Strain Characterization and Microstructure Evolution Under Deformation in 2060 Alloy

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Abstract. A new method of DIC combined with EBSD is developed for the characterization of strain and microstructure evolution during bending. The traditional microhardness point and DIC methods are used to study the microstructure evolution in 2060 alloy during bending; the interested area suffers under tensile stress, the microstructure evolution is collected by SEM, EBSD, digital image correlation (DIC) method during bending. The results shows that the DIC method can both realize the strain tensor characterization of the interested area, and can also express the local strain tensor in the micro-area even more. The degree of grain division in the process of deformation is related to the strain in this region; the grains have larger strain of small angle grain boundary (SLGBs), which results in a new micro-organizational structure. The misorientation is smaller with larger strain degree while the misorientation is larger with smaller strain.

1 Introduction

2060 alloy is the third generation Al-Li production developed by Alcan Inc. in 2011, which significant improvements in elastic modulus, fatigue crack growth resistance, corrosion resistance and plane stress fracture toughness at reduced density as compared to the previous productions[1-3], used in manufacture the fuselage and lower wing skin structure[4, 5]. The key step in 2060 alloy, the process of obtaining appropriate size and shape is the most important step for working as 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[6].

It is regarded that grains are subdivided into cell blocks (CBs) containing ordinary dislocation cells during plastic deformation in FCC metals with high stacking fault energy[7]. During the process of bending, grains in outer side are affect by tensile stress while grains in inner side are affect by compressive stress. In general, specimen under tensile stress is easier to damage in the same stress condition[8].

In the past decades, many studies have been done to investigate the microstructure and dislocation boundaries during deformation, but it is hard to explain the relationship between strain and microstructure due to hard to characterize the relationship at the same time. In the present work, we aimed to find a feasible way to characterise simultaneous changes in strain and microstructure during bending. EBSD and DIC imaging techniques are combined as the most viable method of potential method to characterize the surface changes in specimens; thus, the statistical result of microstructure and strain information within grains is accurately collected.

2. 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. The standard compositional range of 2060 alloy is shown...
in Table 1, together with the composition of the studied alloy analyzed by infrared spectrometer (ICP-AES).

Table 1

| Element | Ag | Cu | Fe | Mg | Mn | Si | Ti | Zn | Zr | Li | Al |
|---------|----|----|----|----|----|----|----|----|----|----|----|
| Nominal | 0.05 | 3.4 | 0 | 0.6 | 0.1 | 0 | 0 | 0.3 | 0.05- | 0.6 | R |
| 2060 | 0.34 | 3.5 | 0 | 0.6 | 0.2 | 0 | 0 | 0.3 | 0.1 | 0.7 | R |

A split sample of 10×3×2 mm (along the rolling direction (RD), transverse direction (TD), and normal direction (ND), respectively) was used. Simples for characterization is surface (RD×ND) was first mechanically polished by sandpaper from 600μm to 4000μm then electrochemically polished by means of 10% HClO4 solution in alcohol at room temperature under applied voltage of 20V for a time of 15s-20s. The simple is bent by cold-rolled forming, and their bend radii are 10, 5, and 3 mm, respectively.

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.

In this study, the DIC was used to characterize the strain evolution during bending, and data are recorded during different stages of bending of a specimen and are later used as an input to a DIC system for strain calculations. According to the principle of strain calculation used in this study, a large number of precipitates (white points in Fig.1) with different sizes are defined as random speckle patterns to record the corresponding displacements, as shown in Fig.1.

Fig.1 Microstructure of 2060 alloy with precipitates distribution in a BSE image

In Fig1, the precipitates randomly dispersed within the grains are evident; the precipitates appear as speckle patterns for strain calculations. In this study, a commercially available DIC system (VIC 2D, CSI, USA) was used. Images processed by the DIC system were collected by a BSE probe installed in a Tescan MIRA3 scanning electron microscope (Tescan, Brno, Czech Republic).

