Effect of Microstructure before Cold Rolling on Texture and Formability of Duplex Stainless Steel Sheet

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The evolution of the microstructure and texture of type 329J4L duplex stainless steel (DSS) sheet during cold rolling and annealing were examined, and the effect of the initial microstructure before cold rolling on texture and formability was investigated. The texture of the α phase in the hot-rolled and annealed sheet had a strong α-fiber texture, and this was stable even in cold-rolled and annealed sheet. However, in the case of a coarse α grain caused by high-temperature annealing prior to cold rolling, the α-fiber texture and colony with (100) // ND orientation in the α phase were reduced in cold-rolled and annealed sheet. This control of the α-fiber texture in the α phase in cold-rolled and annealed sheet improved the elongation, r-value, and ridging characteristics. These results showed that the texture and the formability of type 329J4L DSS cold-rolled and annealed sheet depended on the texture of the α phase and the initial α phase morphology before cold rolling.

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1. Introduction

Duplex stainless steels (DSS), such as type 329J4L, which have a two-phase ferrite (α) and austenite (γ) microstructure, are widely used in the construction of chemical plants, vessels, and tanks, because they have good corrosion resistance and strength.1,2) In recent years, DSS sheets have been adopted for the fabrication of water tanks and heat exchange panels having complicated forms.3) DSS sheets are inferior in terms of ductility compared with austenitic stainless steel sheet such as type 304,2) and therefore an improvement in the ductility of DSS sheet is required.3) The effects of manufacturing conditions on the tensile properties of DSS sheet, especially elongation at room temperature, have been studied by few researchers, and it has been shown that the elongation is related to the hot-rolling texture, as well as the annealing temperature after hot rolling and cold rolling.4–7) However, the mechanism is not clear, and there have been few studies on the characteristics of microstructure and texture in hot rolling, cold rolling, and annealing.8–10)

In addition, the microstructural evolutions in (α + γ) microduplex stainless steel caused by thermo-mechanical processing, which combines deformation and heat treatment, were investigated.11–21) Huang et al.14–16) showed that no recrystallization of the α matrix took place when the initial structure before cold rolling was fine, but recrystallization occurred in the α matrix with [111] (011) initial orientation when the initial structure was coarse. This finding indicates that the recrystallization of the α matrix in (α + γ) microduplex structures strongly depends on the initial structure prior to cold rolling. If the above results obtained by Huang et al.14–16) are taken into consideration, it can be assumed that the change in the microstructure prior to cold rolling causes a change in the texture and formability of cold-rolled and annealed sheets.

The object of this study is to understand the formation of the texture in the consecutive process of sheet manufacture and the effect of the microstructure before cold rolling on the cold-rolling and annealing texture, as well as on formability, such as tensile elongation, r-value, and ridging properties in type 329J4L DSS sheet. In particular, attention is paid to the α phase morphologies prior to cold rolling and the formation of texture after cold rolling and annealing.

2. Experimental Procedures

The chemical composition of commercial type 329J4L hot-rolled sheet used in this study is given in Table 1. The thickness (t) of the plate was 4.5 mm. The stable phase at various temperatures of this material calculated by ThermoCalc and the experimental process are shown in Fig. 1. From this calculation, in this steel the matrix phase is bcc α and the second phase is fcc γ, which is precipitated from the α matrix. The stable phase is α single phase above 1300°C, the fractions of precipitated γ phase change below 1300°C. Hot-rolled specimens were annealed for 60 s at temperatures ranging from 1000 to 1250°C to obtain different size of α grains and γ particles, and this process was followed by air cooling. These annealed specimens, with different structure sizes, were cold-rolled to a 67% reduction on a laboratory rolling mill, and the cold-rolled sheets were annealed for 30 s at 1050°C, 1075°C, and 1200°C, followed by air cooling. Microstructural observations were carried out by optical microscopy in the longitudinal section in the center of the specimens in each process. The ratio of the area of the α phase in the sheets heat treated under various conditions was measured using image analysis equipment. A line analysis

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Table 1 Chemical composition of steel used (mass%).

