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Observation of Orientation Change During Plastic Deformation of Polycrystalline Copper by EBSD Method

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Change in crystal orientation and strain of individual grains during tensile plastic deformation are studied to clarify on the microscopic deformation behavior of polycrystalline copper. The orientation of grain is measured by electron backscatter diffraction (EBSD) technique in the scanning electron microscope. The principal strain of grain is also measured by obtaining the approximated ellipse of strain distribution. The deformation of grains dependent on their initial orientation and the rotation of the principal strain during uniaxial tension are clarified.

Key Words : Polycrystalline Copper, Plastic Deformation, SEM, EBSD Method, Grain Orientation, Crystal Orientation Map

1. INTRODUCTION

Microscopic plastic deformation behavior of polycrystalline metal is complicated, because of the nonuniform deformation of individual grains in polycrystalline aggregates. In order to clarify the deformation behavior of grains during plastic deformation, several analytical and experimental studies have been performed [1-2]. It is known that the deformation of grain is dominated by the crystal orientation of the grain, so that the elucidation of the orientation change induced by the macroscopic plastic deformation is effective to understand the complicated behavior of individual grains in polycrystalline aggregates [3-5].

In the present study, the orientation change of grains during plastic deformation is investigated by the electron backscatter diffraction (EBSD) method, with Link-Opal system incorporated in a scanning electron microscope (SEM). The orientations of about 150 grains in the measuring area are obtained automatically by the system. Meanwhile, the plastic strain of grain is measured by obtaining the approximated ellipse of strain distribution [6], and then the relationship between the orientation change and the deformation behavior of grains is discussed.

2. EXPERIMETAL PROCEDURE

2.1 Specimen

The material used is hot-rolled pure copper sheet with 99.5wt% purity. The shape and dimensions of the specimen for the uniaxial tensile test are shown in Fig. 1. The longitudinal direction of the specimen was

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taken to be parallel to the rolling direction. The measuring area of 500×500μm^2 was chosen at the center of the specimen surface. The number of grains in the measuring area was approximately 150, which is considered to be sufficient for investigating the relationship between the orientation and the deformation behavior of grains statistically. Roughening of surface, high dislocation density and distortion of lattice by residual stress tend to influence negatively for the precise measurement of crystal orientation by EBSD method and may cause poor determination of the orientation. Therefore, the specimen surface was mirror finished by abrasive papers and diamond paste until the maximum height becomes less than 1 μm, and then the specimen was annealed in vacuum at 873 K for one hour. Then, the surface was electro-polished and chemically etched to reveal grain boundaries.

2.2 Orientation Analysis by EBSD Method

Figure 2 shows the schematic illustration of the analyzing system of crystal orientation. The orientation is measured by the EBSD apparatus (Link-Opal system made by Oxford Co. Ltd.) incorporated in the SEM (model S-3500N by Hitachi Co. Ltd.). The formation mechanism of Kikuchi pattern by EBSD method is schematically shown in Fig. 3. On the phosphor screen both Kikuchi lines and diffraction spots are observed. The incident electron beams are scattered inelastically in the sample and diffracted on the crystal planes that satisfy Bragg's condition. The background intensity of diffraction by the inelastic scattering becomes stronger when the direction of the diffraction is closer to the direction of incident electron beam. Therefore, the background intensity is dependent on the angle between the direction of incident electron beam and the

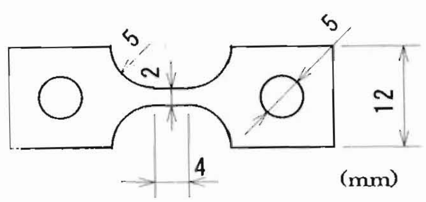


Fig. 1 Shape and dimension of specimen for uniaxial tensile test. (Initial thickness t_0=1.0 mm)

