Influence of Strain Ratio on Surface Roughening in Biaxial Stretching of IF Steel Sheets

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Due to an increasing demand for automobile outer panels with sharper streamlines, surface roughening during press forming is recognized as an important problem to be solved. However, although sheets are subjected to various deformation modes during press forming, the influence of deformation mode on surface roughening is not yet understood. Moreover, surface roughening behavior in Interstitial Free (IF) steels, which are now commonly utilized for outer panels, has not been studied. In the present study, the effect of deformation mode on surface roughening behavior in IF steels was examined, focusing in detail on the effect of texture development. Differences in surface roughness development and changes of microstructure were examined under equi-biaxial and plane-strain tension, using a macroscopic Marciniak test and microscopic in-situ observations. In addition, the influence of the distribution of crystal orientations on surface roughness development was numerically examined using a crystal plasticity finite-element analysis. The results showed that surface roughening was larger for plane-strain tension than for equi-biaxial tension regardless of the IF steels tested, due to the larger difference in deformation resistance among crystal grains depending on crystal orientation. It is therefore suggested that surface quality after press forming could be improved by reducing the difference in deformation resistance among the grains.

KEY WORDS: surface roughening; sheet metal forming; microstructure; texture; interstitial free steel; EBSD; crystal plasticity finite-element analysis.

1. Introduction

Recently, exterior designs of automobiles have tended to become more complicated to meet the diversifying needs of consumers. As a result, there is an increasing demand for outer panels that have sharp streamlines. In draw and stretch forming of such panels, tools with small radii are usually used; as a result, so-called “surface roughening” often occurs near sharp streamlines due to a comparatively large and multi-axial plastic deformation. Because surface roughening affects not only the appearance quality but also the onset of fracture in press forming, it is desirable to reduce surface roughening as much as possible.

Studies to overcome surface roughening in press forming have been conducted on steel sheets and aluminum alloy for a long time. For interstitial free (IF) steels, we had been completely lacking in knowledge of surface roughening, including the influence of microstructures on surface roughening.

In our previous study, surface roughening and the change of microstructure of IF steel sheets during biaxial tension deformation were examined in detail using two types of tests. One was a macroscopic Marciniak type test and the other was a microscopic biaxial tensile test developed by the authors, which enables in-situ continuous observations of sheet surface during biaxial deformation, using a scanning electron microscope/electron backscattered diffraction pattern (SEM/EBSD) method. The results showed that not only the grain size but also the texture of the sheet has a great influence on surface roughening, and that surface roughening became large for sheets which had a large number of crystal grains with orientations in the vicinity of normal direction (ND) (001), due to inhomogeneous deformation derived from their lower deformation resistance.

In our previous study, however, only equi-biaxial tensile deformation was examined. There are various deformation modes in biaxial stretching, and as pointed out by Osakada et al., the behavior of surface roughening may also be affected by the strain ratio. In the present study, therefore, surface roughening and the change of microstructure of IF
steel sheets during biaxial stretching were examined for various strain ratios. Differences in surface roughening behaviors and changes of microstructure were examined and compared between equi-biaxial and plane-strain tension states, using the above-mentioned two types of tests and experimental observation procedures. Furthermore, the influence of the distribution of crystal orientations on the surface roughness development was numerically examined using a crystal plasticity finite-element analysis (CPFEA).24–27

2. Experimental Procedures

2.1. Materials

The materials used in the present study were cold rolled-annealed steel sheets with a single phase of ferrite. The mechanical properties of the materials are shown in Table 1. To examine in-plane anisotropy, r-values were measured at a plastic strain of 0.15 in the rolling direction (RD), transverse direction (TD), and 45° from RD, whereas other results were obtained in the rolling direction (RD). Figure 1 gives the inverse pole figure (IPF) maps in the RD-TD plane obtained by using EBSD. Clearly, both the average grain size and texture were different depending on the material. Materials A, B and C were IF steel sheets, which had a developed texture of {111} in the normal direction (ND). The average grain sizes, d, of the three materials were 29, 9.3 and 16 μm, respectively. On the other hand, material D was an Aluminum-killed steel sheet with comparatively random crystal orientations. The average grain size of material D was 15 μm, which was comparable to material C.

