Development of Biaxial Tensile Test System for *in-situ* Scanning Electron Microscope and Electron Backscatter Diffraction Analysis

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For the further improvement of the press formability of steel sheets, it is important to clarify the relationship between macro mechanical properties and microstructure under multi-axial deformation state. The objective of this work is to develop the experimental system of *in-situ* observation and analysis for biaxial tensile deformation using electron back scatter diffraction patterns (EBSD) with scanning electron microscope (SEM). The appropriate shape of cruciform specimen for the system was examined first by using finite element analysis, and the biaxial tensile test system in vacuum SEM chamber was developed. *In-situ* observation of microstructure during equibiaxial tensile deformation was then conducted using the developed system and the proposed cruciform specimen. The material used in this study was an interstitial-free steel. It was validated by the comparison with the results obtained by the Marciniak type macro test that the developed system realized equibiaxial tensile deformation. Finally, some information obtained from SEM and EBSD analysis was illustrated. It was found for example that the grains with \{001\} plane orientations deformed easily and might cause the surface roughness.

KEY WORDS: *in-situ* observation; interstitial-free steel; electron back scatter diffraction patterns; scanning electron microscope; biaxial tensile test; cruciform specimen; finite element analysis.

1. Introduction

For the weight reduction and the improvement in collision safety high strength steel sheets are being progressively applied to car components. The shape of car components tends to be complicated from the viewpoint of satisfying the elaborate car design in recent years. Therefore, the sheet steels with not only high strength but also high formability are required.1)

The formability of steel sheets is usually evaluated by means of the macroscopic mechanical properties,2,3) such as *r*-value, *n*-value and elongation, which are obtained from uniaxial tensile test. There are tendencies that the drawability and the stretchability are improved by increasing the *r*-value and the *n*-value or uniform elongation, respectively. These macroscopic measures are reported to be significantly affected by microstructures of the sheets. The *r*-value is affected by grains that have \{111\} planes normal to surface of steel sheets.4–6) The *n*-value is controlled by grain size7) or chemical composition.8) Therefore, microstructure analyses by X-ray diffraction (XRD),9–11) scanning electron microscope (SEM)12–14) and electron backscatter diffraction analysis (EBSD)15–17) have been employed for developing steel sheets with high formability.

The observation and analysis technologies in metallography have made further progress in recent years, and the effect of microstructure on the macroscopic mechanical properties can be directly researched by *in-situ* observation18) and analysis of tensile uniaxial test.19–22) Tschopp et al.19) observed the microstructure-dependent local strain behavior during uniaxial tension in polycrystals of nickel based superalloy by *in-situ* SEM and also analyzed the crystallographic orientations by EBSD. They showed that the average maximum shear strain tended to increase with Schmid factor, and that the maximum shear strain near grain boundaries were large. Franciosi et al.20) investigated slip system activity in iron single crystals during uniaxial tension and compression by *in-situ* SEM and also analyzed the crystallographic rotations during the deformation. They observed that a slip line tended to be long and straight when slip systems on \{110\} planes were active, whereas it tended to be curved or wavy when slip systems on \{112\} planes were active. They also discussed the relationship between active slip systems and strain hardening.

The macroscopic mechanical properties are strongly affected by microstructures, and that an *in-situ* observation...
technique is an effective tool to clarify their relationship. The conventional researches of in-situ observation, however, have been carried out under uniaxial tensile state. Steel sheets receive multi-axial deformation during actual forming processes. Therefore, it is indispensable to clarify the influence of microstructural morphology on macroscopic deformation behavior under biaxial tensile state, in order to comprehensively design sheet materials with high strength and high press formability. To the best of our knowledge, however, there are no studies reported so far on the in-situ SEM and EBSD analysis during biaxial tensile tests.

A lot of studies have been performed to investigate deformation behavior under biaxial tension. For example, Kuwabara et al. developed a biaxial tensile system using cruciform specimen and measured the contours of plastic work in steel sheets with various values. They described that the effect of microstructure should be considered to clarify the mechanism of work-hardening in interstitial-free (IF) steels. Kuroda and Ikawa examined the effect of textures on the macroscopic mechanical properties for aluminum alloy sheets. They adopted a crystal plasticity model to find optimum textures in which in-plane anisotropy was small and stretchability was high. Although the microstructural effects on the mechanical properties in biaxial tensile state have been simulated numerically, they have not been studied experimentally by microscopic observation.