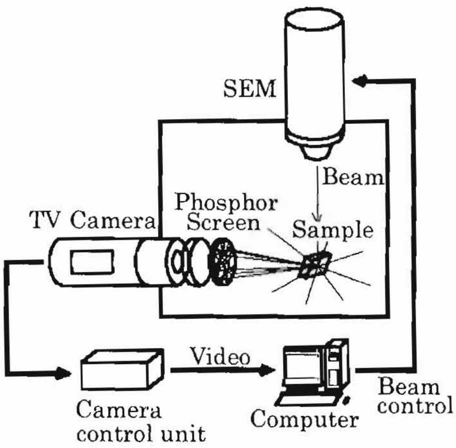


Fig. 2 Link-Opal system to analyze crystal orientation by EBSD method.

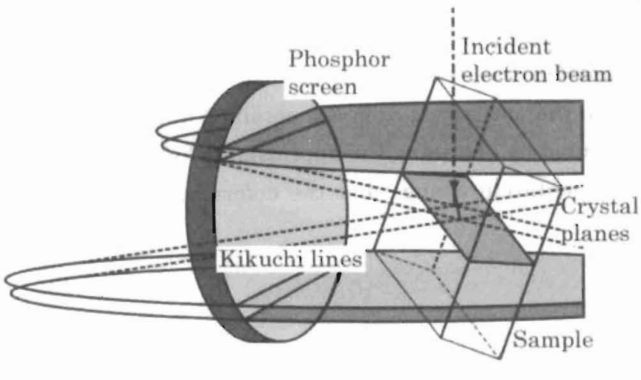


Fig. 3 Formation of Kikuchi pattern by EBSD method.

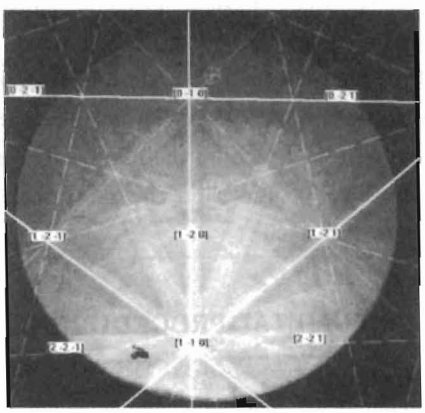


Fig. 4 Example of Kikuchi pattern.

diffraction plane. Since the loss of the background intensity for a pair of diffraction planes occurs three-dimensionally and forms a pair of diffraction cones, the intersections between the scattered beam and the phosphor screen form a pair of hyperbolas. The diffraction angle, however, is very small, so that the hyperbolas are seen as a pair of parallel lines. There are number of planes which induce diffraction of electron beam in a grain and each of them form the similar Kikuchi lines. An example of Kikuchi pattern from pure copper is shown in Fig. 4. The sample stage is inclined so as to set the sample surface as parallel as possible to the direction of the incident beam and as normal as possible to the phosphor screen. This inclination is effective to enhance the forward reflection of the inelastically scattered electron beam and decrease the absorption of the beam into the sample, thus strengthen the intensity of Kikuchi lines. Point analyses are automatically executed at the intervals of 5 μm in the previously selected area. The pattern is recorded and then the crystal orientations in the direction normal to the specimen surface (normal direction) and in the loading direction are calculated in the computer.

2.3 Evaluation of Plastic Strain of Grains

The uniaxial tensile test is conducted by the tensile test apparatus mounted in the scanning electron microscope. The observed grain boundary maps are recorded on the computer at the applied plastic strain ε =0.0, 0.03, 0.07, 0.10 and 0.17. The principal strains of individual grains are calculated from the grain boundary maps before and after deformation, by obtaining the approximated ellipse of the strain distribution [6]. The non-uniform deformation inside grains is not considered in the present study.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Crystal Orientation Map

