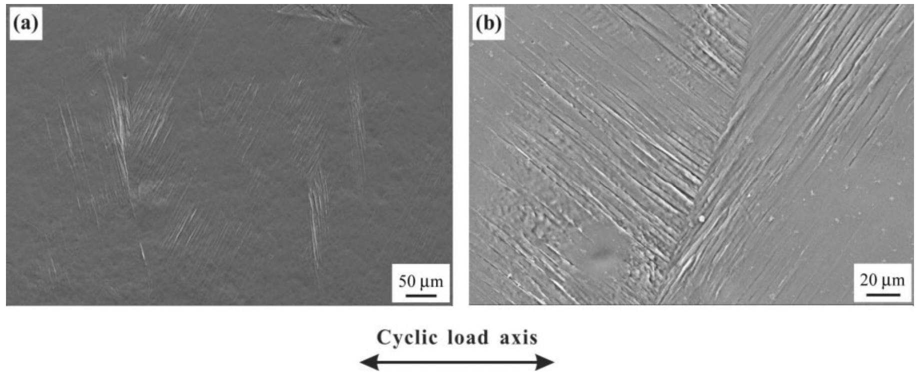

Fig. 6. Surface morphology of the as-cast Al-0.63 %Cu alloy fatigued for 1000 cycles under plastic strain amplitude of 10^{-3}.

These features of the shear bands are similar to the previous observations in other UFG metals or alloys.[7,11,22,41] For example, the shear bands were called as PSB-like shear bands because the extrusions/intrusions are similar to the morphology of PSB in cyclically deformed single crystal copper.[11,30]

Figures 8 and 9 show cyclic deformation morphology of the alloy ECAPed for two and four passes, respectively. The similar shear bands can also be seen on the surface of the specimens. On XZ-plane, shear bands approximately orient at 45° with respect to the cyclic load axis, while on XY-plane shear band direction is nearly perpendicular to the cyclic load axis, independent of the number of ECAP passes. Meanwhile, it is noted that the shear bands do not change their direction and can transfer through the whole specimen, which is quite different from the random distribution of slip bands in coarse-grained materials. In addition, it can be seen from Figures 7–9 that the amount of shear bands is very high and fatigue damage becomes more serious in the specimen ECAPed for four passes. It demonstrates a possible mechanism for the deteriorated strain-controlled fatigue performance caused by ECAP.

According to the previous study,[6,11] it is thought that the formation of shear bands should have close relation to the shear plane of the last ECAP extrusion. The shear plane is the intersection plane between the entrance and exit channels, as shown in Figure 10(a). It is thought that ECAP can produce orientated distribution of defects along the shear plane, which would cause fatigue damage easily occurring along the shear plane,[1,11,31] so the shear bands orient at about 45° with respect to the cyclic load axis. But, it is well known that the shear direction often makes an angle of about 26.6° with respect to the longitudinal direction when ECAP was per-