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
<td>0.5</td>
<td>0.7</td>
<td>0.02</td>
<td>0.003</td>
<td>6.9</td>
<td>25.2</td>
<td>3.0</td>
<td>0.11</td>
</tr>
</tbody>
</table>

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of the nickel, chromium, and molybdenum concentrations in the annealed sheets was performed in the direction of thickness by EPMA (Electron Probe Micro Analysis, accelerated voltage 15 kV, beam step 0.5 μm). The textures were quantitatively examined using the orientation distribution function (ODF). Incomplete pole figures of (200), (211), and (310) for the α phase, and those of (200), (220), and (311) for the γ phase were measured in steps 5° on the sections perpendicular to the normal direction (ND-section) in the center layer of the sheets by means of the Schultz reflection method using Mo Kα radiation. From these pole figures, the ODF was determined using the iterative series-expansion method.22) Figure 2 shows the most important texture components and fibers for the γ phase in ϕ2 = 45° section of ODF (Bunge’s notation). Moreover, EBSD (Electron Back Scatter Diffraction) measurements were performed using OIM (Orientation Imaging Micrograph) software (Ver.4.6) equipped on field emission type scanning electron microscopy (accelerated voltage 25 kV, beam step 1 μm). These observations were made on the rolling plane (ND plane) in the center of some final annealed sheets. Tensile tests of the cold-rolled and annealed sheets were carried out at room temperature in the longitudinal and transverse directions using JIS 13B test pieces. Moreover, the lankford values (r-values) and the ridging characteristics of some final annealed sheets were determined to confirm the influence of the recrystallization textures on formability. The r-values were measured after 10% tensile strain along the longitudinal, transverse, and diagonal directions using JIS 13B test pieces. The average r-values (rm) and the planar anisotropy parameters (Δr) were calculated using the following equation,

\[ r_m = \frac{r_0 + 2r_{45} + r_{90}}{4} \]

\[ \Delta r = \frac{r_0 - 2r_{45} + r_{90}}{2} \]

where, \( r_0, r_{45}, \) and \( r_{90} \) are the r-values of the longitudinal, diagonal, and transverse directions, respectively. The ridging characteristics of the final annealed sheets were determined after 16% tensile strain along the rolling direction using JIS 5 test pieces. The surface roughness profiles of the transverse to the rolling direction of the deformed samples were measured by means of a two-dimensional surface roughness instrument, and the ridging height was defined by the convex (hill) and concave (valley) intervals.

3. Results and Discussions

3.1 Microstructures and textures before cold rolling

Figure 3 shows the microstructures (TD plane) of the hot-rolled (a) and annealed sheets (b) and (c). The hot-rolled sheet contained the α phase (dark) elongated parallel to the rolling direction, and the γ phase (white) precipitated during hot rolling. The interval of the γ phase in the specimen annealed at 1200°C (c) was wider than that in the specimen annealed at 1050°C (b). Figure 4 shows the fractions of the
\(\alpha\) phase by measurement and calculation results, and the thickness of the \(\alpha\) phase in the thickness direction after annealing. The thickness of the \(\alpha\) phase (D) was determined by the interval of \(\gamma\) phase, as it is indicated as D \(_{1,3}\) in Fig. 3(c) for example. As for the fraction of the \(\alpha\) phase, both tendencies were almost the same, and the amount of the \(\alpha\) phase before cold rolling changes to about 60% to 90% during heat treatment. At the same time, the grain size became coarser with high-temperature annealing, and the specimen annealed at 1050°C had a coarseness of 5.5–6.8\(\mu\)m and that of the specimen annealed at 1200°C was 28.6–34.2\(\mu\)m. Figure 5 shows the concentration profiles of nickel, chromium, and molybdenum by EPMA measurement for the specimens annealed at 1050°C and 1200°C. As for the \(\alpha\) phase with high concentration of chromium and molybdenum, it was found that the size of the \(\alpha\) phase under high-temperature annealing was larger than that under low-temperature annealing.

Figure 6 shows the \(\varphi_2 = 45^\circ\) sections of the ODFs measured in the hot-rolled sheets. After hot rolling, the \(\alpha\) phase (a) had a strong \(\alpha\)-fiber ([100](011) \sim [111](011)) especially [100](011) and a weak \(\gamma\) fiber ([111](011) \sim [111](112)), and the \(\gamma\) phase (b) had [110](112) (Brass-orientation) and [112](111) (Copper-orientation). The results for hot-rolling textures of the \(\alpha\) and \(\gamma\) phases in DSS sheet were the same as for the rolling textures of bcc and fcc metals, respectively, and were similar to the previous results.\(^{2,22}\) Figure 7 shows the \(\varphi_2 = 45^\circ\) sections of the ODFs measured in the hot-rolled and annealed sheets. After annealing at 1050°C (a) and (b), in the \(\alpha\) phase (a) there was still a strong presence of \(\alpha\)-fiber, and the texture of the \(\gamma\) phase (b) was about the same as the texture in hot-rolled sheet. Even under high-temperature annealing at 1200°C, there was still a strong presence of \(\alpha\)-fiber in the \(\alpha\) phase (c), and in the \(\gamma\) phase (d) [110](112) was weakened by high-temperature annealing. No investigations were carried out into the recrystallization behavior of DSS hot-rolled sheets. It is concluded that the \(\alpha\) phase in type 329J4L DSS hot-rolled sheets is very hard to recrystallize during annealing.
3.2 Microstructures and textures after cold rolling and annealing

