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Observation of macroscopic shear band in aluminum-based alloy during equal-channel angular pressing

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Abstract: Equal-channel angular pressing(ECAP) is now recognized as an effective technique for fabricating ultrafine grained materials. The results show that prevalent macroscopic shear banding occurs in ECAP as long as the pressing passes reach 2, and the severe macroscopic shear band extends from bottom to top surface and slants to the longitudinal axis of specimen at an angle of about 45°, develops at regular intervals, with a high shear strain accommodation of about 3.7 within the band. Different families of macroscopic shear bands may cut across each other, and over 60% of sample volume is occupied by macroscopic shear band when the ECAP reaches 4 passes.

Key words: equal-channel angular pressing(ECAP); macroscopic shear banding; ultrafine grained material
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1 INTRODUCTION

In recent years, bulk ultrafine-grained (UFG) materials processed by methods of severe plastic deformation (SPD) such as severe plastic torsion straining (SPTS) and equal channel angular pressing (ECAP) have attracted the growing interest of specialists in materials science[1]. This interest is conditioned by unique physical and mechanical properties.

It is a general observation in many of the industrial forming processes that plastic instability develops at high strain levels (generally > 1.0 of true strain), and shear bands, or S-bands as some authors termed form. Macroscopic shear bands were observed in various single and polycrystalline metals with low to high stacking fault energy[2], and in various metalworking processes including rolling, extrusion, plane strain compression, tensile testing and torsion testing[3, 4] etc.

Equal-channel angular pressing, during which specimen is subjected to pure shear deformation[5], is successfully applied in the fabrication of ultrafine grained materials[6-8]. Grain scale shearing characteristics during ECAP was observed and analyzed by Furukawa et al[9]. Semiatin et al[10] observed the macroscopic shear banding of TiAl intermetallic compound. Detailed investigation on macroscopic shear banding in ECAP was necessary. This paper reports the investigation on the macroscopic shear banding characteristics occurred during ECAP of an aluminum alloy.

2 EXPERIMENTAL

An Al-3% Mg-0.5% Zr solid solution alloy was used in the present investigation. The alloy was prepared through conventional ingot metallurgy process. The dimensions of sample before ECAP were 15 mm × 15 mm × 60 mm. The average grain size in the annealed state before ECAP was 50 μm. ECAP was carried out at room temperature, without any intermediate annealing. In the present study, the intersecting angle between the two equal channels was 90°. The ECAP die was designed to yield an effective strain of 1[11] by a single pass. For case of the subsequent passes, the diameter of the exit channel, d 14.6 mm, was slightly smaller than that of the entrance channel, d 15 mm. During ECAP, the sample was rotated 90° around its longitudinal axis between the passes. This pattern of the pressing was commonly designated as route B[12].

Optical microscopy was used for the microstructure characterization of the macroscopic shear bands on three orthogonal sections (S —Horizontal section; L —Longitudinal section; T —Transverse cross section), as shown in Fig. 1. The specimens were anode oxidized in a solution of 38% H_2SO_4, 42% H_2PO_4 and 19% H_2O, and observed under polarized light. True shear strain that a shear band accommodates was estimated by measuring the orientation difference of the microstructure feature within and outside the shear band on L section (as shown in Fig. 2), using equation[13]:

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$$\varepsilon = \frac{1}{2}(\cos\beta_2 - \cos\beta_1) \quad (1)$$

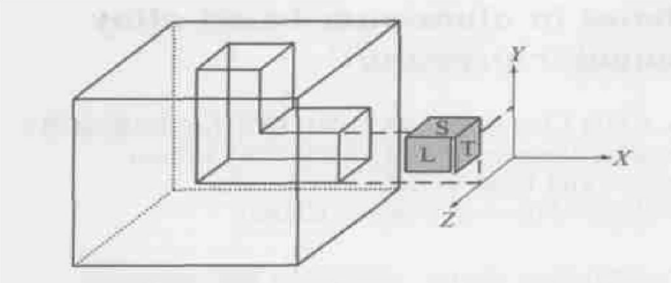

Fig. 1 Orientation of three orthogonal sections
S —Horizontal section; L —Longitudinal section;
T —Transverse cross section

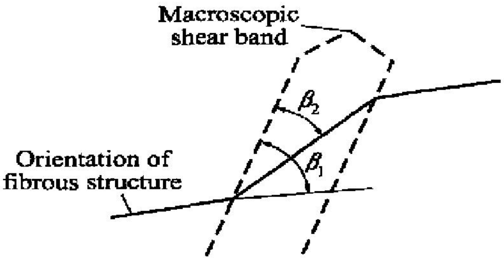

Fig. 2 Orientation change of fibrous microstructure within and outside shear band

3 RESULTS

3.1 Optical microstructure of macroscopic shear band via route B

Fig. 3 gives the OM microstructure features on three orthogonal sections of the experimental samples after ECAP for 2, 3 and 4 passes via route B.

