Proceedings of the 9th International Conference on Aluminium Alloys (2004)
Edited by J.F. Nie, A.J. Morton and B.C. Muddle

Influence of Stress Ratio of Biaxial Tensile Test on the Lüders Band Formation in Al-Mg Alloy Sheets

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Keywords: Al-Mg, Lüders band, biaxial tensile test, stress ratio, slip system

Abstract

The influence of the stress ratio of the biaxial tensile test on the type-B Lüders band formation in an Al-5.5mass%Mg-0.3mass%Cu alloy sheet was investigated. In the case of uniaxial tensile deformation, the slip planes were easily limited, and then the type-B Lüders bands occurred. On the other hand, it was considered that multiple slip easily occurred in the case of balanced biaxial tensile deformation. The sessile dislocations easily formed, the deformation uniformly occurred and the type-B Lüders bands did not occur. Moreover, the Lüders bands direction changed according to the stress ratio because of the difference in the activated slip system.

1. Introduction

It is well known that Lüders bands form in Al-Mg alloy sheets by tensile deformation. In the case of press forming, the formation of the Lüders bands lower the surface quality of the products. Control of the Lüders bands formation is then significant. The Lüders bands are classified in two types; type-A and type-B. The type-A Lüders bands are associated with yield point elongation, and they form at relatively small strains. On the other hand, the type-B Lüders bands occur as the result of nonuniform deformation which is associated with the Portevin-Le Chatelier effect. Most of the previous studies about the Portevin-Le Chatelier effect and the formation of the type-B Lüders bands were carried out in the uniaxial tensile mode [1-3]. The formation of the type-B Lüders bands in the biaxial tensile mode is then not apparent. As the deformation mode is mostly biaxial tension in the case of press forming, clarification of the mechanism of the type-B Lüders bands formation in the biaxial tensile mode is important. In this study, the effect of the stress ratio on the formation of the type-B Lüders bands in the biaxial tensile mode was investigated.

2. Experimental Procedure

The material used in this study was an annealed Al-5.5mass%Mg-0.3mass%Cu alloy sheet with a 1.0mm thickness. Grain size of the specimen was about 55μm in diameter. The yield point elongation of this specimen was below 0.1%, thus the type-A Lüders bands did not appear.

Figure 1 shows the geometry of the biaxial tensile specimen. The specimen had four arms and each arm had seven slits so as to exclude geometric constraint on the deformation of the 60 mm x 60 mm gauge section. Two strain gauges were mounted at the center of the gauge section in each loading direction. Figure 2 is a schematic drawing of the experimental apparatus. This testing apparatus was originally designed and built by Kuwabara et al. [4]. Opposing hydraulic cylinders were connected to common hydraulic lines so that they were subjected to the same hydraulic pressure. The hydraulic pressure of each pair of opposing hydraulic cylinders was independently servo-controlled. Displacements of opposing hydraulic cylinders were equalized using the pantograph-type link mechanism proposed by Shiratori and Ikegami [5], then the center of the cruciform specimen is always maintained at the center of the testing apparatus during biaxial tensile tests. A load cell was included in each loading direction. The biaxial tensile tests were performed under linear loading paths with 71.5 N/s in the direction of maximum principal stress which was parallel to the rolling direction of the specimen. Stress ratios were changed between 8:0 and 8:8. The tensile tests were stopped at the load of 15.5 kN in the direction of maximum principal stress because the arms of the specimen broke at about 16.0 kN. After the biaxial tensile tests, formation of the type-B Lüders bands was observed by visual examination and the measurement of the surface roughness in the direction of maximum principal stress. Moreover, the formation of microbands in the center area of the specimen was observed using a transmission electron microscope (TEM) to confirm the orientation relationship between the microbands and the matrix. The orientation distribution functions (ODFs) in the center area of the specimen before and after biaxial tensile tests were then calculated using the Schulz reflection method so as to discuss the deformation mode in the biaxial tension. Bunge's notation was used in the plots.

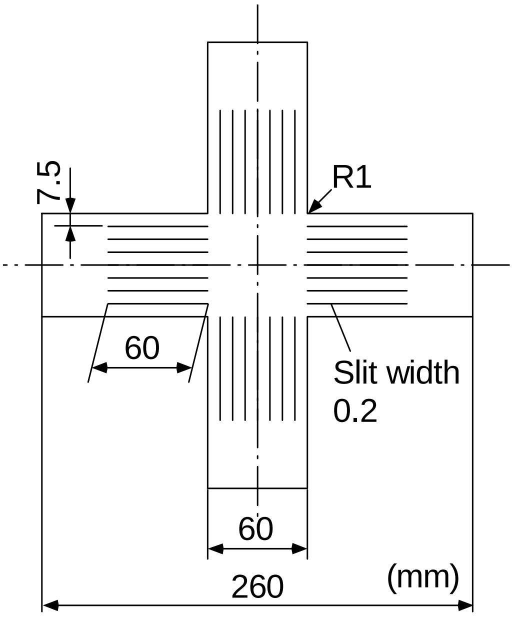

Fig. 1 Geometry of the cruciform specimen.