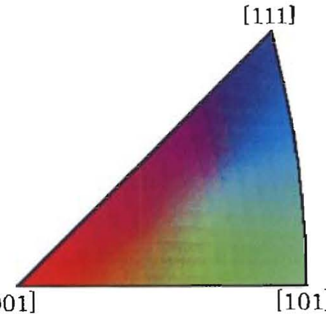
Figure 5 shows the distribution of crystal orientation in the normal and loading directions at the applied strain ε =0.0 (a), 0.03 (b), 0.07 (c), 0.10 (d) and 0.17 (e). The color in the figure represents the crystal orientation that corresponds to the color in the inverse pole figure, and the variation of local orientation with the applied strain can be seen directly. The relationships between the specimen coordinate system, the crystal coordinate system and the slip-plane coordinate system can be determined by the crystal orientations measured in the normal and the loading directions.

It is seen that the major crystal orientations at initial condition (ε =0.0) are the orientations of cube texture {100}<001>, rolling texture {110}<111> and {110}<112>, and recrystallization texture {122}<212>. The directions <100>, <111> and <112> tend to be the loading direction after tensile deformation. It depends, however, on the initial orientation of grains that either <100>, <111> or <112> is preferentially oriented in the loading direction.

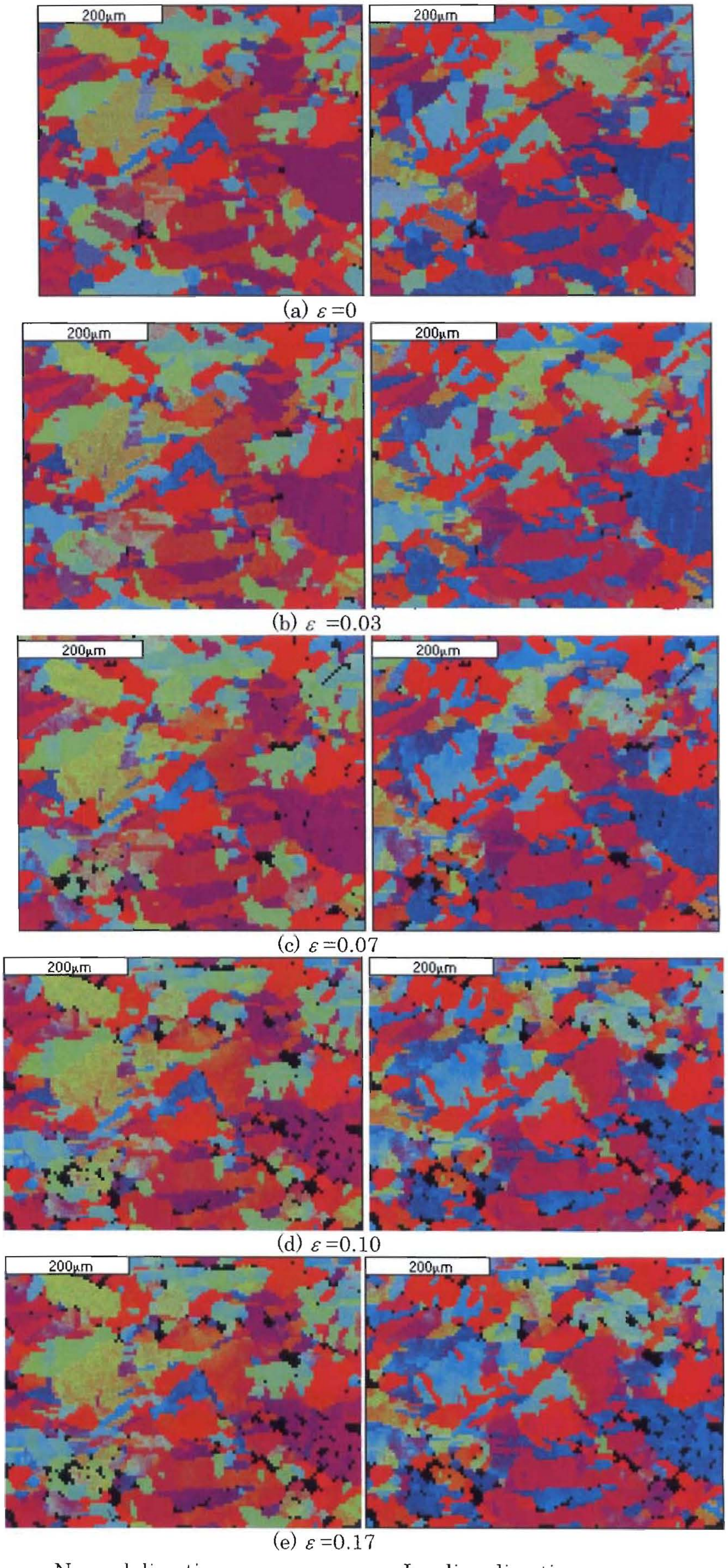
3.2 Plastic Strain of Grains

The variation of principal strain ε_g of grains during uniaxial tensile deformation is shown in Fig. 6. It is seen that there is wide variation in the change of the principal strain in respective grains. The standard deviation S of the principal strain increases with the applied strain, while the coefficient of variation $V = S / \bar{\varepsilon}_g$ ($\bar{\varepsilon}_g$ is the averaged value of ε_g of all grains) once increases and then decreases, as shown in Fig. 7.