2.2. Observation of Surface Roughening in Marciniak Type Biaxial Tension Test

To examine the difference of surface roughening behavior depending on the deformation mode, the change of sheet surface in Marciniak type biaxial tension test21) was first observed. Rectangular specimens with one side length of 300 mm (RD) were stretched by a flat-headed cylindrical punch with a diameter of 100 mm. The other side length was varied from 140 to 300 mm (TD) so that various deformation modes from plane-strain to equi-biaxial tension could be obtained. As a parameter indicating the deformation mode, the following plastic strain ratio \( \beta \) was used,

\[
\beta = \frac{\varepsilon_1}{\varepsilon_3},
\]

where \( \varepsilon_1 \) is the maximum principal strain in RD and \( \varepsilon_3 \) is the minimum principal strain in TD. The punch speed was 10 mm/s. Estimating the average strain rate from the amount of working time and substantial plastic strain in the center of specimen, the order of strain rate was 1.0×10⁻³/s. The plastic strain was evaluated from the changes in length of scribed patterns, with an initial grid of 2 mm drawn on the specimens. The equivalent plastic strain was calculated by von Mises yield criterion, though the materials had some anisotropy (Table 1).

As in our previous study,20) the development of surface roughening was observed after stopping the test at certain punch strokes, until necking occurred. After stopping the test at intervals, 25 mm square specimens were cut from the center part, where the most significant surface roughening could be observed.

Surface profiles were measured by a contact-type roughness meter. Scanning was done in RD with a speed of 0.15 mm/s. In this case, the arithmetical mean deviation of primary profile, \( P_u \),28) was used as a parameter that quantitatively represents the unevenness of surface, since \( P_u \) could also be obtained in the numerical simulation described later. The comparison between the experimental and simulated results is carried out by means of \( P_u \). \( P_u \) was evaluated by Eq. (2) and the evaluation length of \( P_u \) for each line was 1.0 mm in the experiments. The measurements were carried

<table>
<thead>
<tr>
<th>Material</th>
<th>Initial thickness [mm]</th>
<th>YP* [MPa]</th>
<th>TS* [MPa]</th>
<th>u-EL* [%]</th>
<th>EL* [%]</th>
<th>r-value**</th>
<th>Average r-value</th>
<th>Δr***</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.6</td>
<td>150</td>
<td>287</td>
<td>29</td>
<td>54</td>
<td>1.7</td>
<td>1.5</td>
<td>2.1</td>
</tr>
<tr>
<td>B</td>
<td>0.75</td>
<td>270</td>
<td>447</td>
<td>20</td>
<td>34</td>
<td>1.1</td>
<td>1.8</td>
<td>1.6</td>
</tr>
<tr>
<td>C</td>
<td>0.75</td>
<td>185</td>
<td>340</td>
<td>25</td>
<td>44</td>
<td>1.2</td>
<td>1.8</td>
<td>1.7</td>
</tr>
<tr>
<td>D</td>
<td>1.2</td>
<td>270</td>
<td>357</td>
<td>20</td>
<td>39</td>
<td>1.2</td>
<td>0.93</td>
<td>1.5</td>
</tr>
</tbody>
</table>

* Measured in rolling (0°) direction
** Measured at plastic strain of 0.15 in 0°, 45°, 90° from rolling direction
*** In-plane anisotropy of r-value, \( \Delta r = (r_{00} - 2r_{45} - r_{60})/2 \)
out for 10 lines and the average value of \( P_a \) was calculated in the experiments.

\[
P_a = \frac{1}{N} \sum_{i=1}^{N} |P| \ [	ext{m}] \ 
\]

Here, \( P_a \) denotes the ordinate value in ND, \( Z \), from a mean position on a profile curve. \( N \) is the number of measured points.

