Effect of Annealing Temperature and Coiling Temperature on r-value of Nb and B-added Extra Low-carbon Steel

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When a welded can body is expanded in the pail can manufacturing process, it shrinks in the direction of can height. The change of the can height is influenced by the r-value of the steel sheet.

The effect of the annealing temperature and coiling temperature on the r-value of extra low-carbon steel with combined addition of niobium (Nb) and boron (B) was investigated by using commercial steels.

The ferrite grain size of the annealed sheet decreased as the annealing temperature decreased. At the same time, the orientation density of $\{001\} <110>$ increased and the r_{90° -value decreased.

The behavior of the decrease of the r_{90° -value was dependent on the coiling temperature of the hot-rolled sheet. When a low coiling temperature was used, the r_{90° -value decreased rapidly as the annealing temperature decreased.

KEY WORDS: hot rolling; annealing; extra low-carbon steel; texture; r-value.

1. Introduction

When extra low-carbon steel is used as the material for the welded body of a pail can, the change of can height after expansion is large due to the high r-value (Lankford value) of the steel.^{1–3)} Because the weld is hard and has low elongation, an unexpanded convex shape remains at the weld; this damages the can body when the lid is seamed and causes can body defects.¹⁾

The r_{90° -value is particularly important in controlling the change of can height when the circumferential direction of the can body is oriented at 90° to the rolling direction of the steel sheet, and reducing r_{90° is effective for controlling height changes.¹⁾

As the r_{90° -value of Nb- and B-added extra low-carbon steel is small, the change in the can height after expansion is also small. This type of steel has non-aging properties and has the steel sheet strength necessary for large-scale welded cans. It also has other characteristics such as high weld strength in the welded part. Because of this combination of properties, this steel is used in pail cans and other products with similar requirements.^{1,2)}

As already reported, the orientation density of $\{001\} <110>$, which is the stable orientation after cold rolling, increases and the r_{90° -value decreases in the annealed steel sheet in manufacturing at a high cold rolling reduction exceeding 90%.²⁾ However, there are cases where cold rolling at a high cold rolling reduction in the tandem mill must unavoidably be performed at a lower rolling speed than the

mill specification due to concern about surface defects.⁴⁾ Thus, the possibility that production volume may decrease due to this rolling speed limitation is conceivable in operation at a high reduction exceeding 90%.

Therefore, it is considered necessary to reduce the r_{90° -value by controlling the annealing temperature and coiling temperature, which are thought to have a small influence on production volume.

It has been reported that the average r-value of the steel concerned decreases if the finishing temperature is reduced when the slab reheating temperature is $1\,250^\circ\text{C}$.⁵⁾ It has also been reported that the r-value of B- and Ti-added extra low-carbon steel decreases when the coiling temperature decreases,⁶⁾ and the average r-value of Nb-added extra low-carbon steel decreases when the annealing temperature decreases.⁷⁾

However, no examples of a detailed examination of the influence of the annealing temperature and coiling temperature on the r-value of Nb- and B-added extra low-carbon steel were found.

Therefore, in this report, the mechanism by which the annealing temperature and coiling temperature control the r-value in Nb- and B-added extra low-carbon steel was examined.

2. Experimental Procedure

2.1. Specimens

The Nb- and B-added extra low-carbon steel used as the sample material was a commercial steel with the chemical composition shown in **Table 1**. The hot rolling, cold rolling and annealing conditions were as shown in **Fig. 1**. To

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examine the influence of the coiling temperature, the coiling temperature was set to 652°C or 680°C. The annealing temperature was set to various levels from 700°C to 730°C.

2.2. Evaluation of Material

Cross-sectional microstructural observation of the hot-rolled sheet and the annealed sheet was performed by optical microscopy at the 1/2 sheet thickness positions in the rolling direction. The intercept method according to JIS G 0551 was used in measurements of the ferrite grain size.