Figure 8 shows the microstructures (TD plane) of cold-rolled (a and b) and annealed sheets (c and d). The final annealing temperature of these samples is 1075°C. Shear bands were seen in cold-rolled structure, but the effect of the initial structure could not be identified clearly by optical microscopy. Blicharski\(^{20}\) stated that the formation of shear bands was induced by the presence of \(\gamma\) phase in the \(\alpha\) matrix, and there might be influence of the fractions of the \(\gamma\) phase prior to cold rolling. A detailed investigation of the inhomogeneous deformed structures between \(\alpha\) and \(\gamma\) phase will be necessary in future. The effect of the initial structure before cold rolling on the microstructure of final annealed sheets was not clear. In addition, the fractions of the \(\gamma\) phase in the final annealed samples at 1075°C were about the same with around 63%, without affecting the annealing temperature after hot rolling.

Figure 9 shows the \(\varphi_2 = 45^\circ\) sections of the ODFs measured in the cold-rolled sheets. Both the specimen annealed at 1050°C after hot rolling (a) and (b) and the specimen annealed at 1200°C after hot rolling (c) and (d) had similar textures. In the \(\alpha\) phase, they had the \(\alpha\)-fiber that was a typical cold-rolling texture of bcc. In the \(\gamma\) phase, they had \{110\}\{112\} orientation that was typical of the cold-rolling texture of fcc. Figure 10 shows the \(\varphi_2 = 45^\circ\) sections of the ODFs measured in the final annealed sheets. In the \(\alpha\) phase (a) and (c), both the specimen annealed at 1050°C after hot rolling (a) and the specimen annealed at 1200°C after hot rolling (c) had an \(\alpha\)-fiber texture. The feature of \(\alpha\)-fiber in the \(\alpha\) phase was similar to the results of previous studies\(^{8,10}\) but the intensity of the \(\alpha\) phase texture in the specimen annealed at 1200°C after hot rolling (c) was much lower than that annealed at 1050°C after hot rolling (a). This result suggests that the texture of the \(\alpha\) phase in DSS cold-rolled and annealed sheet is affected by the initial structure prior to cold rolling. On the contrary, in the \(\gamma\) phase (b) and (d), the effect of the initial structure was not clearly observed. Figure 11 shows the relation between the \(\alpha\) phase morphologies before cold rolling and the orientation densities of each preferred orientation in the final annealed sheets. In the \(\alpha\) phase, the orientation densities of the \(\alpha\)-fiber components after final
Fig. 7 $\varphi_3 = 45^\circ$ sections of the ODFs of (a) and (c) $\alpha$ phase and (b) and (d) $\gamma$ phase after annealing at (a) and (b) 1050°C and (c) and (d) 1200°C.

Fig. 8 Optical microstructures of (a) and (b) cold-rolled and (c) and (d) final annealed sheets annealed at (a) and (c) 1050°C and (b) and (d) 1200°C before cold rolling.
annealing, especially [100](011) and [211](011), decreased with coarsening α grain prior to cold rolling. On the other hand, the microstructure prior to cold rolling had very little influence on the orientation in the γ phase after final annealing.

Figure 12 shows the local orientation maps obtained for the sheets with a final annealing temperature at 1075°C using EBSD measurements. In the α phase (a and c), both the specimens annealed at 1050°C (a) and 1200°C (c) after hot rolling had four dominant orientations; (100), (110), (111), and (211) // ND. In the specimen annealed at 1050°C after hot rolling, the grain colony having (100) // ND was clearly observed and this was identified with [100](011) colony by analysis. By contrast, in the specimen annealed at 1200°C after hot rolling, the colony was barely observed and the grain having (111) // ND increased. In the γ phase (b) and (d), both the specimens annealed at 1050°C (b) and 1200°C (d) after hot rolling had two dominant orientations; (110) and (311) // ND, and the difference of both was uncertain. It was made clear by macro and micro measurements of the crystal orientation that the microstructure prior to cold rolling had an influence on the crystal orientation distribution of the α phase of cold-rolled and annealed sheet. Huang et al.\(^\text{14}\) showed that no recrystallization of the α matrix took place when the initial α sub-grain size was not larger than 10 μm, but recrystallization occurred in an α matrix with [111](011) initial orientation when the initial α sub-grain size was 15.6 μm. Although the decision methods of the initial α grain size are different, this is similar to the result obtained by Huang et al.\(^\text{14}\) from a point of view that the initial α structure before rolling has the influence on the recrystallization behavior of the α phase in duplex structure. Additionally, there are some reports that the recrystallization progresses when the ratio of α phase is high,\(^\text{10,19}\) it is guessed that the α phase morphology prior to cold rolling affects the local inhomogeneous deformation during cold rolling, the nucleation sites, or the growth of subgrains.\(^\text{10,14,19}\)