As shown in Fig. 3(a), after 2 passes of ECAP, on longitudinal section(L), the outstanding feature is the shear bands. These bands are nearly parallel to each other and form a definite angle of about 45° to the flow out direction X. On crossing the shear band boundary, the microstructure changes sharply in their appearance, a strong fibrous feature appears in the shear band and a nearly equiaxed feature appears outside the band.

Not only on longitudinal section, but also on horizontal(S) and transverse(T) sections shear bands perpendicular to the flow out direction and parallel to the transverse direction Y are prevailing observed. Because of the strain accommodation in the shear bands, the microstructures are S-shaped on crossing the shear bands. As on L section, the microstructure features are obviously different within and outside the shear bands on S and T sections, but the difference is not as strong as that on L section.

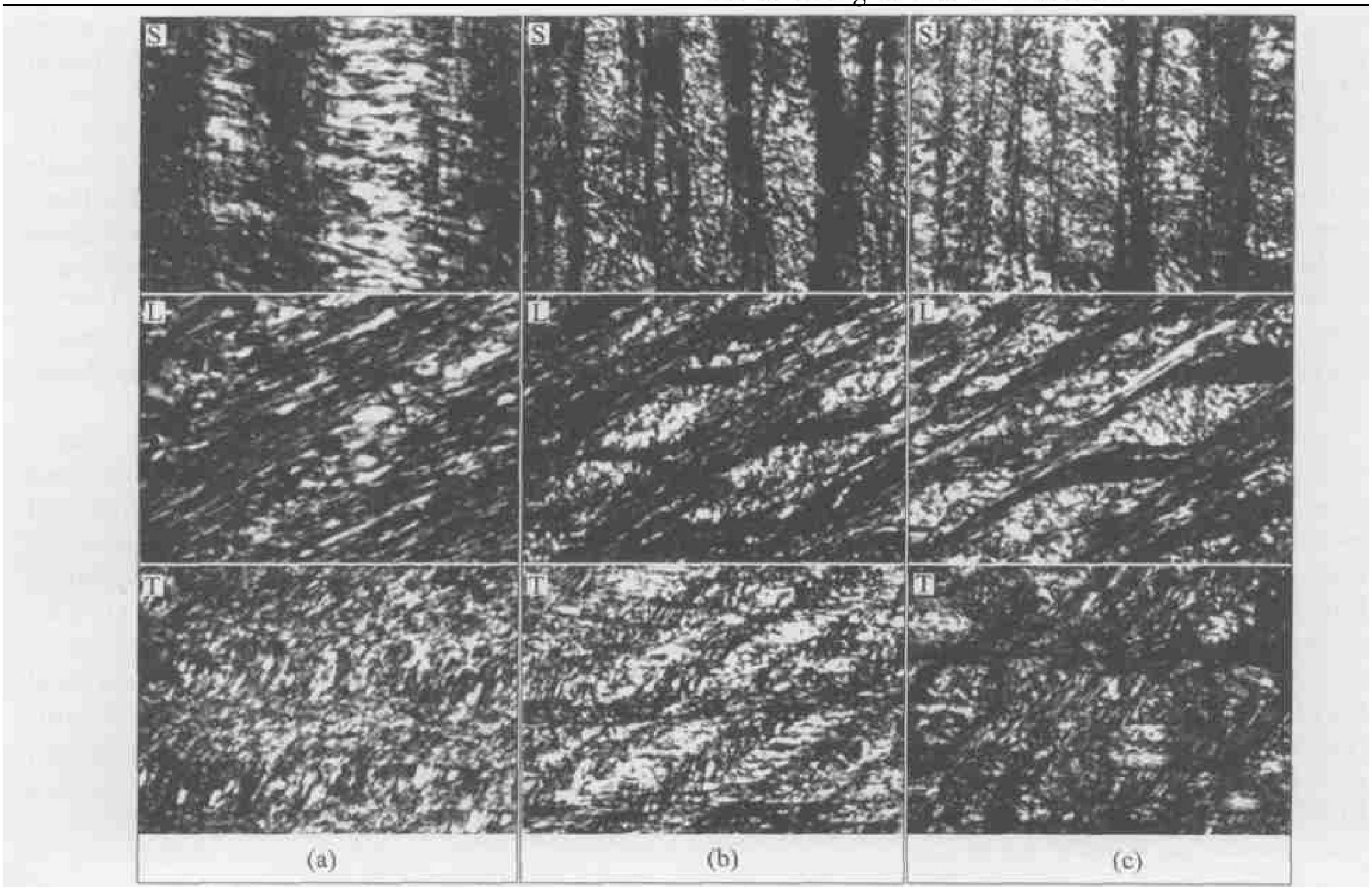

Fig. 3 Structure features of macroscopic shear bands on three orthogonal sections after ECAP via route B to 2 passes(a), 3 passes(b) and 4 passes(c)

Increasing ECAP passes via route B, as shown in Fig. 3(b), results in the increase of shear band families on three orthogonal sections.