The amount of Nb precipitate in the steel was analyzed by performing galvanostatic electrolysis (20 mA/cm²) of the sample in a 10% acetylacetone-1% tetramethylammonium chloride-methanol solution and analyzing the extracted residue by inductively coupled plasma emission spectroscopy. The amount of B precipitate was analyzed by decomposing the sample for an hour with a 10% bromine-methanol solution at 60°C, followed by analysis of the extracted residue by inductively coupled plasma emission spectroscopy.

The r -values in the rolling direction, at 45° to the rolling direction and perpendicular to the rolling direction were measured by the tension method, and the results were defined as r_{0° , r_{45° , and r_{90° , respectively. The mean r -value r_{mean} was calculated as $(r_{0^\circ} + 2r_{45^\circ} + r_{90^\circ})/4$. The test specimens were given 15% elongation at the tension speed of 10 mm/min with a specimen shape in which the parallel part of the JIS 13 B test specimen was adjusted to the length of 50 mm. In this process, the gauge length used to measure the amount of change in the direction of tension was 20 mm. The change of sheet width before and after tension and the gauge length change in the direction of tension were measured, and the r -value was calculated.

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

C	Si	Mn	P	S	Al	Nb	B	N
0.0016	0.01	0.31	0.017	0.018	0.050	0.020	0.0008	0.0024

Fig. 1. Schematic diagram of test conditions.

To investigate the texture, the samples were chemically polished by oxalic acid to reduce the sheet thickness and remove strain. The annealed samples were then measured at the 1/2 thickness position. An X-ray diffractometer (Rigaku, RINT2200) was used in these measurements, and (110), (200), (211) and (222) pole figures were prepared by the Schultz reflection method. The crystal orientation distribution function (ODF: Orientation Distribution Function) was calculated from these pole figures by the iterative series expansion method, and the $\phi_2=45^\circ$ cross section of the Euler space (Bunge method) was drawn. The contour line spacing was assumed to be one.

3. Results

3.1. Influence of Coiling Temperature on Microstructure of Hot-rolled Steel Sheets

Figure 2 shows optical micrographs of the hot-rolled steel sheet at the 1/2 layer. In comparison with the coiling temperature condition of 652°C, coarsening of the ferrite grain size had occurred under the coiling temperature condition of 680°C.

The results of measurement of the amount of precipitated Nb and precipitated B in the hot-rolled steel sheet are shown in **Table 2**. The precipitated Nb/total Nb ratio was approximately the same under the coiling temperature conditions of 652°C and 680°C. The precipitated B/total B ratio was also substantially the same.

3.2. Influence of Annealing Temperature on Annealed Steel Sheet Properties

Figure 3 shows cross-sectional optical micrographs of the annealed steel sheet at the 1/2 layer with the coiling temperature of 652°C. **Figure 4** shows cross-sectional optical micrographs of the annealed steel sheet at the 1/2 layer with the coiling temperature of 680°C. The relationship between the recrystallized area fraction and the annealing temperature is shown in **Fig. 5**.

With the coiling temperature of 652°C, an unrecrystal-

Table 2. Amount of precipitated Nb and precipitated B in hot-rolled sheet.

Coiling temperature (°C)	Precipitated Nb/Total Nb	Precipitated B/Total B
652	0.27	1.0
680	0.29	1.0

(a) Coiling temperature: 652°C
Grain size: 8.4 μm

(b) Coiling temperature: 680°C
Grain size: 9.2 μm

Fig. 2. Optical micrographs showing ferrite in hot-rolled sheet (1/2 layer).

Fig. 3. Optical micrographs showing ferrite in annealed sheet (coiling temperature: 652°C).

Fig. 4. Optical micrographs showing ferrite in annealed sheet (coiling temperature: 680°C).

lized area was observed at the annealing temperatures of 700°C and 710°C. Recrystallization was completed at these temperatures when the coiling temperature of 680°C was used.