In addition, the sheet surface was observed by SEM for areas of 200 \( \mu \text{m} \) square. Crystal orientations in microscopic scale were measured by SEM/EBSD method. To maintain surface unevenness as much as possible the polishing of specimens for EBSD was limited to a range of 2 \( \mu \text{m} \) depth.\(^2\)

### 3.1 Influence of Strain Ratio on Surface Roughening

#### 3.2 Observation of Influence of Strain Ratio on Surface Roughening in Macroscopic Marciniak Type Tension Tests

Figures 2(a) and 2(b) show the surface profiles of materials C and D, respectively, for the plane-strain (\( \beta = 0.0 \)) and the equi-biaxial (\( \beta = 1.0 \)) tension in the Marciniak type biaxial tension tests. The vertical axis \( Z \) indicates the position from the mean position. In the figures the applied mean equivalent plastic strain, \( e_{eq}^p \), and the parameter of surface roughness, \( P_a \), are indicated. As mentioned above, materials C and D are IF and Aluminum-killed steels, respectively. Materials C and D have different textures while the crystal grain sizes are almost the same.

From Fig. 2(a) of material C it is seen that the unevenness is larger on the whole for \( \beta = 0.0 \) than for \( \beta = 1.0 \), while the local wave length is smaller for \( \beta = 0.0 \) than for \( \beta = 1.0 \). This is recognized also from the value of \( P_a \). \( P_a \) at \( e_{eq}^p \) of 0.27 for \( \beta = 0.0 \) is 1.2 \( \mu \text{m} \) and is larger compared with \( P_a \) at a larger \( e_{eq}^p \) of 0.32 for \( \beta = 1.0 \). On the other hand, in material D, there is almost no difference in surface roughness between \( \beta = 0.0 \) and \( \beta = 1.0 \) (Fig. 2(b)).

Figure 3 shows the evolutions of \( P_a \) in Marciniak type tests for various strain ratios. As a matter of course the surface roughness \( P_a \) increases with strain for all the materials. However, the dependence of the evolution of surface roughness on the strain ratio is quite different between IF steels (materials A, B and C) and the Aluminum-killed steel (material D). The surface roughness increases with the equivalent plastic strain almost independent of the strain ratio for material D. This result coincides with the conventional knowledge.\(^7,8\) On the other hand, the evolutions of \( P_a \) are different depending on the strain ratio \( \beta \) for materials A, B and C. Also for materials A, B and C, the surface roughness increases with the equivalent plastic strain in the range of the strain under 0.2, almost independent of the strain ratio. In addition, the rate of increase is smaller for the material with smaller grain size. These are consistent with the results of the conventional research.\(^4,7,9,14\) However, above 0.2 surface roughness increases more rapidly for \( \beta = 0.0 \) than for \( \beta = 1.0 \) in materials A, B and C.
surface to be clearly observed, secondary electronic images (SEI) were photographed with the specimens tilted in the vertical direction. IPF maps present the crystal orientation distributions. The applied equivalent plastic strain is given in each image.

Comparing the SEI of Fig. 4 at the equivalent plastic strain of 0.36 for $\beta = 0.0$ with that of 0.52 for $\beta = 1.0$, it is clear that the surface roughness is larger for $\beta = 0.0$ than for $\beta = 1.0$, for material C. On the other hand, there is almost no difference in the SEI of Fig. 5 at the equivalent plastic strain of 0.33 for $\beta = 0.0$ and at that of 0.36 for $\beta = 1.0$. These results are consistent with the results obtained from the macroscopic observation shown in Fig. 2.

The IPF maps of Fig. 4 show that the changes of crystal orientations occur within the grains more rapidly for $\beta = 0.0$ than for $\beta = 1.0$. As a result, the grains with orientations other than ND {111} and ND {001} increase for $\beta = 0.0$ for material C. As shown in Fig. 1(d) material D has originally random orientations. From the IPF maps of Fig. 5 it is seen that ND {001} and ND {111} orientations increase during deformation both for $\beta = 0.0$ and $\beta = 1.0$.

### 3.3. In-situ Observation of Surface Roughening in Microscopic Biaxial Tension Tests

In order to continuously observe surface changes during biaxial stretching and to examine the effect of strain ratio, in-situ observations were conducted using the SEM/EBSD method developed by the authors.

**Figures 6 and 7** show the changes of microstructure at sheet surface of material A during microscopic biaxial tension tests for $\beta = 0.0$ and $\beta = 1.0$, respectively. In these figures image quality (IQ), IPF and Taylor factor maps are shown. IQ maps show the degree of accumulated strain energy, and Taylor factor maps are used as an index to indicate the deformation resistance of each crystal grain.\(^{30,31}\)

In this study the Taylor factor was evaluated by assuming 24 slip systems of body-centered cubic structure and uniform deformation with regard to the crystal orientation at each observation point, and corresponds to the reciprocal of the Schmid factor. A lower Taylor factor means lower resistance for deformation.