If it becomes possible to observe directly and analyze the evolution of microstructure in biaxial tensile state, the great progress will be attained. For this purpose, the in-situ observation system for biaxial tensile test is developed in this study. The ideas for conventional in-situ observation system for uniaxial tensile test can be evolved into the minimized biaxial tensile test that can be carried out in the vacuum chamber of field emission-scanning electron microscopy (FE-SEM). However, it is difficult to obtain large and uniform strain during biaxial tensile test by simply minimizing conventional cruciform specimens. It is necessary to develop the appropriate cruciform specimen for in-situ observation of biaxial tensile deformation using SEM and EBSD analysis.

In this study, first, the optimal design and geometry of the cruciform specimen for the test system is examined using a finite-element analysis (FEA) focusing on the case of equibiaxial tensile condition. Next, the optimal specimen obtained from the simulation is actually manufactured, and the in-situ observations of biaxial tension are carried out using the developed test system. The results show the in-situ observations are sufficiently realized by the system. Furthermore, the in-situ observation results of biaxial tensile test by SEM and EBSD analysis are discussed.

2. Optimal Geometry of Cruciform Specimen for the Biaxial Tensile Test System with In-situ SEM-EBSD Analysis

2.1. Analytical Condition of the Geometry of the Specimen

To observe and analyze the microstructure using SEM-EBSD during biaxial tensile test system, it is necessary to employ small cruciform specimens in which the uniform biaxial deformation can be attained. And, it is preferred that the obtained biaxial strain at the center of the specimen is as large as possible. The conventional cruciform specimens have usually some slits paralleled to the arm to obtain uniform deformation at the center of specimen. When minimizing simply the conventional cruciform specimens slits with adequately small width cannot be manufactured due to the limitation of ability of wire electric discharge machining. And the strain concentration occurs easily near the slit end.

In order to find the optimal geometry of the specimen for the biaxial tensile test system, FEA was carried out. DEFORM-3DTM v10.2 was employed as the FEA solver with static implicit method.

Figure 1 shows the shape and geometry of the cruciform specimen used for FEA. The external size of specimen is determined depending on the size of stage in the vacuum chamber and visual field of SEM used later in this study, and the total length is 40 mm. To avoid the large reduction in the cross section of arm, four slits are arrayed in the 45° direction to tensile directions, in contrast with the conventional specimens. The width of slit is 0.15 mm. The size of the flat and square gauge part is set to be 1.1 mm from the loading capacity of the tensile test system. The arm thickness is 1.4 mm and the arm width, W, is varied from 1.3 to 6.0 mm with the slit length, fixing the size of square...
The specimens with thin gauge part are also prepared to obtain larger strain. Figures 1(c) and 1(d) show the shapes of the center part with a thickness reduction. While the bottom side has the concavity, the top side is kept flat supposing the analyses by SEM and EBSD. The round part has a radius of 1 mm. We call this type of reduction area the reduction pattern R. The reduction ratio is defined as the ratio of reduced thickness, \( t_r \), to the arm thickness, \( t_a \) (\( = 1.4 \text{ mm} \)).

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Figure 2 shows the finite-element model of the specimen. The model consists of approximately 250,000 tetrahedral elements. For effective calculation, the mesh size at the center, which is assumed to be the deformable region, is 2.5 times as fine as that near the arms. The size at the center is conformed to the grain size of the specimen (approximately 10–20 \( \mu \text{m} \)). The origin of the coordinates is set at the center of top surface of specimen. The \( x \)-, \( y \)- and \( z \)-coordinates are set to be the transverse direction (TD), rolling direction (RD) and nominal direction (ND), respectively. The slit length, \( L_{slit} \), is the length from arm end to slit end. Note again that the arm width, \( W \), is varied with the slit length, fixing the size of square gauge part at the center.

Numerical simulations are conducted by enforcing the displacement of each node at boundary layers on the arms. The displacements in \( x \)- and \( y \)-directions, \( \delta_x \) and \( \delta_y \), are set to be equal, focusing on the equibiaxial deformation.

