Study of Strain characterization and microstructure evolution under compression stress in Al-Li alloy

Xiao Jin[1,2 a], GuoDong Zhang[1], Fei Xue[1] and YanFen Zhao[1]

1 Suzhou Nuclear Power Research Institute, Suzhou 215004, PR China;

2 Laboratory of Advanced Materials, School of Material Science and Engineering, Tsinghua University, Beijing 100084, PR China.

[a]jin_xiao2002@163.com

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Abstract: The strain variation and microstructure evolution of 2060-T8 alloy during bending are investigated by Micro-hardness point method (MHPM) and Digital Image Correlation (DIC), electron backscattered diffraction (EBSD). Experimental result shows DIC method can be used to characterize the strain micro-region on average and it can also represent the local strain tensor in the micro-region compared to the traditional MHPM. The strain is unevenly distributed in grains due to the mis-orientation between the adjacent grains difference, the mis-orientation has a blocking effect on the slip of dislocations during deformation in polycrystalline sample. The result shows the mis-orientation between adjacent grains is smaller with larger strain, while the mis-orientation between adjacent grains is larger with smaller strain. The degree of grain division in the process of deformation is related to the strain in this region, a new microstructure such as band structure is observed in grains with larger strain.

Introduction

The 2060 alloy is one of the third-generation Al–Li products, which is widely used for aerospace structures due to its excellent properties of high strength and low density[1-3]. The key step of alloy working as aircraft structural component is obtaining appropriate size and shape for aircraft structural component, and one commonly used deformation processing is bending, which is an environment-friendly and low waste method in the manufacture of structural parts[4, 5].

It is regarded that the outer line of specimen is under tensile stress and inner line of specimen is under compressive stress during bending[6, 7]. Lots of work have been carried in the microstructure evolution under uniaxial tensile stress, the results show typical band structure are observed which is defined as geometrically necessary boundaries (GNBs)[8-11]. This microstructure evolution has a very significant impact on mechanical properties[12-14]. The microstructures and strain evolution of the tensile stress region are studied so much is due to fact that the region is easy to crack under tensile stress, and the region under compressive stress is not easy to crack during the deformation, so it is relatively less for its research.

In the present study, we aimed to find a quasi-in situ experimental method combined with strain measurement and microstructure characterization during bending, and the microstructure evolution are studied further more. It is important to understand the microstructure evolution under compressive stress because it greatly influences the mechanical properties of 2060 alloy and results of its research hardly can been found at present.

Experimental

In the present work, the material used for this study was a commercially 2060 aluminum alloy made by Alcoa Inc., the heat treatment is T8. In this study, T8 heat treatment of interested material is

identified as: solution heat treatment at a temperature about 500 °C in accordance with AMS2722, during which the grains near the surfaces are recrystallized and artificial aging has been performed at (143 ± 2.8) °C for 35 h. The typical microstructure of 2060-T8 alloy is shown in Fig.1[15], from picture the pancake-shaped grain structure with partially recrystallization, in rolling direction the grains are significantly flattened and elongated, and the grain dimensions in surfaces are comparably larger than those in center of the sheet. During the experiment process, specimen is bent to 10mm, 5mm and 3mm, respectively, and relevant test are carried out under the different bend radius condition.
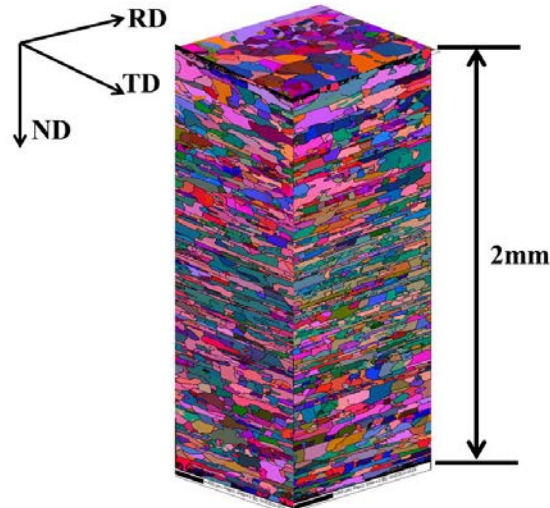