From Fig. 6 the following tendencies can be recognized. The IQ maps reveal that the contrast between light and shade becomes clear as the deformation progresses, namely inhomogeneous deformation occurs for $\beta = 0.0$. The IPF maps reveal that the crystal orientations change gradually even in the grains (cf. dotted circle and square, for example). This may be caused by inhomogeneous deformation. In the Taylor factor maps, crystal grains with small values around 2.0 and large values over 4.0 are widely mixed. This shows that for $\beta = 0.0$ the deformation resistance is not uniformly distributed from the beginning of deformation. The distribution of Taylor factor remains unchanged even after deformation. From a comparison of the IQ and IPF maps it is found that the contrast of IQ map becomes clear at the position where the crystal orientation changes sharply (cf. rectangle surrounded by broken line, for example). From the comparison between IPF and Taylor factor maps it is found that the Taylor factor is smaller at parts with the orientation ND {001}.

From Fig. 7 the following tendencies are found. In the IQ maps the contrast increases only slightly during deformation. Compared with the IQ maps in Fig. 6 it is clear that the deformation occurs homogeneously for $\beta = 1.0$. The IPF maps show that the changes of crystal orientations are not remarkable compared with those of Fig. 6. The Taylor factor maps show that the Taylor factor values are distributed only in a narrow range between around 2.0 and 3.0, and remain almost unchanged during deformation for $\beta = 1.0$. From a comparison between IPF and Taylor factor maps it is found...
that the Taylor factor is smaller at the parts with the orientation ND {001} for $\beta = 1.0$, similar to the case for $\beta = 0.0$.

Figures 6 and 7 have shown experimentally the difference in the change of sheet surface during biaxial stretching depending on the strain ratio. However, it is impossible to use the exact same specimens in the experiments for two strain ratios. Therefore, the calculations of Taylor factor were carried out for specimens with the same microstructures at the start of biaxial stretching for $\beta = 0.0$ and $\beta = 1.0$, using the microstructures and textures shown in Fig. 1.

Under these conditions, Fig. 8 shows the obtained results for materials C and D. For both materials, crystal grains with small values around 2.0 and large values over 4.0 are widely mixed for $\beta = 0.0$, while grains with values between...
around 2.0 and 3.0 exist for $\beta = 1.0$, similar to Figs. 6 and 7. It is considered that the larger difference in deformation resistance may cause the inhomogeneous deformation and easier occurrence of surface roughening for $\beta = 0.0$ than for $\beta = 1.0$. Even for $\beta = 0.0$ material D has many grains with middle values around 3.0. As a result, the difference in deformation resistance between the neighboring grains is smaller for material D (Aluminum killed steel) than material C (IF steel). This may be the reason why the surface roughness development remains smaller even for $\beta = 0.0$ in material D than in material C.

### 4. Discussion

As mentioned above, it has been found from the experimental results that surface roughness development differs according to the strain ratio and the microstructure of material. Here, the influence of distribution of crystal orientations on the surface roughening is numerically analyzed by CPFEA. Before the numerical simulation of surface roughening using CPFEA is discussed, the reliability of the model used in this study is examined by a comparison with some results of fundamental experiments.
4.1. CPFEA Model Used in This Study

In this study, a strain-rate dependent model was utilized to represent the slip rate of each slip system. The two families of slip systems, 12 {110} < 111 > and 12 {112} < 111 > slip systems, were considered. The reference-strain rate and the rate-sensitivity parameter were taken to be $\dot{\gamma}_0 = 0.002/s$ and $m = 0.02$, respectively. Please refer to our previous studies for details of the model.

4.2. Verification of Reliability of CPFEA Model

First, the verification was carried out for the stress-strain relationships in simple shear deformation of ferritic single crystal sheets. For the preparation of the single crystal sheets and the experimental procedure of the simple shear test, please refer to the literature. Three samples with different crystallographic orientations were employed. Table 2 presents the crystallographic orientations of the samples used in the present study. In the simulation, the representative volume element was an eight-node solid element with selective reduced integration. The same crystallographic orientation was embedded into all eight integration points. The simulation procedures are detailed in the literature. Because the preparation of the materials followed the literature, the material parameters reported in the literature were also employed in the present study.

