Note

Effect of Nitrogen on Planar Anisotropy of the r -value and Texture in Lean Duplex Stainless Steel Sheets

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The planar anisotropy of the r -value of duplex stainless steel sheets showed reverse V-type. To ascertain the possibility of control, the anisotropies and textures of cold-rolled and annealed sheets with different amounts of nitrogen, based on 21.2%Cr-1.5%Ni-5.0%Mn-0.02%C steel, and for different annealing temperatures after hot rolling were investigated. With a decrease in the amount of nitrogen and an increase in the annealing temperature before cold rolling, the anisotropy changed to V-type from reverse V-type. In addition, the singular texture with weak α_{bcc} -fiber and strong Goss orientation in the α phase of the low-nitrogen added sheet was observed.

KEY WORDS: duplex stainless steel; nitrogen; r -value; planar anisotropy; texture; orientation distribution function; cold rolling; annealing; microstructure.

1. Introduction

Duplex stainless steels (DSS) with a low Ni and Mo content, called lean DSS, are considered as alternative materials for conventional austenitic stainless steels such as Type 304 (18%Cr-8%Ni).¹⁾ Nitrogen addition is effective for corrosion resistance, in improving the mechanical properties and weldability; its role in the development of modern DSS has been reported.²⁾ When materials are applied to sheet products, sheet formability and planar anisotropy, in addition to strength and elongation, are important. With regard to the planar anisotropy of the Lankford value (r -value) of DSS sheets, it has been reported that high-alloy Type 329J4L (25%Cr-7%Ni-3%Mo-0.02%C-0.1%N) shows a noticeable planar anisotropy of so-called reverse V-type with the maximum value in the 45° direction, and that its texture is quite different from that of a single-phase material.^{3–9)} In addition, lean Type 32101 (21%Cr-1.5%Ni-5%Mn-0.02%C-0.2%N) also shows reverse V-type planar anisotropy, but its anisotropy

is lower than that of Type 329J4L.⁹⁾ In austenitic single-phase materials, reverse V-type anisotropy has been reported,^{10,11)} but the degree is smaller than DSS sheets. In the reports of ferritic stainless steel sheets with single-phase, most are V-type anisotropy, and it is known to be in reverse V-type with high reduction (approximately 90%) in cold rolling.^{11–13)} However, there are few studies on the control of the planar anisotropy of DSS sheets.⁷⁾ In this study, the highest attention was paid to the possibility of controlling the anisotropy of 21.2%Cr-1.5%Ni-5.0%Mn-0.02%C DSS sheets, using changes in the amount of nitrogen, and annealing temperature before cold rolling.

2. Experimental Procedures

The alloys with nitrogen contents changed to 0.05%, 0.11%, 0.16%, 0.22%, and 0.25% based on 21.2%Cr-1.5%Ni-5.0%Mn-0.02%C (mass%) steel were vacuum-induction melted and cast as 50 kg ingots. The stable phases and precipitations at various temperatures for these steels were calculated using Thermo-Calc. (TCFE7) software, and the results are shown in Fig. 1. These calculations suggest that the γ phase stabilizes as the amount of added nitrogen increases. The plot in this figure shows the nitrogen contents and annealing temperatures used in this study. After hot rolling at 1180°C, the hot-rolled sheets with 4 mm thickness were annealed at 1000, 1100 and 1200°C for 60 s and then cooled via water immersion. These annealed sheets were cold-rolled to 1 mm thickness (75% reduction) on a laboratory rolling mill with a roll diameter of 100 mm. Then, the cold-rolled sheets were annealed at 1000, 1050 and 1100°C for 60 s and air-cooled. In addition, the heating rate in annealing for the hot-rolled and the cold-rolled sheets was approximately 5°C/s. The r -values of the JIS 13B test pieces cut from the final annealed sheets were measured after 10% tensile deformation at angles of 0°, 45°, and 90° with respect to the rolling direction. The average r -value (r_m) was calculated using the following equation.

$$r_m = (r_0 + 2r_{45} + r_{90}) / 4 \dots\dots\dots (1)$$

Microstructural observations were performed using optical

Fig. 1. Calculated equilibrium phase diagram. The plot in this figure shows the nitrogen contents and annealing temperatures before cold rolling used in this study.