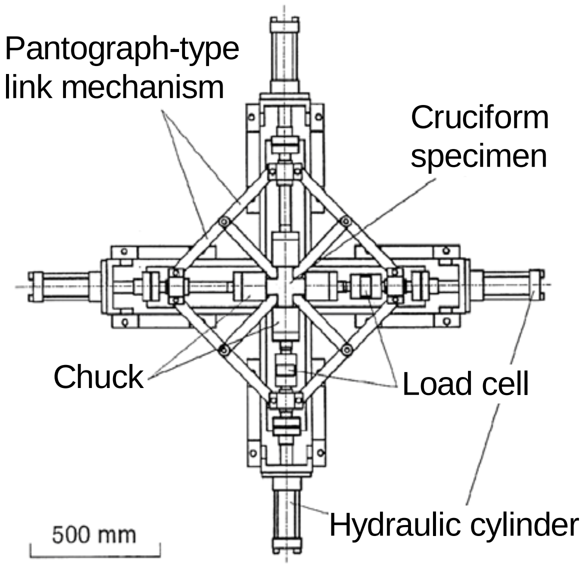

Fig. 2 Experimental apparatus for biaxial tensile test.

3. Results

Figure 3 shows the appearance of the specimens after the biaxial tensile tests, and Table 1 shows the relationship between the stress ratio, strain, stress state and type-B Lüders bands formation. The type-B Lüders bands were observed at the stress ratio between 8:0 and 8:6, while they were not observed at 8:7 and 8:8. Furthermore, the direction of the Lüders bands changed according to the stress ratio.

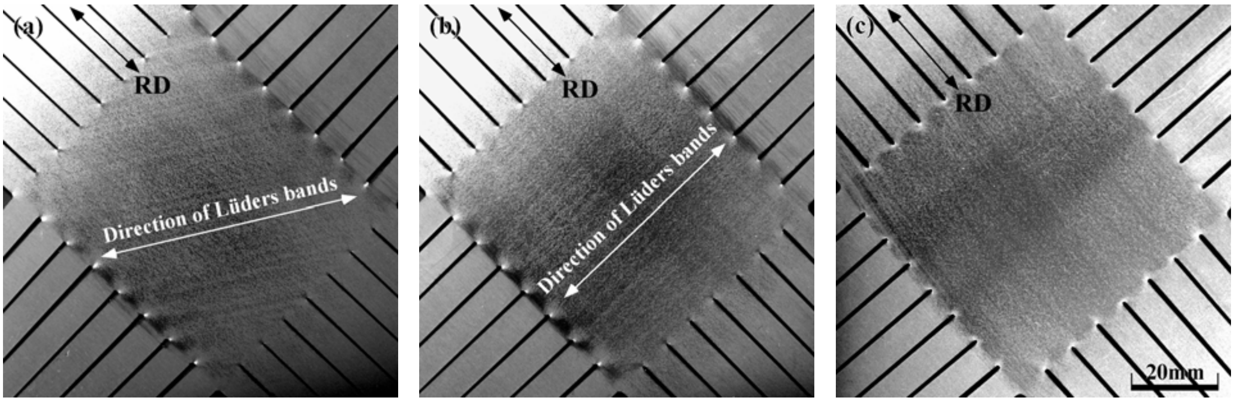

Figure 3: Appearance of the specimens after biaxial tensile tests. The stress ratios (σ R.D.:σ T.D.) were (a) 8:0, (b) 8:4 and (c) 8:8.

Table 1: Relationship between stress ratio (σ R.D. σ T. D.), strain, stress state and type-B Lüders bands formation

Stress ratio	Major strain*	Minor strain*	Stress state	Lüders bands**
8:0	0.093	-0.046	Uniaxial	Observed, 57°
8:2	0.065	-0.014		Observed, 66°
8:4	0.053	-0.001	Plane strain	Observed, 90°
8:5	0.053	0.003		Observed, 90°
8:6	0.048	0.009		Observed, 90°
8:7	0.039	0.018		Not observed
8:8	0.033	0.033	Balanced biaxial	Not observed

* Tensile tests were stopped when the tensile load became 15.5kN in the maximum principal stress direction.