Fig. 1 Triplanar EBSD micrograph of 2060−T8 alloy

The composition of the of the studied alloy analyzed by infrared spectrometer, and the element content (wt.%) is follow: Ag(0.34), Cu(3.52), Fe(0.03), Mg(0.66), Mn(0.29), Si(0.02), Ti(0.03), Zn(0.34), Zr(0.1), Li(0.73), Al(Rest).
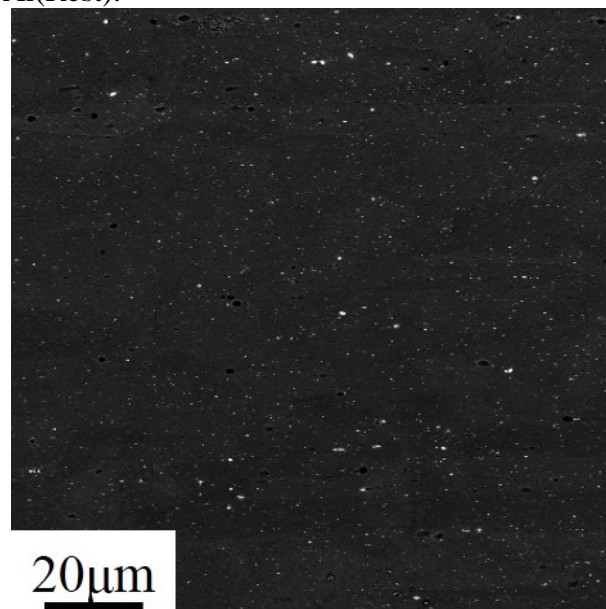

Fig.2 Microstructure of 2060 alloy with precipitates distribution in a BSE image

EBSD data collected by Oxford Nordly 2, Accelerating voltage of 20 kV, magnification of 300× and a working distance of 15 mm were used to scan over the same area of SEM scan, step size is 2μm.

The DIC technology is used to characterize the strain evolution of interested region during deformation, and data are recorded during different stages of deformation[16-18]. The data of DIC require contain features obviously, as shown in Fig.2. In this map, a large number of precipitates (white points in Fig.2) with different sizes are defined as random speckle patterns to record the corresponding displacements. The precipitates randomly dispersed within the grains are evident, the precipitates appear as speckle patterns for strain calculations. Then these similar maps at different

deformation stages collected by BSE probe are used as an input data to a DIC system for strain calculations.

Results and discussion

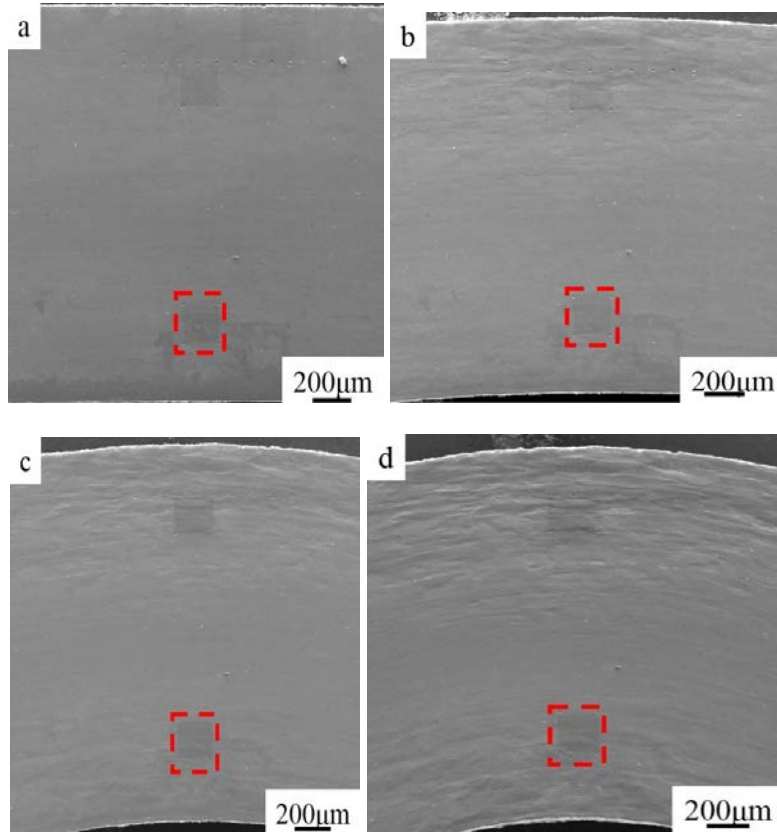### (1) Traditional method of strain measurement