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microscopy on the longitudinal section at the center of the sheet thickness. The textures were quantitatively determined using the orientation distribution function (ODF). Incomplete pole figures of the (310), (200), and (211) planes for the α phase and the (220), (200), and (311) planes for the γ phase of the ND-sections at the center layers of the sheets were measured with the Schultz reflection method using MoK α radiation. From these pole figures, the ODF (Bunge's notation) was determined using the iterative series-expansion method.^{14,15)}

3. Results and Discussions

Figure 2 shows the microstructures of the hot-rolled and annealed sheets with different amounts of added nitrogen and for different annealing temperatures. In the case of 0.05%-nitrogen-added steel, the α matrix (dark) elongated parallel to the rolling direction and the γ phase (white) precipitated after annealing at 1 000 and 1 100°C. After the annealing at 1 200°C, the α phase significantly coarsened, and an extremely slight presence of the γ phase was observed at the grain boundary of the α phase. On the other hand, 0.25%-nitrogen-added steel had more γ phase than 0.05%-nitrogen-added steel, and it was constituted of a relatively elongated two-phase structure even after high-

Fig. 2. Optical microstructures of hot-rolled and annealed sheets with (a–c) 0.05% and (d–f) 0.25% nitrogen addition, for annealing at (a and d) 1 000°C, (b and e) 1 100°C, and (c and f) 1 200°C before cold rolling.

temperature heat treatment at 1 200°C.

Figure 3 shows the microstructures of the sheets after cold rolling and annealing at 1 000°C with different amounts of added nitrogen and for different annealing temperatures before cold rolling. All the samples showed the elongated two-phase structure, but the microstructure of 0.05%-nitrogen-added steel was coarser than that of 0.25%-nitrogen-added steel; the fraction of γ phase increased with an increase in the nitrogen amount. In the case of annealing at 1 200°C before cold rolling for 0.05%-nitrogen-added steel, the fine γ phase dispersed; it could precipitate during annealing after cold rolling.

Figure 4 shows the effects of nitrogen addition and annealing temperature at (a) 1 000°C and (b) 1 200°C before cold rolling on the planar anisotropies of the r -values of the final sheets after cold rolling and annealing at 1 000°C. In the case of the sheets were annealed at 1 000°C before cold rolling, steels with high nitrogen addition ($>0.1\%$) showed reverse V-type planar anisotropy with the maximum value in the 45° direction, and this was similar to the case of 1 100°C annealing before cold rolling. Such reverse V-type was also observed in earlier studies of DSS sheets.^{3–9)} However, the planar anisotropy changed when the added nitrogen amount decreased to 0.05% at the same annealing condition. With an increase in the annealing temperature before cold rolling, the anisotropies of high-nitrogen-added steels decreased, and the r -values for the 0° and 90° directions increased, whereas and those for the 45° direction decreased. This effect of annealing conditions is similar to an earlier result obtained for Type 329J4L.⁷⁾ Furthermore, the low-nitrogen-added steel that underwent high-temperature annealing at 1 200°C before cold rolling showed notable changes in the V-type planar anisotropy with the maximum value in the 90° direction. Thus, based on this experiment, it was revealed that the anisotropy of

Fig. 3. Optical microstructures of sheets after cold rolling and annealing at 1 000°C with (a and b) 0.05% and (c and d) 0.25% nitrogen addition, for annealing at (a and c) 1 000°C and (b and d) 1 200°C before cold rolling.

the r -value of DSS sheets strongly depends on the nitrogen amount rather than the conventionally reported influence of microstructure before cold rolling.

The texture is related to the r -value of steel materials, and the texture of the α matrix is dominant in the r -value of DSS sheets.^{8,9)} Figure 5 shows $\varphi_2 = 45^\circ$ sections of ODFs in the α and γ phases of cold-rolled and annealed sheets of 0.05%- and 0.25%-nitrogen-added steels with final annealing at 1 000°C. The features of a strong α_{bcc} -fiber and an undeveloped γ_{bcc} -fiber, for low-temperature annealing before cold rolling, were observed in high-nitrogen-added steel. These