3. Results and discussion

3.1 Traditional method of strain measurement

One of the strain characterization is micro-hardness point method, which record the displacement of point (such as micro-hardness points) and calculating the strain of the region during the deformation. It is wildly used in measurement of plane strain[4, 9].

In present work, this traditional is used to verify the error of the new method. The interested region is near the outer liner of bent simple where the tension strain is larger relatively, as the red dotted line in Fig.2. Fig.2 shows the morphology under different bend radius, four angles in rectangle is marked
with micro-hardness, the relative displacement of the four points are record during bending and calculate the amount of strain in the region.

Fig.2 Morphology of simple with different bend radius: (a) unbend; (b) r=10mm; (c) r=5mm; (d) r=3mm

Fig.3 shows the strain changed in the red dotted line region during bending. From the Fig.3, the strain tensor $\varepsilon_{xx}$ increased rapidly with the bend radius decreased, when the bend reach 3mm, the strain rise to nearly 0.14. The strain tensor $\varepsilon_{yy}$ decreased with the bending radius decreasing, and the variation range is small. The strain tensor $\varepsilon_{xy}$ almost unchanged during bending.

Fig.3 The strain changed during bending

From the result of changes in strain, this interested region can be believed as uniaxial tension. But one of the disadvantage of this method is not have enough accuracy, when the strain need measure, the displacement of mark points around this region should be calculated. This method appears to be
insufficient when characterizing the strain in the smaller area, the reason is that there is no mark points around the region used for tracking calculation.

3.2 Strain measurement and microstructure evolution

3.2.1 DIC method of strain measurement

![Fig.4 Strain distribution with DIC method under different bend radius:](image)

(a) r=10mm; (b) r=5mm; (c) r=3mm; (d) EBSD map before bending

Fig.4 shows the strain distribution with DIC method under different bend radius in the region of red dotted line in Fig.2 (The darker of red colour, the larger strain which have. The darker of blue colour, the smaller strain which have.). From the Fig.4, there is a significant nonuniformity of strain distribution in the region during bending, and this distribution is uneven with the bending radius decreases. Fig.4(d) is the EBSD map from the same area before bending, contrast Fig.4(d) to other maps in Fig.4, it can be observed that there is a significant difference in the amount of strain on each of the grains in this region. There is a strain concentration on some grains, and with the decrease of the bending radius, the change of strain on different grains is also obviously different, eg. when the bend radius reach 3mm, there are large strain near the grain4, grain11 and grain 14, and strain near grain 10 and grain 12 is smaller.

From Fig.3, the main strain in this area is $\varepsilon_{xx}$, which means the strain in this area during bending can be approximated seemed as deformed under uniaxial stress. Fig.5 shows the Schmidt factor in this area under uniaxial tension, from the map grain11 and grain12 have the max Schmidt factor, the value near to 0.5. In general, the greater the Schmidt factor have, the more prone to deformation. From the Fig.4(c), the region where the strain distribution is greatest is not within the grains 11 and grains 12, but across the grains 12 and grains 15 and the like across the grains. So it is difficult to explain the mechanism with Schmidt factors.
Further analysis of the misorientation between grains in this region, the relationship between the grains’ orientation can be obtained, as shown in Table 2. Combined the Fig. 4(d) and Table 2, the region get larger strain under tensile stress have smaller misorientation, such as: the misorientation between grain2 and grain4 is 27.4°, the misorientation between grain11 and grain12 is 29.8°, the misorientation between grain12 and grain15 is 27.9°. While the region get smaller strain have larger misorientation, such as: the misorientation between grain1 and grain2 is 56.3°, the misorientation between grain10 and grain12 is 44.6°. The similar phenomenon occurred in other region, the misorientation is smaller between grains when the strain is larger, while the misorientation is larger between grains when the strain is smaller. The reason 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 [10], 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 misorientation 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 coordinatio. 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 the area and making the area hard to deformation [11, 12].