### 3.3 Tensile elongations of cold-rolled and annealed sheets

Figure 13 shows the relation between the α phase morphologies prior to cold rolling and the elongation of final sheets annealed at 1075°C for 30 s. The elongation improved with a coarse α grain prior to cold rolling. Although the elongation in the transverse direction was low compared with the elongation in the longitudinal direction, both elongations were improved by a coarse α grain prior to cold rolling. Figure 14 shows the effect of the final annealing temperature on the elongation of the specimen with various sizes of α phase before cold rolling. In this paper, grain was...
classified as “fine” when the size of the α grain prior to cold rolling was D = 5.5~6.8 μm, and as “coarse” when D = 28.6~32.4 μm, and the influence of the final annealing temperature was taken into consideration. Moreover, the α/γ phase fraction after final annealing is described throughout the figure. In the case of high-temperature annealing such as 1200°C, the elongation was lower than that of the specimens annealed at 1050°C and 1075°C. The change in final annealing temperature brought about the change in the fraction of the phases, and the α phase increased with high-temperature annealing as shown throughout the figure. Although it is known that the ductility is affected by the fraction of phases,4,5) even if the final annealing temperature is changed, the influence of the initial microstructure, i.e. the microstructure before cold rolling, does not change. It is concluded that the tensile elongation of DSS sheet is strongly dependant on the α phase morphologies before cold rolling.

3.4 Effects on r-value and ridging properties

With ferritic stainless steel and mild steel sheets, it is well known that the r-value is improved by promotion of the (111) // ND recrystallization orientations.24,25) Moreover, the ridging phenomenon in ferritic stainless steel sheet has been explained by the anisotropic plastic flow caused by the orientational colonies that originate mainly in cast and hot-rolling structures and are of α-fiber texture.26–33) That is to say, the textures and orientation distributions of the α phase
influence both characteristics. There are few studies about $r$-value and ridging of DSS sheet, \(^7,8\) and the change of these characteristics is expected when the texture of the matrix $\alpha$ phase changes as mentioned above. Table 2 shows the effect of the size of the $\alpha$ phase before cold rolling on the $r$-value and ridging height of DSS sheets.

**Table 2** Effect of size of $\alpha$ phase before cold rolling on $r$-value and ridging height of final annealed sheets.

<table>
<thead>
<tr>
<th>Initial $\alpha$ structure</th>
<th>$r_0$</th>
<th>$r_{45}$</th>
<th>$r_{90}$</th>
<th>$r_m$</th>
<th>$\Delta r$</th>
<th>Ridging height ($\mu m$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine ($D = 5.5 \mu m$)</td>
<td>0.37</td>
<td>0.95</td>
<td>0.41</td>
<td>0.7</td>
<td>-0.6</td>
<td>40</td>
</tr>
<tr>
<td>Coarse ($D = 28.6 \mu m$)</td>
<td>0.55</td>
<td>0.89</td>
<td>0.65</td>
<td>0.8</td>
<td>-0.3</td>
<td>14</td>
</tr>
</tbody>
</table>

The coarse $\alpha$ phase in $(\alpha + \gamma)$ DSS sheet is dominant over the mechanical properties, and is greatly dependent upon the initial structure before cold-rolling.
4. Conclusions

To clarify the formation of the texture in type 329J4L DSS sheet and the effects of the microstructure prior to cold rolling on the textures and the formability, the cold rolling and annealing textures and the formability of sheets with different α phase morphologies before cold rolling were investigated. The main results can be summarized as follows:

(1) The texture of the α phase in hot-rolled sheet had a strong α-fiber texture, and this was stable even in cold-rolled and annealed sheet. However, in the case of a coarse α grain due to high-temperature annealing prior to cold rolling, the α-fiber texture and colony with (100) // ND orientation of the α phase in cold-rolled and annealed sheet were reduced.

(2) By controlling the α-fiber texture of the α phase in cold-rolled and annealed sheet, the elongation, r-value, and ridging characteristic improved. It was concluded that the formability of type 329J4L DSS sheet greatly depended on the texture of the α phase, and the initial α phase morphology before cold rolling was important in controlling texture in final annealed sheets.

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REFERENCES