The material used in the experiments described later is an IF steel sheet, and the following values obtained from uniaxial tensile test of the sheet are used in the simulations: Young modulus, \( E = 208 \text{ GPa} \). Poisson ratio, \( \nu = 0.3 \).

Flow stress, \( \sigma = 577(0.0064 + \varepsilon^p)^{0.25} \text{ MPa} \), where \( \varepsilon^p \) is the plastic strain.

For convenience’s sake, isotropic hardening law was applied. As forming limit, the simulation was conducted until the equivalent strain at the slit end reached the limit strain, \( \varepsilon_{\text{limit}} \), of 1.1 which was obtained from the strain at fractured part in uniaxial tensile test.

The calculations were carried out for six types of specimen with various slit lengths, \( L_{slit} \) and reduction ratios, \( t_r/t_a \), shown in Table 1, to find out the optimal geometry of specimen to realize the large strain at the center.

### Table 1. Geometrical conditions of specimen in FEA.

<table>
<thead>
<tr>
<th>Type of specimen</th>
<th>Slit length, ( L_{slit} ) [\text{mm}]</th>
<th>Reduction ratio, ( t_r/t_a ) [%]</th>
<th>Reduction pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.10</td>
<td>0</td>
<td>–</td>
</tr>
<tr>
<td>B</td>
<td>1.6</td>
<td>0</td>
<td>–</td>
</tr>
<tr>
<td>C</td>
<td>2.3</td>
<td>0</td>
<td>–</td>
</tr>
<tr>
<td>D</td>
<td>3.7</td>
<td>0</td>
<td>–</td>
</tr>
<tr>
<td>E</td>
<td>1.6</td>
<td>29</td>
<td>R</td>
</tr>
<tr>
<td>F</td>
<td>1.6</td>
<td>50</td>
<td>R</td>
</tr>
</tbody>
</table>

Fig. 3. Distribution of equivalent strain at displacement of 0.16 mm.
and 0.19 mm for type D, respectively. The local strain concentration near the slit end was seen at the earlier stage for the longer slit. At the same time, with increase in slit length, the flat gauge part becomes small and the obtained strain becomes relatively large. Figure 4 shows that the maximum strain increases with the slit length, while it drops at the slit length of 3.7 mm (type D). The maximum strains are larger for the slit lengths of 1.6 and 2.3 mm (types B and C) than the slit lengths of 0.1 and 3.7 mm (types A and D).

Figure 5 shows the evolutions of distributions of $\varepsilon_{x}$ and $\varepsilon_{y}$ along the $x$-axis for type B. The strains increase with displacement. It is found that the strain distributions are sufficiently homogeneous even for the large displacement of 0.20 mm at least in the center range from $-0.10$ to 0.10 mm, where the in-situ observations are supposed to be done. The similar results were obtained for the strain distributions along the $y$-axis and also 45° direction to $x$- or $y$- axis.

Figure 6 shows the distributions of the strain ratio, $\beta = \varepsilon_{y}/\varepsilon_{x}$, along the $x$-axis for various slit lengths at the displacement of 0.16 mm. The fluctuation of strain ratio is the smallest for the slit length of 1.6 mm, and the almost constant strain ratio of 1.0 is obtained at the center range from 0 to 0.1 mm.

It is concluded that the most homogeneous equibiaxial tensile state is obtained for the slit length of 1.6 mm.

2.2.2. Effect of Reduction Ratio

The above results were those calculated for specimens with no thickness reduction. In order to examine the effect of the reduction ratio, calculations were carried out for three various reduction ratios of 0 (type B), 29 (type E) and 50 (type F) %, fixing the slit length to be 1.6 mm (cf. Table 1).

Figure 7 shows the relation between the reduction ratio and the maximum equivalent strain at the center of top surface. Compared to the case of no reduction, the maximum strain is larger for 29 and 50% reduction ratios, while the largest strain is obtained for the reduction ratio of 29%. From the viewpoint of ease of preparation of specimen, it is desired that the reduction ratio is maintained as small as possible. Therefore, the reduction ratio of 29% ($t_{r}=0.4$ mm) is considered to be enough to obtain large strain.

2.2.3. Improvement of Reduction Pattern

The abovementioned results of FEA have shown that the most homogeneous and largest strain in equibiaxial tension state is obtained for type E, namely for the specimen with a slit length of 1.6 mm and a reduction ratio of 29%, among the six types of specimen shown in Table 1. However,
there still remains a problem. The calculated results shown above are only those at the top surface, where the in-situ observations will be carried out. Therefore, in this section, the deformation through the thickness direction is examined.