In Fig. 3(b), the occurrence of the multi-family shear bands divides the whole longitudinal section into three regions with different structural characteristics:

1) The most distinctive structure feature is the region of shear band family formed in the third ECAP pass which cut through all the other structure features;

2) Shear band family forms in the second ECAP pass, which cuts the background microstructure, and being cut through by the shear band family formed in the third ECAP pass;

3) The region with minimum strain, where traces of original equiaxed grain structure feature can be found, is encapsulated by shear band families formed in the second and third ECAP passes. The fibrous feature of the structure is not very strong within this region.

Estimating from the longitudinal section, the volume fraction of macroscopic shear bands, including the two shear band families formed in the second and third ECAP passes, reaches about 50%. The structures on horizontal(S) and transverse(T) sections can also be divided into three regions, as those on longitudinal section(L).

The microstructure corresponding to 4 passes ECAP via route B, as shown in Fig. 3(c), is more complex due to the additional family of shear band formed in the fourth ECAP pass on longitudinal section. Four distinctive regions can be found. The volume fraction of macroscopic shear bands, including the three shear band families formed in the second, third and fourth ECAP passes, reaches about 60%. The structures on horizontal and transverse sections are similar to those in Fig. 3(b), except the additional family of shear band.

3.2 Montaged optical micrographs

Fig. 4 gives the optical structure on longitudinal section (L) after 3 passes of ECAP via route B. Estimation from the montaged graph shows that the macroscopic shear bands form an angle of 44.75° ±4.68° to the flow out direction X, with an evenly distributed band width of (47.7 ±21.3) μm and a inter-bands spacing of (137.5 ±72.5) μm. The true shear strain of the band accommodates is 3.69 ±1.96. The macroscopic bands extend from the top surface to the bottom of the specimen, without obvious changing in their orientations. Besides the wide macroscopic shear bands observed in Fig. 4, thin macroscopic shear bands are also observed.

4 DISCUSSION

The investigations on macroscopic shear banding show that the prevalent macroscopic shear banding occurs in ECAP as long as the pressing passes reach 2.

The macroscopic shear band in ECAP is a planar shaped macroscopic deformation heterogeneity cutting through the whole sample, extending from top to bottom of the sample, which is inclined to the sample axis X with a definite angle of about 45°. High shear strain of 3.69 ±1.96 is accommodated in the shear band, which corresponds very well to the strain levels of 1 - 6 observed in shear bands of medium to high SFE materials developed in rolling deformation[14].

The macroscopic shear bands may cut across each other in the case of route B to form a complicated mixture of several families of macroscopic shear bands according to ECAP passes. Being crossed by the subsequent macroscopic shear band family, the shape of the previously formed macroscopic shear bands becomes more and more complicated. Usually, as shown in Fig. 4, the previously formed macroscopic shear bands change their orientation sharply to align with the direction of the subsequent macroscopic shear bands when crossed by the later formed macrosopic shear bands in the

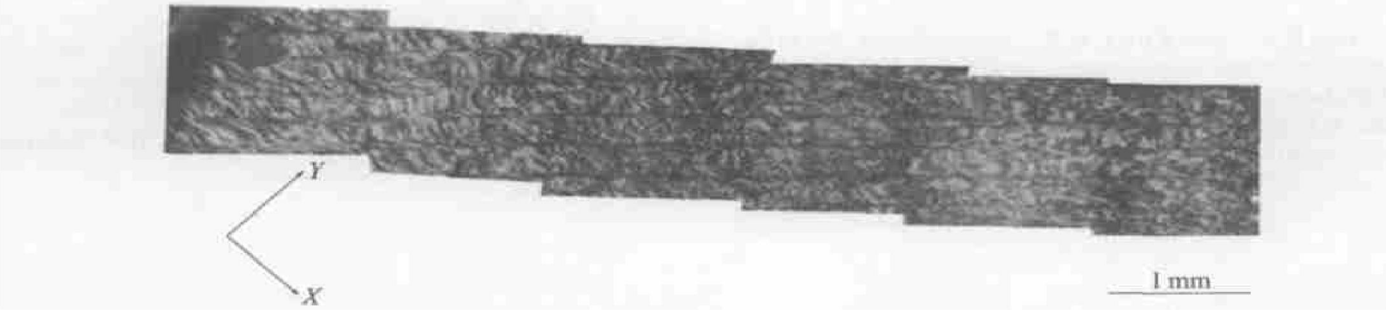

Fig. 4 Montaged optical micrographs showing macro-scale long shear band on longitudinal section after 3 passes of ECAP via route B
(The band extends from top to the bottom of the sample forming an angle of 45° to the sample axis X)

subsequent ECAP pass.