Figure 8 shows the distribution of the angle between the principal direction of strain and the loading direction at each stage of the plastic deformation. Although large variation of the angle appears when the applied strain is small, the principal directions of strain gradually rotates to the loading direction with the increase of the applied strain. The initially activated slip system is different for individual grains, which determine the angle between the slip direction and the loading direction. Hence, the difference of crystal orientation of grains induces wide variation of the principal direction in the early stage. With increasing the



Inverse pole figure and orientation key for crystal orientation map.



(a) ε=0

(b) ε =0.03

(c) ε=0.07

(d) ε=0.10

(e) ε=0.17

Normal direction Loading direction

Fig. 5 Crystal orientation map in normal and loading directions by EBSD method.

applied strain, however, the active slip direction rotates to the loading direction and multi-slips begin to occur, thus the principal direction is considered to become close to the loading direction.

3.3 Comparison of Orientation and Strain of Grains

Figure 9 shows the variations of principal strain of grains that have the initial orientations of the cube texture {100}<001> and the rolling textures {110}<111> and {110}<112>. The principal strain of grains with {100}<001> orientation is relatively small, while those with {110}<111> and {110}<112> are relatively large, compared with the averaged value of all grains. The same tendency has been recognized in the experiment with another specimen of the same material. Further investigations, however, seem to be necessary to clarify the relationship between the crystal orientation and the strain of grains, including the orientation dependency represented by Schmid factor of the active slip system and the deformation resistance under the multi-slip.

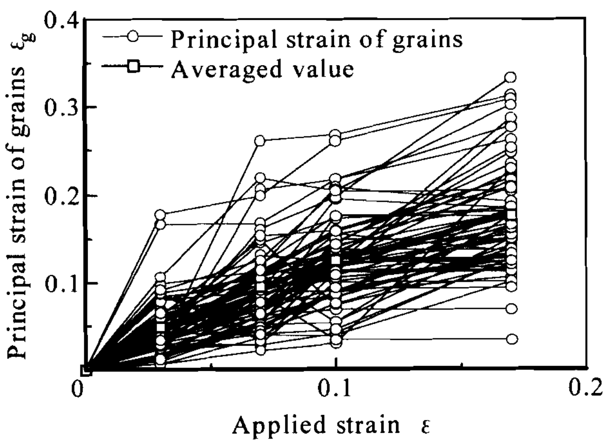


Fig. 6 Distribution of principal strain of grains during uniaxial tensile deformation.