Fig.3 Morphology of simple with different bend radius：(a) unbend；(b) r=10mm；(c) r=5mm；(d) r=3mm

Before the DIC technology applied in characterization of surface strain, the Micro Hardness Point Method (MHPM) is one of the most commonly method in this area[19]. The principle of MHPM is according to displacement of gradient F at coordinate points round the interested region during deformation and calculate the strain tensor during deformation.

In this experiment, region near the inner line of bent simple is followed, as the red dotted line shown in Fig.3. The surface of specimen embossed obviously during the bending in images. The micro hardness points are made at the four corners of red dotted rectangle as feature points, then specimen is bent to 10mm, 5mm and 3mm respectively. The relative coordinates of four micro hardness points are record during deformation, then the average amount of strain in this region is calculated, as shown in Fig.4

Fig.4 shows strain changed in the red dotted line region during bending, and three strain tensors (ε_{xx}, ε_{xy}, ε_{yy}) are studied. The major strain tensor ε_{xx} increased rapidly during bending, the value of ε_{xx} reach 0.14 when the bend radius near 3mm. The strain tensor of ε_{yy} increase with the decrease of the bend radius, while the variation range is small. The strain tensor of ε_{xy} almost unchanged during deformation. From the results of variation in strain tensors, it is concluded the strain in interest region can be equivalent treated as in the process of uniaxial compression.
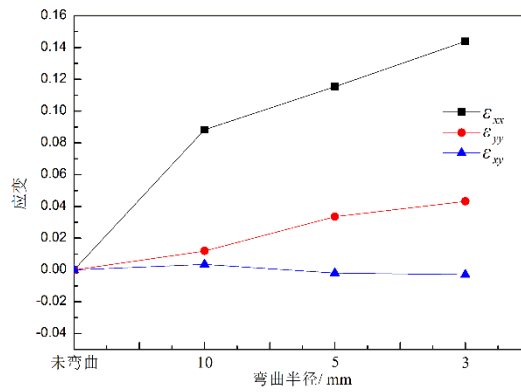
Fig.4 The strain changed during bending

The MHPM can characterize a region of the average strain changes effectively, but it is hard to show the strain of micro-region, because there are have not enough features for tracking and calculation, it is inadequate in analysis the micro-region microstructure evolution combined with EBSD result.