Figure 9 shows the comparison between the measured and simulated stress-strain relationships for the three types of specimens shown in Table 2. Although the stress values obtained by the simulation are somewhat larger compared to those in the experiments, the simulation results agree qualitatively well with the experimental ones.

Next, verification was carried out for the changes of crystal orientations during biaxial tension of material A. The changes of crystal orientations were measured for the experimental results shown in Figs. 6 and 7. The IPF maps shown in Fig. 10 are the same as those at equivalent strain of zero in Figs. 6 and 7. The changes of orientations of the grains 1, 2 and 3 until the equivalent strain of 0.14 for $\beta = 0.0$, and those of the grains 4, 5 and 6 until the strain of 0.13 for $\beta = 1.0$, were measured and are shown in the lower figures in Fig. 10.

In the simulation, 200 $\mu$m-square IPF maps were modeled by using 10 000 eight-node solid elements with a length of 2 $\mu$m, assuming columnar grains with a length of 2 $\mu$m in the depth direction. Displacement boundary conditions were given to the sides of the square such that the prescribed strain ratio was realized. The calculated changes of crystal orientations during biaxial tension are shown in the lower figures of Fig. 10, and good agreements with the experimental results are recognized.

It may be concluded from the above comparisons with
the experimental results that the CPFEA model used in this study is reliable for the following numerical simulations concerning surface roughening where the stress and the rotation of crystal grains have important roles.

4.3. Numerical Simulation of Surface Roughening Behavior of Steel Sheets by CPFEA

In order to examine the influence of distribution of crystal orientations on surface roughening in stretch forming, numerical simulations were carried out by means of the CPFEA model. The model used is shown in Fig. 11. The calculation domain was 15 µm in the longitudinal (x: RD) direction, 46 µm in the width (z: ND) direction, and 6 µm in the depth (y: TD) direction, and it was composed of approximately 5,000 cubic elements with a length of 2 µm.

The calculations were carried out under the following conditions. As in the case of Fig. 10, the crystal orientation distribution shown in Fig. 12 was obtained by discretizing directly an IPF map in the RD-ND cross section of material C. The displacement in the x direction was given to the right y-z plane while fixing the left y-z plane in the x direction. The displacement in the y direction was applied to the hidden x-z plane while fixing the front x-z plane in the y direction. The amounts of displacement in the x and y directions were set to follow the prescribed strain ratio. The bottom x-y plane was fixed in the z direction. From the profile of the upper free surface the surface roughening can be appreciated.

Using this approach, Fig. 13 shows the obtained results at a mean equivalent strain of 0.2 for \( \beta = 0.0 \) and \( \beta = 1.0 \). The figures show not only the surface profile but also the strain distribution in the RD-ND cross section, which cannot be experimentally obtained. Large strain occurs at the position near the grains with orientations in the vicinity of ND(001) in Fig. 12. In addition, inhomogeneous deformation bands in the thickness direction are observed at the locations where the difference in crystal orientation is large. The figures show that large deformation occurs at the left part where the difference in crystal orientation is large. It is confirmed from this result that the surface roughening is affected by inhomogeneous deformation of crystal grains near the surface and in inner layers. The localization of the equivalent strain is larger for \( \beta = 0.0 \) than for \( \beta = 1.0 \), which leads to larger surface roughening for \( \beta = 0.0 \) than for \( \beta = 1.0 \). In the figures the surface roughening parameters \( P_a \) calculated...
by Eq. (2) from the surface profile are also indicated. The parameter \( P_a \) is 0.6 \( \mu m \) for \( \beta = 0.0 \), while it is 0.2 \( \mu m \) for \( \beta = 1.0 \).