** The angles show the direction of the Lüders bands to the maximum principal stress direction.

Figure 4 shows the relationship between the surface roughness of the gauge section of the specimens and equivalent strain calculated by the von Mises yield criterion. Surface roughness is proportional to the equivalent strain at the stress ratios from 8:0 to 8:6. On the other hand, the surface roughness at the stress ratios of 8:7 and 8:8 is smaller than that from 8:0 to 8:6. That is, the surface roughness of the specimens which formed the type-B Lüders bands is greater than that of the specimens without the type-B Lüders bands.

4. Discussion

The type-B Lüders bands were observed after uniaxial tension (stress ratio was 8:0) and they were not observed after balanced biaxial tension (stress ratio was 8:8). Figure 5 shows the TEM structures after the tensile tests.

In the case of uniaxial tension, micro-bands were observed parallel to the <110> direction of the matrix. That is, the microbands developed along the {111} slip planes. On the other hand, the microbands were also parallel to the <110> direction of the matrix for the balanced biaxial tension. However, many microbands developed in two directions at right angles. The mechanism of the difference in the type-B Lüders bands formation between the uniaxial tension and balanced biaxial tension was then considered as follows. In the case of uniaxial tension, the slip systems, which have the highest Schmid factor, mainly act. However, when the dislocation pinning by magnesium atoms occur, nonuniform deformation easily occur because the slip systems are limited. Serrated deformation occurs by the repetitive dislocation pinning and release, then the type-B Lüders bands form and propagate. While, for the balanced biaxial tension, it was suggested that the number of activated slip systems was more than that of uniaxial tension because the microbands developed in two directions. The sessile dislocations then form easily, the deformation propagates uniformly, and the type-B Lüders bands did not form.

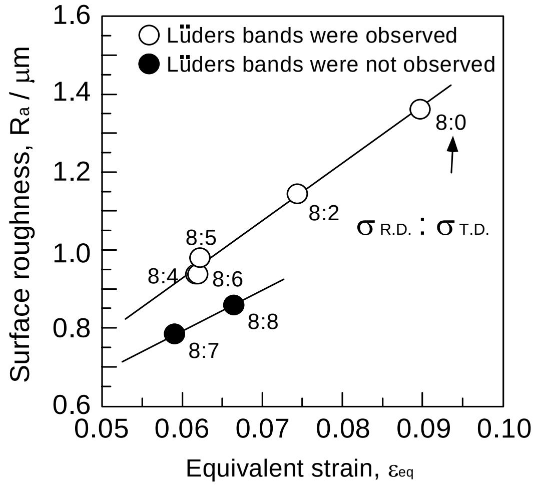

Figure 4: Relationship between surface roughness and equivalent strain after biaxial tensile tests.

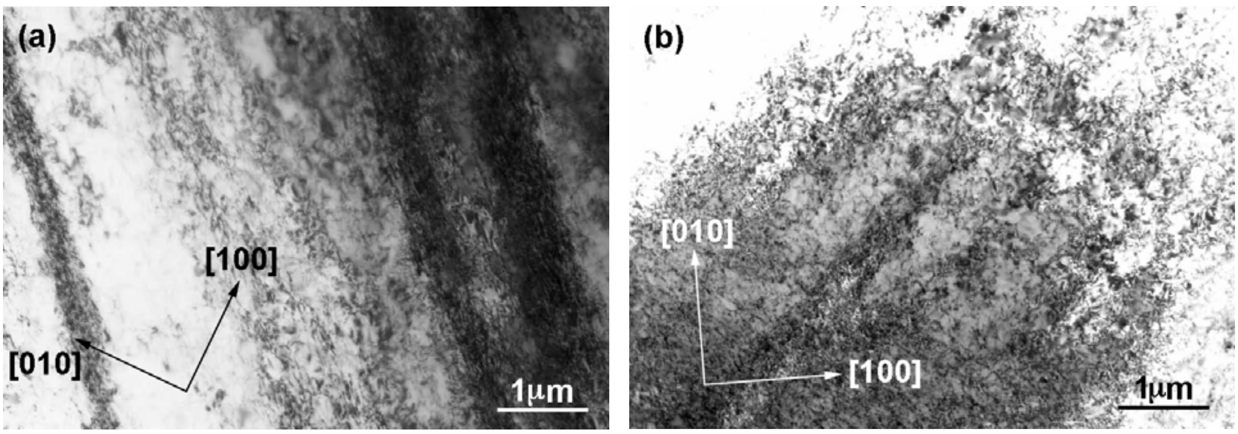

Figure 5: TEM structures after biaxial tensile tests. Stress ratios (σR.D.:σT.D.) are (a) 8:0 and (b) 8:8.