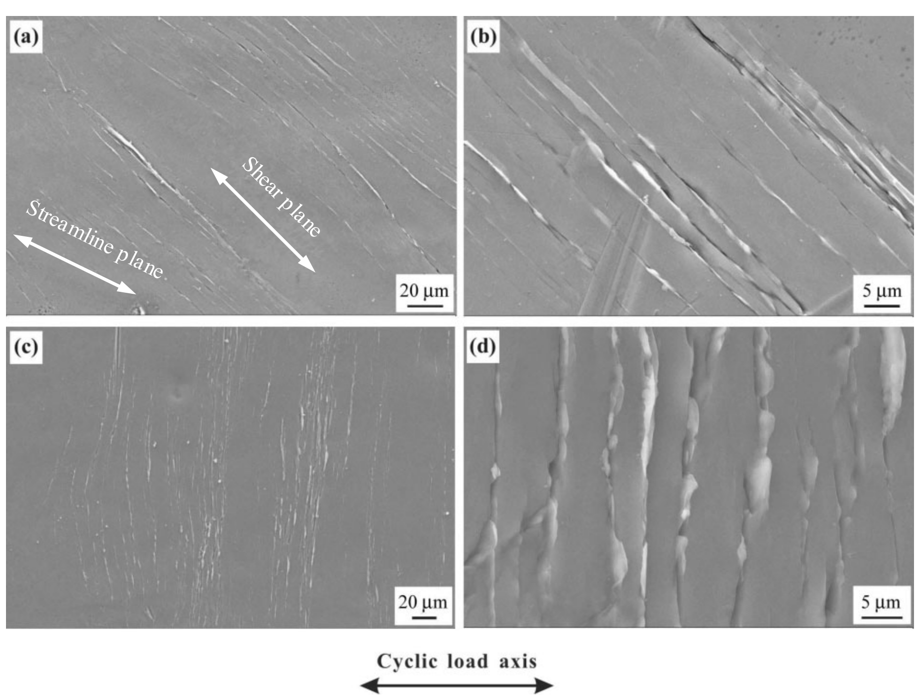

Fig. 7. Shear bands on the surface of the specimen ECAPed for one pass and fatigued for 1000 cycles under plastic strain amplitude of 10^{-3}. (a) and (b) observed on XZ-plane, (c) and (d) observed on XY-plane.

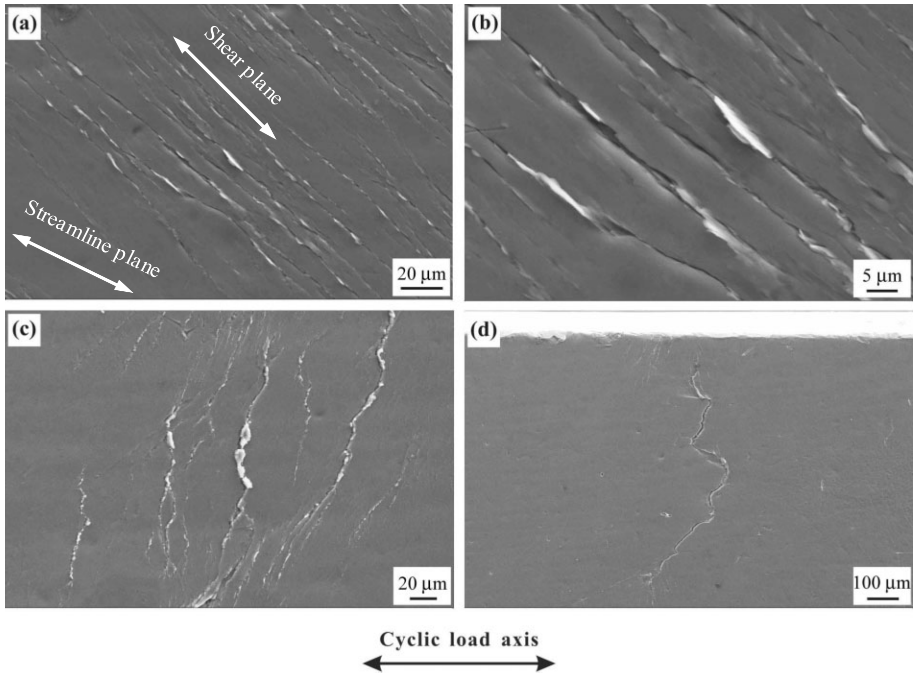

Fig. 8. Shear bands on the surface of the specimen ECAPed for two passes and fatigued for 1000 cycles under plastic strain amplitude of 10^{-3}. (a) and (b) observed on XZ-plane, (c) and (d) observed on XY-plane.

formed using a die having an angle of 90°[34,35,42,43] (See Fig. 10(a)). When the alloy was subjected to ECAP, an elongated and oriented grain structure appears with an inclination to the extrusion of 26.6° relative to the longitudinal direction, which is consistent with the shear direction, as shown in Figure 10(b). So the defects should distribute along the 26.6° streamline plane, but not along the 45° shear plane. It is indicated that fatigue damage should occur more easily along the 26.6° streamline plane than along the 45° shear plane. Accordingly, the previous viewpoint about the formation of shear bands under uniaxial tension or compression should be further discussed as below.