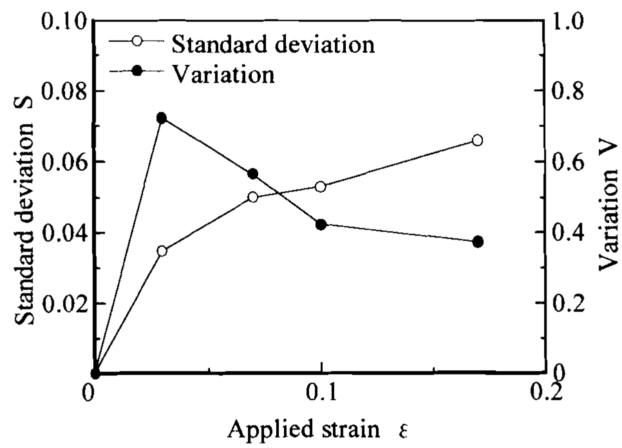


Fig. 7 Standard deviation and variation of coefficient of principal strain of grains.

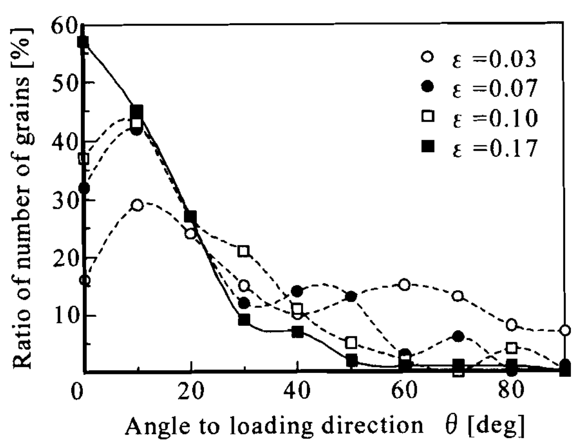


Fig. 8 Distribution of angles between principal direction of strain and loading direction of grains.

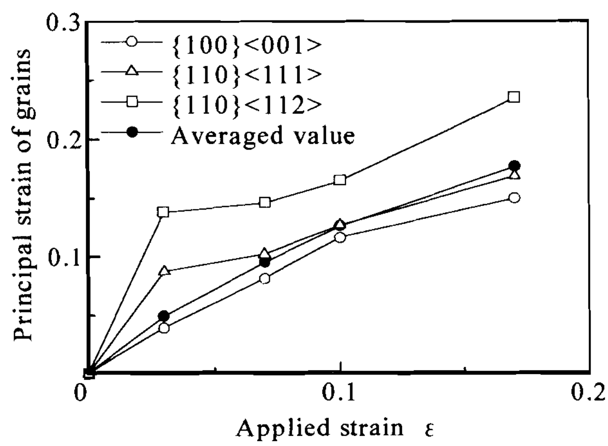


Fig. 9 Change in principal strain of grains with initial orientation {100}<001>, {110}<111>, {110}<112>, and averaged valuefor all grains.

4. CONCLUSIONS

The variation of orientation of individual grains in polycrystalline copper during tensile plastic deformation is experimentally studied, by means of the electron backscatter diffraction (EBSD) method. The principal strain of grains is also measured. The main conclusions are summarized as follows.

(1) After the tensile plastic deformation, the orientations <100>, <111> or <112> of the grains tend to rotate in the loading direction. The rotation depends on the initial orientation of the grain, that is, either <100>, <111> or <112> is preferentially oriented.

(2) The standard deviation of the principal strain of grains increases with the applied strain. Its variation, however, increases at first stage, then decreases with the increase of the applied strain.

(3) The direction of the principal strain of grains becomes close to the loading direction with the increase of the applied strain.

(4) The principal strain of grains is dependent on its initial orientation. The principal strain of grains with the initial cube texture {100}<001> is relatively small, while those with the rolling texture {110}<111> and {110}<112> are relatively large.

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