results are similar to those reported previously.^{8,9)} After high-temperature annealing before cold rolling, the intensity of the α_{bcc} -fiber in the α phase became considerably weaker; this result is similar to that obtained for Type 329J4L, and it is guessed that the α phase morphology before cold rolling affects the local inhomogeneous deformation during cold rolling, the nucleation sites or the growth of subgrains during annealing.⁷⁾ In contrast, for 0.05%-nitrogen-added steel, the intensity of the α_{bcc} -fiber in the α phase was relatively weak, and the $\{110\}\langle 001\rangle$, *i.e.*, Goss orientation, developed with high-temperature annealing before cold rolling. Moreover, compared to the change in the α phase, the texture of the γ phase was hardly influenced by the nitrogen content and annealing temperature before cold rolling, and was mainly in the $\{211\}\langle 111\rangle$, *i.e.*, Copper orientation. In earlier reports,^{16,17)} it was illustrated that the r -value of the $\{100\}\langle 011\rangle$ and $\{211\}\langle 011\rangle$ ideal orientations belonging to the α_{bcc} -fiber shows reverse V-type anisotropy, and that the Goss orientation in the 90° direction is remarkably higher than that in the 0° and 45° directions. Considering this and the change in texture for the amount of nitrogen used in this study, it was inferred that the change in anisotropy of DSS sheets with nitrogen content and annealing temperature before cold rolling is caused by the drastic change in texture of the α phase. To show it quantitatively, Fig. 6 shows the planar anisotropies of the measured and calculated r -values in cold-rolled and annealed sheets of 0.05%- and 0.25%-nitrogen-added steels with final annealing at 1 000°C. The predictive calculations of the planar anisotropies of the r -value were conducted using ODFs of Fig. 5 in conjunction with the Taylor model like previous study.⁸⁾ In addition, for the α and γ phases, the relaxed-constraints (RC1323) model with a critical resolved shear stress (CRSS) ratio of the $\{211\}$ and $\{110\}$ glide plane ($\tau_{\{211\}}/\tau_{\{110\}}$) assumed to be 1.1 and full-constraints (FC) model were applied, respectively. In previous study,⁸⁾ the authors illustrated that the texture of the α phase in DSS sheets was dominant for the anisotropy of the r -value. From this result like conventional knowledge,⁸⁾ the predicted results obtained by the texture of the α phase are relatively closer to the experimental values in comparison

Fig. 4. Effects of amount of nitrogen and annealing temperatures of (a) 1 000°C and (b) 1 200°C before cold rolling on the r -value of final annealed sheets at 1 000°C.

Fig. 5. $\varphi_2 = 45^\circ$ sections of ODFs of (a, c, e and g) α phase and (b, d, f and h) γ phase after final annealing at 1 000°C with (a–d) 0.05% and (e–h) 0.25% nitrogen addition, for annealing at (a, b, e and f) 1 000°C and (c, d, g and h) 1 200°C before cold rolling. (i) Some important fiber textures and orientations in Euler space ($\varphi_2 = 45^\circ$ section).

Fig. 6. Planar anisotropy of the r -value measured and calculated from the α and γ phases after final annealing at 1 000°C with (a and b) 0.05% and (c and d) 0.25% nitrogen addition, for annealing at (a and c) 1 000°C and (b and d) 1 200°C before cold rolling.

with the predicted results obtained by the texture of the γ phase. Furthermore, in the sample (Fig. 6(b)) with low-nitrogen addition and high-temperature annealing before cold rolling that Goss orientation developed in the α phase, it was predicted that the anisotropy of the α phase became V-type unlike others. Thus, due to low-nitrogen addition and high-temperature annealing before cold rolling, the r -value for the 45° direction decreases with a decrease in the $\{100\}\langle 011\rangle$ and $\{211\}\langle 011\rangle$ orientation densities in the α phase, and the r -value for the 90° direction increases with an increase in Goss orientation. Hence, it was inferred theoretically that the planar anisotropy changed to V-type from reverse V-type.

The aforementioned development of Goss orientation in the α phase of DSS sheets with low nitrogen content is extremely characteristic. In earlier studies of Fe–N alloys, Goss orientation in recrystallization texture developed due to the nitrogen in solid solution and the deformed microstructure, *i.e.*, it was related to the shear band.^{18,19)} In contrast, in the case of high-nitrogen-added steel, despite high-temperature annealing at 1 200°C, the γ phase is relatively stable and most of the nitrogen is distributed into it. This is related to the weak texture in the α phase and low anisotropy of high-nitrogen-added steel with high-temperature annealing before cold rolling. About the formation of texture in final annealed sheet, especially in the α -phase, it is necessary to examine from cold rolling texture in the future. In addition, as factors influencing the texture, it is necessary to consider the difference in the volume fraction of the γ phase and the hardness of the α and γ phases primarily with the amount of nitrogen,⁹⁾ *etc.*, and the quantitative examination of each factor is a future problem. However, in this study, since the planar anisotropy of the r -value of duplex stainless steel sheet can be roughly evaluated from the texture in the α phase, it is concluded

that the influence of the volume fraction of the γ phase in the cold-rolled and annealed sheet is small.

4. Conclusions

It was recognized that the amount of nitrogen influenced the anisotropy of the r -value of 21.2%Cr–1.5%Ni–5.0%Mn–0.02%C DSS sheets. With a decrease in the amount of nitrogen and an increase in the annealing temperature before cold rolling, the anisotropy changed to V-type from reverse V-type. Presumably, this change is caused by the weakened α -fiber texture and the development of Goss orientation in the α phase of the cold-rolled and annealed sheet.

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