Figure 8 shows the distribution of equivalent stress in \( x-z \) cross-section at \( y = 0 \) of specimen for type E. It can be seen that the stress is not homogeneous in the thickness direction of specimen. The stress at the top side is smaller than that at the bottom side. Such non-uniform stress distribution would be caused by the reduction pattern. The bending moment generates and, as a result, the strain becomes larger at the bottom side than the top side.

From the viewpoint of avoiding the bending moment, we propose another reduction pattern X. Figure 9 shows the newly proposed reduction pattern with X shape. The gauge length is 1.1 mm, which is the same as that of reduction pattern R (cf. Fig. 1). The direction of maximum bending moment in this case is parallel to 45° to the tensile directions. By changing the direction of maximum bending moment, the bending moment becomes relatively low in the tensile directions. The distribution of equivalent stress for the reduction pattern X with a slit length of 1.6 mm and a reduction ratio of 29% is shown in Fig. 10. Figure 11 shows the distribution of equivalent stress along the \( z \)-axis for the reduction patterns R and X. The stress difference between the top and bottom sides is much smaller in the reduction pattern X than that of the reduction pattern R.

Figure 12 shows the obtained maximum equivalent strain for the reduction patterns R and X. The strains at the top and bottom surfaces are almost uniform for the pattern X. And the strain at the top surface is lager for the pattern X than the pattern R. This is also an important improvement because the observation of microstructure is carried out from the top surface where the larger strain is attained.

At the end of this section we would like to validate that the homogeneity of deformation in \( x \)- and \( y \)-directions is obtained also for the reduction pattern X using Fig. 13, which shows the distributions of strains \( e_x \) and \( e_y \) along the \( x \)-axis on the top and bottom surfaces. It is seen that the strains are distributed uniformly in the region where the in-situ observations are supposed to be done. The similar results were obtained for the strain distributions along the \( y \)-axis. And the strain ratio is approximately 1.0 in the observation area at the center.
3. In-situ Observation of Biaxial Tensile Test Using SEM-EBSD Analysis

3.1. Experimental Apparatus and Procedures

Based on the simulation results mentioned above, the experimental apparatus was originally developed and the in-situ observation of biaxial tensile test using SEM-EBSD analysis was carried out.

Figure 14 exhibits the experimental apparatus developed in this study. The size of the apparatus is 166 mm in length, 140 mm in width and 42 mm in height, due to the limitation of space of the vacuum chamber of FE-SEM. The two servomotors enable biaxial tension. In case of the conventional macro biaxial tensile tests, the pantograph mechanism is often applied to synchronize the movements in two directions. However, in the present system, the crosshead motions in x and y directions are separately given by two servomotors because of the limitation of space. The maximum load of 1 kN is available in each direction. The displacements of x and y crossheads are synchronized by software. The displacement of each crosshead is measured by using step gauge on the back surface of crosshead. The crosshead speed can be controlled from 0.50 to 50 μm/s at intervals of 0.50 μm/s.

Figure 15 shows the schematic of the data measurement setup adopted for in-situ SEM-EBSD analysis. The biaxial testing system is controlled by the computer PC1. After providing predetermined displacements in both tensile directions using the software control, the crossheads are held mechanically by using gears embedded in the system. Subsequently, in-situ SEM-EBSD analyses are conducted under biaxial tension. The backward displacement during the holding state is approximately only 1 μm in both tensile directions. The SEM-EBSD analyses are usually conducted with a tilt angle of 70°. In this study, however, the tilt angle of 58° is given due to the space limitation. PC2 is used for EBSD analyses. The crystal orientations on the top surface of specimen are calculated by OIM collection v6.1. The SEM observations and EBSD analyses are performed at 500 magnification in the square visual field with a side length of 200 μm at the center of specimen. The step size of EBSD analysis is 1.0 μm. PC3 is used for controlling the electron beam of FE-SEM and for obtaining the image. The strain during the test was calculated from the displacement of crosshead. And thickness strain was calculated assuming the volume constancy.