### Table 2 The Euler angle and misorientation [13] of main grains in interested region

| grain  | Euler angle / ° | Neighbor grain       | Micrientation / ° |
|--------|-----------------|----------------------|------------------|
| grain1 | 311.02, 33.65, 69.99 | grain1-grain2       | 56.3             |
| grain2 | 31.82, 44.49, 31.41 | grain1-grain4       | 50.7             |
| grain3 | 56.99, 6.38, 86.17 | grain2-grain3       | 24               |
| grain4 | 163.23, 52.49, 47.05 | grain2-grain4       | 27.4             |
| grain5 | 285.55, 1.29, 81.34 | grain3-grain4       | 46.7             |
| grain6 | 8.12, 21.58, 80.04 | grain3-grain16      | 31.5             |
| grain7 | 30.06, 34.31, 43.82 | grain4-grain5       | 58               |
| grain8 | 290.87, 42.57, 79.77 | grain4-grain6       | 41.3             |
| grain9 | 264.54, 51.21, 50.85 | grain4-grain7       | 27.7             |
| grain10| 61.84, 6.23, 32.03  | grain6-grain8       | 46.8             |
| grain11| 122.69, 27.05, 59.55 | grain6-grain7       | 23.2             |
| grain12| 40.68, 36.17, 48.5  | grain7-grain8       | 48               |
| grain13| 152.65, 41.37, 48.16 | grain8-grain9       | 44.8             |
| grain14| 119.96, 26.69, 63.46 | grain8-grain10      | 44.6             |
| grain15| 266.24, 41.42, 58.07 | grain9-grain11      | 37.5             |
| grain16| 64.65, 26.93, 12.7  | grain11-grain12     | 41.2             |
|        |                  | grain12-grain15     | 27.9             |
|        |                  | grain12-grain10     | 30.7             |
|        |                  | grain12-grain14     | 39.8             |
|        |                  | grain12-grain13     | 29.1             |
3.3 Microstructure Evolution in interested area

Fig. 6 shows the microstructure evolution under different bend radius. From map the number of SLGBs increased significantly with the bend radius decreased, this SLGBs result by the large number of dislocations slip in grains. The region have more number of SLGBs while the strain is large, and the region with smaller strain have less number of SLGBs. In Fig. 5(c), the band structures [14] formed by SLGBs is observed in grain 4, grain 8 and grain 12. In the previous uniaxial tensile experiments, a similar structure has been found, and it is considered that this banded structure is a cell structure that occurs when grain is split and the strain reaches a certain degree in the process of deformation. The dislocation density is high at the cell wall, and the dislocation density is expressed as a SLGBs in the reconstructed map of EBSD, when the deformation degree is low, the strain is not enough to form a cell structure inside the grain, and there are a large number of randomly distributed dislocations in the grain, that is a large number of scattered small grain boundaries in the grain [13, 15].

![Image](image_url)

**Fig. 6** The microstructure of interested area under different bend radius: (a) Un bend; (b) \( r=10\) mm; (c) \( r=5\) mm; (d) Complex of microstructure and strain map when \( r=5\) mm (Black line is the large angle grain boundary, red line is SLGBs)

4. Conclusions

The traditional microhardness point and DIC methods is used to studied the microstructure evolution during deformation. A new method of strain change and microstructure evolution during bending is developed by DIC combined with EBSD, the conclusions shows as follow:

1. The microhardness point method can only characterize the average tensor tensor in the interested area, and the DIC method can both realize the strain tensor characterization of the interested area, and also can express the local strain tensor in the micro-area even more.
2. The degree of grain division in the process of deformation is related to the strain in this region, the grains have larger strain occurred a obviously split phenomenon, which resulting in a new micro-organizational structure.
3. The strain degree is relate to the misorientation between grains, and the larger misorientation have a obviously block effect on the dislocations slips. The misorientation is smaller have larger strain degree while the misorientation is larger have smaller strain.

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