Also, the direction of the type-B Lüders bands changed according to the stress ratio. Figure 6 shows the changes in the ODFs before and after biaxial tension. In the case of uniaxial tension (stress ratio was 8:0), the orientation density of the ND-rotated Cube components from {100}<014> to {100}<011> decreased, while the density of the Cube and ND-rotated Cube components from {100}<001> to {100}<014> increased. Moreover, the orientation density from {110}<001> to {110}<223>, which contained Goss and Brass components, also decreased. For the uniaxial tension, it was considered that the deformation occurred at the maximum shear stress planes because the shrinkage in the width direction could occur, then the angle between the direction of the type-B Lüders bands and the direction of the maximum principal stress was 57 degrees. On the other hand, the orientation density of the Cube and ND-rotated Cube components from {100}<001> to {100}<016> increased also in the case of the plane strain tension (stress ratio was 8:4). However, the decrease in the orientation density of the ND-rotated Cube from {100}<013> to {100}<011> was smaller than that of uniaxial tension, and the orientation density of the {110} plane components, which contained the Goss, Brass and P components, increased. It was considered that shear deformation preferentially occurred at the {110} plane components because the shrinkage in the width direction could not occur, then the type-B Lüders bands formed and propagated at right angles to the direction of maximum principal stress. In addition, the orientation density of the {100} plane components which contained Cube and ND-rotated Cube components generally decreased, while the density of the {110} plane components did not change in the case of the balanced biaxial tension. It was considered as the result of randomizing the texture because of the uniform deformation.

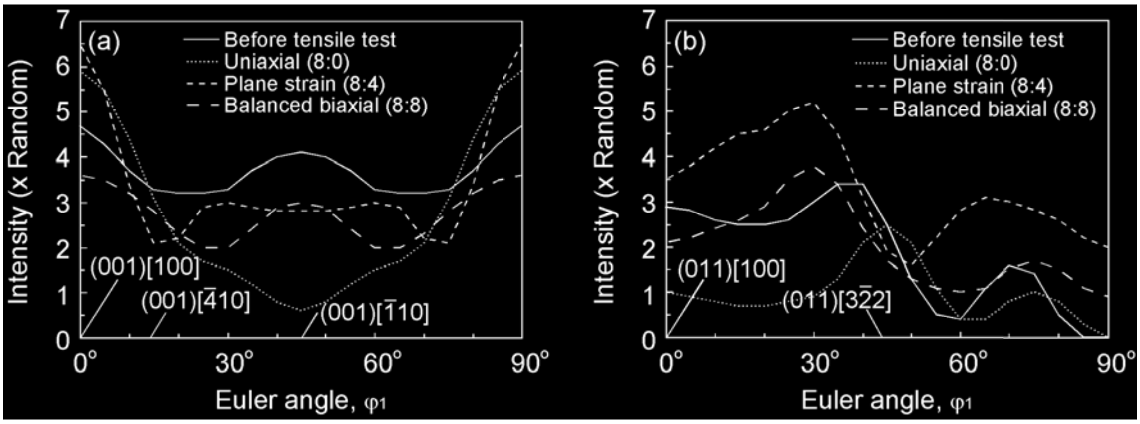

Figure 6: Orientation distribution functions before and after biaxial tensile tests. Euler angles are (a) ϕ=0°, φ2=0° and (b) ϕ=45°, φ2=0°.

5. Conclusions

Based on the experimental results, the influence of the stress ratio of the biaxial tensile test on the type-B Lüders band formation in an Al-5.5mass%Mg-0.3mass%Cu alloy sheet is considered as follows.

1. In the case of uniaxial tension (stress ratio was 8:0), the type-B Lüders bands formed and propagated with the angle of 57 degrees to the direction of maximum principal stress. It was considered that the slip systems were limited in uniaxial tension, then nonuniform deformation easily occurred when the dislocation pinning by magnesium atoms occurred. Serrated deformation occurred by the repeated dislocation pinning and release, then the type-B Lüders bands formed and propagated.

2. In the case of plane strain tension (stress ratio was 8:4), the type-B Lüders bands also formed, but the angle between the directions of the bands and the maximum principal stress changed to 90 degrees. It was considered that shear deformation preferentially occurred at the {110} plane components.

3. For the balanced biaxial tension (stress ratio was 8:8), the type-B Lüders bands did not occur. It was suggested that the number of activated slip systems was more than that of the uniaxial tension. The sessile dislocations then easily form, the deformation uniformly propagates, and the type-B Lüders bands did not form.

Acknowledgements

The authors acknowledge Associate Professor T. Kuwabara and Mr. T. Morita, Tokyo University of Agriculture and Technology in Japan, for the biaxial tensile tests.

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