(2) Strain measurement and microstructure evolution
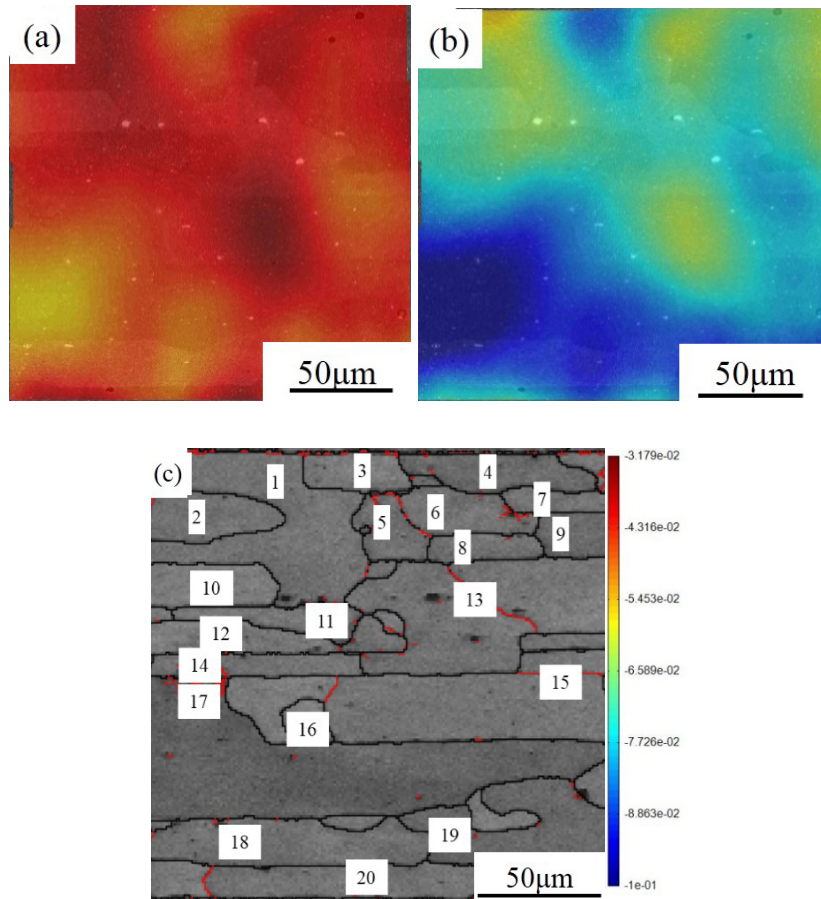
(2.1) DIC method of strain measurement

Fig.5 The cloud map of strain during bending under different radius:

(a) r=10mm, (b)r=5mm, (c) EBSD map of interested region before deformation.

The DIC technology can meet the requirements of strain evolution calculation in micro-region, and even a particular region of the strain changes can be reflected by this method in case there are enough feature points inside. In this work, a large number of random dispersal precipitation phases in the material meet this demand well, there are two completely different colors in the BSE images(the matrix is black and precipitates is white) .

Fig.5 shows the interested region with cloud map of strain distribution under different bend radius and EBSD map with grains distribution before deformation. Fig.5(a) and Fig.5(b) show the strain distribution when the bend radius reach 10mm and 5mm(strain distortion due to surface float seriously when the bend radius reach 3mm), a general version of result that the amount of strain increase with the bend radius decreased. Compared with Fig.5(c), it is found that train distribution is not consistent of all locations in the interest region, which can be determined that the MHPM is inaccurate reflect the strain in all locations in interested region (the darker blue mean larger strain and the darker red mean smaller strain). In addition, strain in every grain also is different from others. There are obvious strain concentration on some grain, and strain in different grains are also significantly different with the bend radius reduced. For example, when the bend radius is 5mm, the strain concentration mainly occurs in regions such as grain1 and grain3, and the other micro-region of strain concentration is near grain17.

It is believed that the main strain tensor is ε_{xx} in interested region from Fig.4. That is, the interested region can be approximately seem as being deformed under uniaxial compressive stress during the bending process. Therefore, Schmid factor analysis is a common method in grain strain capacity under uniaxial compressive stress[9, 20, 21]**.** Fig. 6 shows the Schmid factor analysis of each grain in interested region under the uniaxial compressive stress. Grains with larger Schmitt factors are grain6, grain8 and grain13 as shown in Fig. 6, which mean these grains are easier to have deformation. In the case of uniaxial compressive stress, grains with larger strain is not the above-mentioned grains, but across multiple grain micro-regions. Combined with Fig.5, it can be seen that although the Schmid factor of grain3, grain5, grain15 and grain17 is not the largest, the amount of strain in these grains are larger relatively.
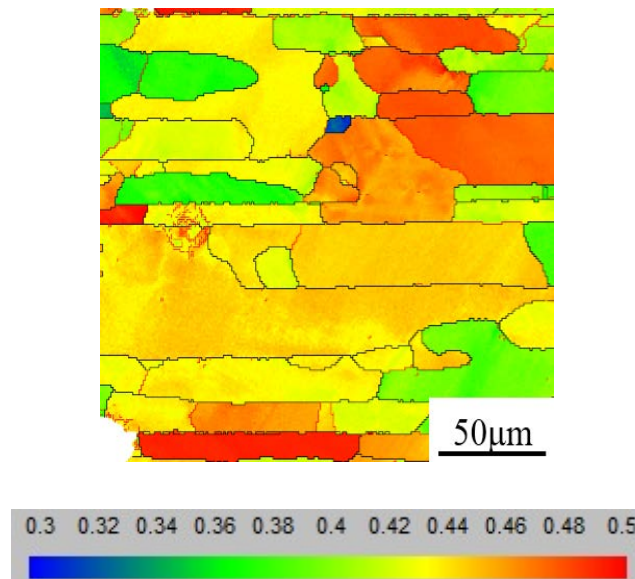