Table 2 shows the mechanical properties of the test material used in this study. The material was the IF steel sheet with a thickness of 1.6 mm and has single phase of ferrite. A conventional uniaxial tensile test was conducted in the rolling direction at the crosshead speed of 3.0 mm/min. The gauge length and width of specimen were 50 mm and 25 mm, respectively.

The specimen was cut from the sheet by a wire-electrical
discharge machine. RD was set to one of two tensile directions. Then the X shaped reduction area was made by machining. The thickness was reduced to 1.4 mm ($t_a$) by buffing. The dimensions of specimen were set to be optimal ones obtained from FEA. Namely, the slit length was 1.6 mm, the arm width was 3.0 mm and the reduction ratio was 29% ($t_r = 0.4$ mm) (cf. Figs. 1 and 9). The photos of cruciform specimen from the top and bottom sides are shown in Fig. 16. The top side was electrically polished for the SEM-EBSD analysis.

The experiment was conducted in equibiaxial tensile state with a crosshead speed of 2.5 μm/s in each direction.

### 3.2. Experimental Results and Discussion

#### 3.2.1. Validation of Equibiaxial Deformation in the Present Test System

In order to ascertain whether the equibiaxial deformation is realized in the developed test system or not, some results are first compared with those obtained by the Marciniak type macro biaxial tests\(^{37}\) using the same test material. The Marciniak-type in-plane biaxial stretching tests were conducted using a flat-headed punch with a diameter of 100 mm and a rectangular specimen with a side length of 200 mm. The test punch speed was 5.0 mm/min. The tests were stopped at the equivalent strain of 0.10, 0.15, 0.20 and 0.25, and the crystal texture and the Vickers hardness were measured.

The texture for the Marciniak test was measured by X-ray diffraction (XRD). The orientation distribution function (ODF) was calculated under anisotropic condition. The crystal orientation in this paper is expressed using the Bunge’s form of the Euler angles ($\phi_1$, $\Phi$, $\phi_2$).\(^{44}\) The similar data processing was performed for the EBSD analysis of the micro biaxial test. Generally, the maximum intensities of ODF $\phi_2=45^\circ$ plane are seen at {111} orientation in texture of IF steels. The texture of {111} orientation has been reported to affect the $r$-value,\(^{45}\) which is an important mechanical property in press forming. Figure 17 shows the evolutions of the maximum intensity of {111} orientation in the micro test and the Marciniak type macro test as a function of the equivalent strain, $\varepsilon_{eq}$. The results measured in uniaxial tensile test are also shown for reference in this figure. In contrast with the case of uniaxial tensile state, the maximum intensity increases with strain in both the micro and the macro biaxial tests. The results for the two biaxial tests agree well with each other qualitatively and quantitatively. It is reported that stabilized orientations under compressive deformation were {111} and {001} in loading direction, while under tensile deformation {110}.\(^{45}\) In case of biaxial tension in RD and TD, the deformation state is mechanically the same as compression in thickness direction. Therefore, the result of Fig. 17 for biaxial tension is consistent with the abovementioned report.

Figure 18 shows the evolutions of Vickers hardness for the micro and the macro tests as a function of strain. The hardness was measured at the center of specimen; at points quarter thickness apart from the top surface on the TD-ND cross section. A fairly good agreement between the two tests can be seen also in Vickers hardness, exhibiting that the magnitudes of plastic deformation given to the two samples are almost the same.

From the above comparisons it can be concluded that the equibiaxial deformation is actualized in the micro test.
system developed in this study.

3.2.2. In-situ Observation of Surface Roughness and Analysis of Microstructure Morphology

Now, we would like to exhibit some information available only from the in-situ observation of biaxial tensile test using SEM-EBSD analysis developed in this study.

**Figure 19** shows SEM images of the surface of specimen during the test. It is observed that the surface roughness grows with the progress of biaxial deformation, and that the concave parts correspond to some crystal grains. It is also found that the slip bands develop in various directions. Prominent slip bands are observed in the concave parts. One of the concave parts is designated with a circle in Fig. 19. These results suggest that the specific crystal grains are deformed preferentially and become concave parts. This could be attributed to the difference in deforming resistance of grains. It is well known that the stretchability is strongly influenced by the surface roughness. The clarification of the mechanism of development of roughness will be a great contribution to the material design.