The volume fraction of macroscopic shear band accumulates with the increase of ECAP passes via route B. Over 60% of sample volume is occupied by macroscopic shear bands when the ECAP reaches 4 passes. This is very different from the case of rolling where the volume of shear band material rarely exceeds 5%. This difference of volume fraction of shear bands may be contributed to the different grain structure formed in rolling and ECAP to the nearly same true equivalent strain of about 4[15]. In other investigation, Iwahashi et al[16] found that route B is the best and fast process for grain refinement in ECAP. The results in this study suggest that this may be resulted from the high volume fraction of shear bands and the cutting across of different macroscopic shear band families in this ECAP.

5 CONCLUSIONS

1) Prevalent macroscopic banding occurs in ECAP via route B. The macroscopic shear band is a planar shaped macroscopic deformation heterogeneity cutting through the whole sample, extending from top to bottom of the sample, being inclined to the sample axis X with a definite angle of about 45°. High shear strain of 3.69 ± 1.96 is accommodated in the shear band.

2) During ECAP via route B, the macroscopic shear bands cross each other to form a complicated mixture of several families of macroscopic shear bands. Being crossed by the subsequent macroscopic shear bands, the shape of the previously formed macroscopic shear bands becomes more and more complicated.

3) The volume fraction of macroscopic shear band accumulates with the increase of ECAP passes via route B. Over 60% of sample volume is occupied by macroscopic shear bands when the ECAP reaches 4 passes.

REFERENCES

[1] Valiev R Z, Islamgaliev R K, Alexandrov I V. Bulk nanostructured from severe plastic deformation [J]. Progress in Material Science, 2000, 45(2): 103-189.

[2] Korbel A, Embury J D, Hatherly M, et al. Microstructural aspects of strain localization in Al-Mg alloys[J]. Acta Metall, 1986, 34(10): 1999-2009.

[3] Duggan B J, Lee C S. Deformation banding, original grain size and recrystallisation in FCC in intermediate-to-high SFE metals[J]. Scr Metall Mater, 1992, 27(11): 1503-1507.

[4] Rosen G I, Jensen D J, Hughes D A, et al. Microstructural and local crystallography of cold rolled aluminium [J]. Acta Metall Mater, 1995, 43(7): 2563-2579.

[5] Segal V M, Reznikov V I, Drobyshevskiy A D, et al. Plastic working of metals by simple shear[J]. Russian Matall, 1981, 1: 99-105.

[6] Neishi K, Horita Z, Langdon T G. Grain refinement of pure nickel using equal-channel angular pressing[J]. Materials Science and Engineering A, 2002, 325(1-2): 54-58.

[7] Wang J, Iwahashi Y, Horita Z, et al. An investigation of microstructural stability in Al-Mg alloy with submicrometer grain size[J]. Acta Mater, 1996, 44(7): 2973-2982.

[8] LIU Zu-yan, LIANG Guo-xian, WANG Er-de, et al. Effect of equal channel angular pressing on structure of Al alloy 2024[J]. Trans Nonferrous Met Soc China, 1997, 7(2): 160-162.

[9] Furukawa M, Iwahashi Y, Horita Z, et al. The shearing characteristics associated with equal channel angular pressing[J]. Mater Sci Eng A, 1998, 257(2): 328-332.

[10] Semiatin S L, Seetharaman V I, Weiss I. Hot workability of titanium and titanium aluminide alloys—an overview[J]. Mater Sci Engineer A, 1998, 243: 1-24.

[11] Iwahashi Y, Wang J, Horita Z, et al. Principle of equal-channel angular pressing for the processing of ultra-fine grained materials[J]. Scripta Mater, 1996, 35(2): 143-146.

[12] Stolyarov V V, Zhu Y T, Alexandrov I V, et al. Microstructure and properties of pure Ti processed by ECAP and cold extrusion[J]. Materials Science and Engineering A, 2001, 299(1-2): 59-67.

[13] XIA K, WANG J. Shear, principal, and equivalent strains in equal-channel angular pressing [J]. Metall Mater Trans A, 2001, 32(10): 2639.

[14] Ridha A A, Hutchinson W B. Recrystallisation mechanisms and the origin of cube texture in copper[J]. Acta Met, 1982, 30(10): 2639-2643.

[15] Horita Z, Wang J T, Furukawa M, et al. Submicron-grained Al-3% Mg alloy: fabrication and microstructure [J]. Bulletin of the Japanese Institute of Metals, 1993, 32(12): 898-900.

[16] Wahashi Y, Horita Z, Nemoto M, et al. The process of grain refinement in equal-channel angular pressing[J]. Acta Mater, 1998, 46(9): 3317-3331.

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