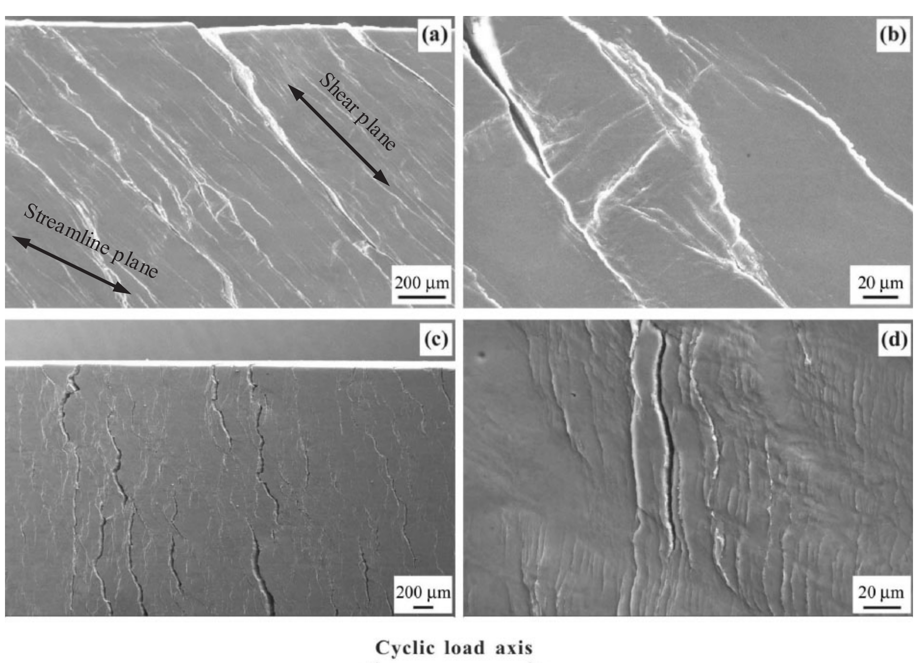

Fig. 9. Shear bands on the surface of the specimen ECAPed for four passes and fatigued to failure under plastic strain amplitude of 10^{-3}. (a) and (b) observed on XZ-plane, (c) and (d) observed on XY-plane.

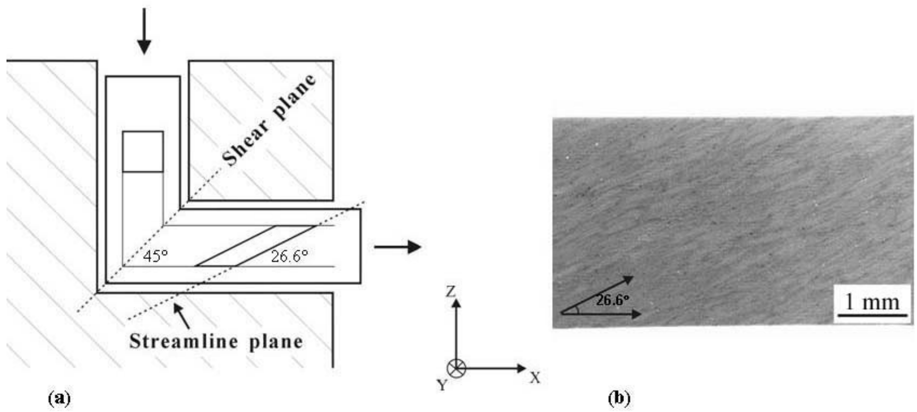

Fig. 10. Illustration of streamline structure forming, (a) illustration of the ECAP process, (b) SEM micrograph of the Al-0.63 %Cu alloy ECAPed for one pass (XZ-plane).