Figure 14 shows the comparison of Taylor factor maps between \( \beta = 0.0 \) and \( \beta = 1.0 \) at the initial state in the RD-ND cross section. A good correspondence is found between the concentration of plastic strain shown in Fig. 13 and the positions where Taylor factor is low. Taylor factor values are distributed in a wide range for \( \beta = 0.0 \), while only in a narrow range for \( \beta = 1.0 \), similar to Fig. 8. The difference in Taylor factor values among the grains is larger for \( \beta = 0.0 \) than for \( \beta = 1.0 \). The difference in Taylor factors between grains A and B shown in Fig. 14 is 0.63 for \( \beta = 0.0 \) and 0.17 for \( \beta = 1.0 \) in the vicinity of grain boundary. It is considered that the difference in the strain concentration shown in Fig. 13 depending on strain ratio is derived from the difference in deformation resistance between the neighboring grains. This result implies that the inhomogeneous deformations of polycrystalline grains are effected not only by the initial crystal orientations but also by their deformation mode.

Figure 15 shows a comparison between the experimental and calculated changes of the parameter \( P_a \) during biaxial stretch forming. Because the surfaces of the real sheets in experiments were not perfectly flat before stretching, the comparison is carried out for the increment of \( P_a \) from its initial value. The results calculated by the CPFEA model correspond well to the experimental ones both qualitatively and quantitatively.

It should be noted that the parameter \( P_a \) was also evaluated in the simulation shown in Fig. 10. However, from this simulation the calculated surface roughening was much smaller than in reality: the parameter \( P_a \) was about 10 times smaller than those shown in Fig. 13. This result suggests that the consideration of the distribution of crystal orientations in the thickness direction is essential when surface roughening is evaluated using CPFEA.

In our previous paper we showed experimentally that not only the grains at the superficial layer but also those at the near-surface inner layers have an effect on surface roughening. Namely, the difference of deformation resistance depending on the orientations of grains near sheet surface has an influence on surface roughening. This raises the question of whether surface roughness development could be reduced if material with grains with relatively similar orientations could be produced. In order to examine this, a numerical experiment was carried out for the sheet with the imagined crystal orientations shown in Fig. 16. While the distributions of grain sizes and shapes are the same as with the real sheet shown in Fig. 12, the crystal orientations of the grains in the superficial layers, i.e., from the first to fifth layers from the surface, were assumed to be within \( \pm 10 \) degrees from the orientation ND \{111\}.

The results of the above numerical experiments are shown in Fig. 17. Although the surface roughness development is still larger for \( \beta = 0.0 \) than that for \( \beta = 1.0 \), it is remarkably reduced in comparison with Fig. 13(a). The surface
roughness parameter \( P_n \) is reduced from 0.6 \( \mu m \) to 0.4 \( \mu m \) for \( \beta = 0.0 \), while it remains almost unchanged at a low value of 0.2 \( \mu m \) for \( \beta = 1.0 \). It is confirmed from these results that the difference of deformation resistance among the grains depending on the orientation has a great influence on surface roughness development. This result gives us a possible direction to produce materials which prevent surface roughening and have good formability in stretch forming.

5. Conclusions

The influence of strain ratio on surface roughening in biaxial stretching of IF steel sheets was investigated in this study. Macroscopic and microscopic tests were carried out under plane-strain and equi-biaxial tension for IF steel and Aluminum-killed steel sheets, and the surface roughness development and the texture evolution were examined. Furthermore, a crystal plasticity finite-element analysis (CPFEA) was used to discuss the influence of the distribution of crystal orientations on the surface roughness development. The results obtained are summarized as follows.

(1) While the surface roughness increases with the equivalent plastic strain almost independent of the strain ratio for the Aluminum-killed steel sheet, surface roughness development depends on the strain ratio for IF steel sheets. For IF steel sheets the surface roughness becomes larger under plane-strain tension than under equi-biaxial tension.

(2) For IF steel sheets, inhomogeneous changes in crystal orientations occur within grains more rapidly under plane-strain tension than under equi-biaxial tension. It is considered from the Taylor factor distributions that the larger difference in deformation resistance for plane-strain tension than for equi-biaxial tension leads to more inhomogeneous deformation for plane-strain tension; thus, the resultant surface roughening is larger for plane-strain tension than for equi-biaxial tension. For the Aluminum-killed steel sheet, the difference in deformation resistance among the grains is small even under plane-strain tension.

(3) The simulation results of the surface roughening development obtained by CPFEA, which considers inhomogeneous distribution of crystal orientations, show good agreement with the experimental results. Moreover, it is confirmed from the simulation that the difference in deformation resistance among the grains has a great influence on surface roughness development.

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