Fig.6 The distribution of Schmidt factors before deformation

Another consideration of uneven strain distribution is that the mis-orientation of grains in the polycrystals[22]. Table 1 shows the grains' Euler angle and mis-orientation between adjacent grains in interested region. Combined with Fig.5 and Table 1, it is found that strain concentration is closely related to the mis-orientation between adjacent grains. For example, it is found that the strain concentration occurred between grain3 and grain5, while the mis-orientation between two grains is 11.8°. Another micro-region of strain concentration is round grain17, it is found that mis-orientation between grain17 and round grains are small, mis-orientation between grain 17 and grain 14 is 29°, mis-orientation between grain 17 and grain 18 is 26°, mis-orientation between grain 17 and grain 15 is 31.4°. The result show the smaller mis-orientation between grains are easier to have larger deformation. In addition, the size of the grain 17 is much larger than other grains, the strength of the

grain is lower than grain boundary relatively at room temperature, so that the grain is easier to be deformed than grain boundary, maybe it is another reason for grain 17 have larger strain.

In the region with smaller strain, it is found that the mis-orientation between grains are larger. Most micro-region s round grain1 have smaller strain, because the mis-orientation between grain1 and round grains are larger, the mis-orientation between grain1 and grain2 is 47.2°, mis-orientation between grain1 and grain3 is 53.6°, mis-orientation between grain1 and grain10 is 51.3°, mis-orientation between grain11 and grain5 even reach 59.2°. Most of the regions with smaller strain distribution have smaller mis-orientation between grains, but there are exceptions, there is no significant strain concentration between grain4 and grain7, while the mis-orientation between these two grains is 18.7°. The reason for this phenomenon may be that the strain in this region is limited due to round grains have smaller strain.

Table 1 All grains' Euler angle and mis-orientation between adjacent grains in interested region.

Arain	Euler angle / °	Adjacent grains	Mis-orientation / °
grain1	35.31，36.42，24	grain1-grain2	47.2
grain2	282.32，45，22.05	Grain1-grain3	53.6
grain3	32.71，89.52，37.76	grain1-grain10	51.3
grain4	208.86，35.33，53.89	Grain1-grain11	56.1
grain5	299.6，27.06，88.13	grain1-grain5	59.2
grain6	287.88，30.16，86.63	grain1-grain13	54.2
grain7	221.85,43.66,29.27	grain1-grain12	55.7
grain8	125.24,42.86,57.7	grain3-grain4	55.2
grain9	312.22,44.75,68.59	grain3-grain5	11.8
grain10	65.84,52.43,46.08	grain4-grain6	42.3
grain11	93.37,45.97,20.3	grain4-grain7	18.7
grain12	153.34,45.21,14.22	grain5-grain6	13.4
grain13	174.08,25.66,15.29	grain5-grain13	48.2
grain14	211.23,44.68,40.33	grain6-grain7	45.7
grain15	317.13,44.59,56.31	grain6-grain8	31.4
grain16	39.75,50.44,66.49	grain7-grain9	35.3
grain17	67.2,31.04,60.99	grain8-grain13	31.3
grain18	202.88,44.49,7.34	grain9-grain13	56.8
grain19	191.57,40.99,14.92	grain10-grain11	43.7
grain20	203.33,45.05,38.79	grain11-grain12	55.7
		grain12-grain14	45
		grain14-grain15	56.31
		grain14-grain17	29
		grain14-grain15	24.2
		grain15-grain16	31.4
		grain16-grain17	30.4
		grain17-grain18	26
		grain18-grain19	8.5
		grain18-grain20	31.8
		grain19-grain20	33.7