**Figure 20** shows the results of EBSD analysis observed during biaxial tensile test. In this figure three kinds of maps are used. The inverse pole figure (IPF) maps observed in ND are employed to indicate the crystal orientation distribution. The grain average misorientation (GAM) maps are used to indicate the degree of deformation of grain. And the Taylor factor maps are used to relatively indicate the deformation resistance of grain. The Taylor factor maps were calculated for 40401 observation points, assuming 24 slip systems of BCC structure and uniform equibiaxial deformation.

As we expected, it is found from the IPF maps that the crystal orientation varies gradually with the progress of deformation depending on the grains, and that the variation of orientation is relatively large near grain boundaries. The grains with near {111} plane orientations tend to rotate to {111} plane orientations with the progress of deformation. This result corresponds to Fig. 17. The GAM value increases with the progress of deformation depending on the grains, and there can be seen the correspondence between

<table>
<thead>
<tr>
<th>Equivalent strain, $\varepsilon_{eq}$</th>
<th>SEM image</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (Before test)</td>
<td><img src="image1" alt="SEM image" /></td>
</tr>
<tr>
<td>0.071</td>
<td><img src="image2" alt="SEM image" /></td>
</tr>
<tr>
<td>0.13</td>
<td><img src="image3" alt="SEM image" /></td>
</tr>
</tbody>
</table>

**Fig. 19.** SEM images during biaxial tensile test.

<table>
<thead>
<tr>
<th>Equivalent strain, $\varepsilon_{eq}$</th>
<th>IPF</th>
<th>GAM</th>
<th>OIM</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (Before test)</td>
<td><img src="image4" alt="IPF image" /></td>
<td><img src="image5" alt="GAM image" /></td>
<td><img src="image6" alt="OIM image" /></td>
</tr>
<tr>
<td>0.071</td>
<td><img src="image7" alt="IPF image" /></td>
<td><img src="image8" alt="GAM image" /></td>
<td><img src="image9" alt="OIM image" /></td>
</tr>
<tr>
<td>0.13</td>
<td><img src="image10" alt="IPF image" /></td>
<td><img src="image11" alt="GAM image" /></td>
<td><img src="image12" alt="OIM image" /></td>
</tr>
</tbody>
</table>

**Fig. 20.** IPF, GAM and Taylor factors in OIM during biaxial tensile test.
the increase in the GAM value and the variation of crystal orientation in IPF maps. On the other hand, it is interesting that the GAM and IPF maps reveal that the GAM value near the \{001\} and \{10\} plane orientations tends to increase. From the comparison between the IPF maps and the Taylor factor maps, it is found that the Taylor factor of grain with the \{001\} plane orientation is relatively low. Accordingly, it is considered that the grains with \{001\} plane orientations can be easily deformed in equibiaxial tensile state and \{001\} plane orientations become concave parts with the progress of deformation as shown in Fig. 19. Such micro inhomogeneous deformation may cause the surface roughness. The detailed investigation will be done in our future works.

4. Conclusions

In this study, the experimental system of in-situ observation and analysis of microstructure during biaxial tensile deformation using electron back scatter diffraction patterns (EBSD) with scanning electron microscope (SEM) has been developed.

First, the optimal design and geometry of cruciform specimen for the test system was examined by finite element analysis focusing on the case of equibiaxial tensile condition. The size of flat and square gauge part at the center of specimen was set to be 1.1 mm and the arm thickness was 1.4 mm. Under these conditions the numerical results showed that the sufficiently homogeneous and large strain of 0.2 was attained for the specimen with a slit length of 1.6 mm and a thickness reduction at gauge part of 0.4 mm (reduction ratio of 29\%) in case of the reduction pattern X.

Next, the biaxial tensile test system in vacuum SEM chamber was actually manufactured. The in-situ observation of microstructure during equibiaxial tensile deformation was then conducted using the developed system and the proposed cruciform specimen. The realization of equibiaxial tensile deformation was validated by the comparison between the results obtained from the test system and the Marciniak type macro test.

Finally, some results of in-situ observation and analysis were illustrated. The results revealed for example that the occurrence of surface roughness during biaxial tensile deformation was related to the deformation of grains with certain crystal orientations. The detailed investigation will be done in our future works.

We hope that the test system developed in this study will be a useful tool to give information for designing sheet materials with high strength and high press formability.

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