From the above discussion, although the observations show that the shear bands are parallel to the shear plane of the last ECAP extrusion, it is suspect that the formation of shear bands induced by fatigue is associated with the 45° shear plane. And the formation of shear bands should also not be attributed to the 26.6° streamline plane because the angle between shear bands and cyclic load axis is far from 26.6°. Accordingly, shear band direction should depend on other factors. In order to clarify the question, shear bands on the surface of the rolled pure Al specimen fatigued after 5000 cycles were observed, as shown in Figure 11. It can be seen that the angle between the shear bands direction and cyclic load axis is still about 45° on XZ plane, and is still around 90° on XY plane. The shear band direction is the same as that in the Al-0.63 %Cu alloy subjected to ECAP. So the observations above further prove that there is no one-to-one relationship between the shear bands induced by fatigue and the shear plane of the last ECAP extrusion. This results is contrary to the previous opinions of some researchers.[6,15] As for the reason why the fatigued shear bands orient at 45° with respect to the cyclic load axis, it can be explained that the orientation of the shear bands in fatigue might be mainly affected by the maximum shear stress, which further induced the fatigue crack initiation as discussed below.

Fatigue Crack Initiation

From Figures 7 and 8 no obvious cracks can be found along the shear bands in the specimens ECAPed for one and two passes, except for some extrusions and intrusions. However, there is a clear crack not initiating among the shear bands, as shown in Figure 8(d), and the area near the crack is still smooth. The reason for the formation of the crack may be that microcracks initiating at θ phase (Al_2Cu) or some defects aggregate and grow up under cyclic load. With increasing the number of ECAP passes, as shown in Figures 9(a) and (b), it is obvious that many shear bands split and fatigue cracks propagate along the shear bands in the specimen ECAPed for four passes, as reported by some investigators.[7,18,22] According to above observations, the deformation and damage of the ECAP-processed Al-Cu alloy mainly occur along the shear bands at high number of ECAP passes, as well as aggregation and growth of microcracks initiating at θ phase (Al_2Cu) or some defects at low number of ECAP passes.

Conclusions

Strain-controlled fatigue tests of Al-0.63 wt.%Cu alloy subjected to different number of ECAP passes were performed. The following conclusions can be drawn:

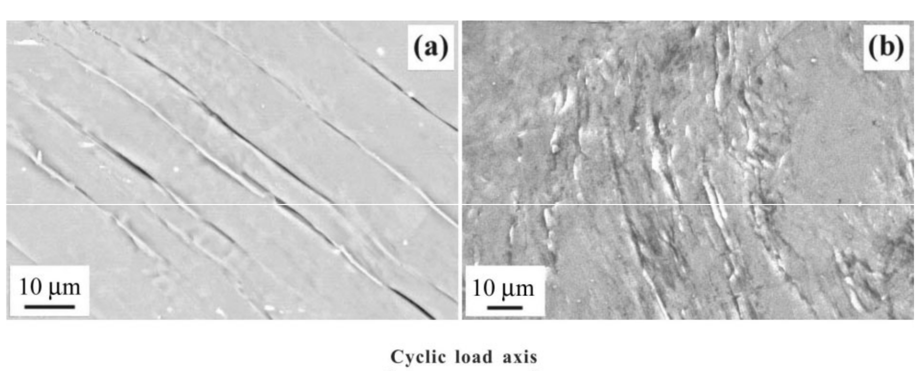

Fig. 11. Shear bands on the surface of the rolled pure Al specimen fatigued for 5000 cycles under plastic strain amplitude of 10^{-3}, observed on (a) XZ-plane and (b) XY-plane.

(1) The ECAPed Al-Cu alloy displays obvious cyclic softening.
(2) Multipass ECAP treatment can decrease the shape parameter of hysteresis loops of the Al-Cu alloy, indicative of a large Bauschinger effect. The variation of Bauschinger effect with the number of ECAP passes is contrary in comparison with that of ECAP-processed UFG Cu.
(3) The shear bands orient at about 45° with respect to the cyclic load axis on XZ-plane, while make an angle of around 90° with respect to the cyclic load axis on XY-plane. There is no one-to-one relationship between the shear bands induced by fatigue and the shear plane of the last ECAP extrusion, indicating that the formation of shear bands in fatigue is mainly affected by the maximum shear stress.
(4) The deformation and damage of the ECAP-processed Al-Cu alloy mainly occurred along the shear bands at high number of ECAP passes, as well as aggregation and growth of microcracks initiating at θ phase (Al_2Cu) or some defects at low number of ECAP passes.

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