The reason for the close relationship of mis-orientation and strain concentration is that the grain boundary has a blocking effect on the slip of the dislocations. The dislocation moves in the polycrystals in the process of deformation of the polycrystalline sample[21], the grain boundary has some resistance to the slip of the dislocations due to the grain orientation difference on both sides of the grain boundary, when the mis-orientation is large dislocation is difficult to slip from grain into the second grain. Multiple slip systems need to start at the same time in order to meet the grain boundary deformation of the coordination. This also leads to dislocations that are difficult to pass through the grain boundary and block at the grain boundary, which increasing the strength of micro-region and making micro-region hard to deformation [23, 24].

(2.2) Microstructure evolution during bending

Fig.7 show the microstructure evolution at interested micro-region under different bend radius. From Fig.7(a)-(c), the small angle grain boundary(SAGB) in grains increased rapidly with bend radius decreased, it can be indicated that the grain in interested micro-region have a significant plastic deformation during bending. In Fig.7(c), the band structure can be observed obviously, the traces are analyzed to be parallel to the {111} slip plane, it can be speculated that the band structure is GNBs structure.
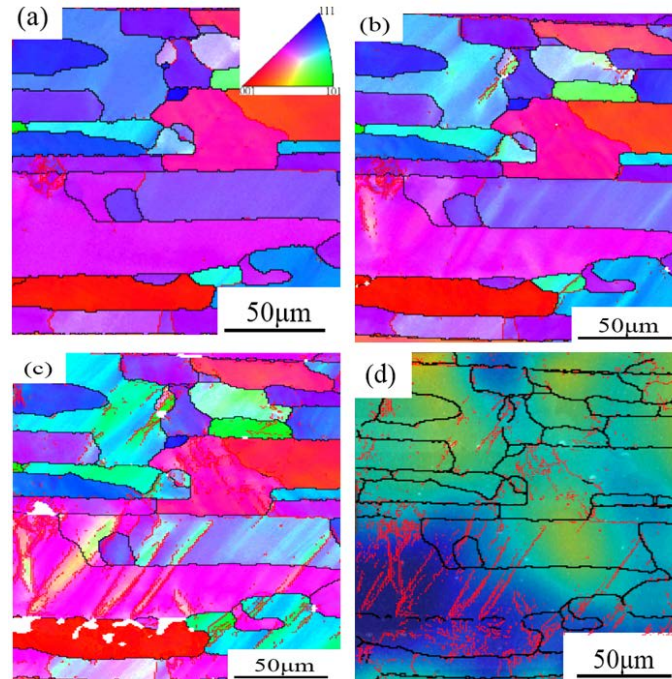
Fig.7 microstructure evolution under different bend radius: (a)unbend；(b) r=10mm；(c) r=5mm；(d) strain combined with microstructure at r=5mm（Black line mean large angle grain boundary, red line mean small angle grain boundary）

The results of the present study show that this band structure is related to the grain's orientation and strain [25]. The extended planar boundaries are termed GNB as they are believed to accommodate systematic slip differences in the grain. This is also in agreement with the typically alternating sign of the mis-orientation across adjacent GNBs[11].

Conclusions

The traditional MHPM and advanced DIC combined EBSD is used in study the strain and microstructure evolution during bending in compressive stress region. The conclusions of this study are as follows.

1. The traditional MHPM can only characterize the average strain change in micro-region, while DIC method can be used to characterize the strain micro-region on average and it can also represent the local strain tensor in the micro-region.

2. It is conclude that the amount of strain in grains are related to mis-orientation between the adjacent grains with EBSD and DIC methods of quasi-in situ experiments. The different mis-orientation has a distinctly different blocking effect on the slip of the dislocations. In general, the mis-orientation between adjacent grains is smaller with larger strain, while the mis-orientation between adjacent grains is larger with smaller strain.

3. The degree of grain division in the process of deformation is related to the strain in this region, a new microstructure such as band structure is observed in grains with larger strain.

Acknowledgements

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