Figure 6 shows the relationship between the annealing temperature and the average r -value (r_{mean}), r -value (r_{0°) in the rolling direction, r -value (r_{45°) inclined 45° from the rolling direction and r -value (r_{90°) inclined 90° from the rolling direction for the coiling temperature condition of 652°C. The r_{mean} -value, r_{0° -value and r_{90° -value decreased when the annealing temperature decreased.

Figure 7 shows the relationship between the grain size and the annealing temperature with the coiling temperature of 652°C. Because the deformation microstructure remained, the ferrite crystal grain size of the unrecrystallized material was excluded from the examination of the grain size comparison. Coarsening of the grain size of the annealed steel sheet was observed when the annealing temperature increased.

Next, the relationship between the r -value and the annealing temperature with the coiling temperature of 680°C is shown in **Fig. 8**. As with the coiling temperature of 652°C,

Fig. 5. Relationship between recrystallized area fraction and annealing temperature (coiling temperature: 652°C).

Fig. 6. Relationship between r-value and annealing temperature (coiling temperature: 652°C).

Fig. 7. Relationship between grain size and annealing temperature (coiling temperature: 652°C).

the r-value decreased when the annealing temperature decreased.

Figure 9 shows the relationship between the grain size and the annealing temperature with the coiling temperature of 680°C. As with the coiling temperature of 652°C, coarsening of the grain size of the annealed sheet was observed as the annealing temperature increased.

3.3. Influence of Coiling Temperature on r_{90° -Value

Figure 10 shows the relationship between the annealing temperature and the r_{90° -value, which is a key value for

Fig. 8. Relationship between r-value and annealing temperature (coiling temperature: 680°C).

Fig. 9. Relationship between grain size and annealing temperature (coiling temperature: 680°C).

Fig. 10. Relationship between r_{90° -value and annealing temperature.

Fig. 11. Relationship between r_{90° -value and grain size.

expanded cans. The r_{90° -value decreased when the annealing temperature decreased. Similar r_{90° -values were obtained at the annealing temperature of 730°C with the coiling temperatures of 652°C and 680°C. The behavior of the decrease in the r_{90° -value differed as the annealing temperature decreased; that is, with the coiling temperature of 652°C, $r_{90^\circ}=1.4$ was obtained at the annealing temperature of 720°C, but with the coiling temperature of 680°C, $r_{90^\circ}=1.4$ was obtained at the annealing temperature of 700°C.

Figure 11 shows the relationship between the r_{90° -value and grain size. The r_{90° -value decreased as the grain size decreased, and the relationship between the grain size of the annealed steel sheet and the r_{90° -value was substantially the same with the coiling temperatures of 652°C and 680°C.

3.4. Texture of Annealed Steel Sheet

Figure 12 shows the texture in the 1/2 layer of the annealed steel sheet with the coiling temperature of 652°C. **Figure 13** shows the α -fiber (RD// $\langle 110 \rangle$, $\phi_1=0^\circ$, $\phi_2=45^\circ$)

and γ -fiber (ND// $\langle 111 \rangle$, $\Phi=55^\circ$, $\phi_2=45^\circ$) in the 1/2 layer of the annealed steel sheet. At the annealing temperature of 700°C, at which unrecrystallized grains remained, the accumulation of orientation density of the low-angle side of the α -fiber was high, and the accumulation of the γ -fiber had decreased. Moreover, the increase in the orientation density of $\{001\} \langle 110 \rangle$ in the annealed steel sheet was larger with lower annealing temperatures.

Next, **Fig. 14** shows the texture in the 1/2 layer of the annealed steel sheet with the coiling temperature of 680°C. Similarly, **Fig. 15** shows the α -fiber and γ -fiber in the 1/2 layer of the annealed steel sheet.

The increase in the orientation density of $\{001\} \langle 110 \rangle$ in the annealed steel sheet was larger with low annealing temperatures.

Figure 16 shows the relationship between the r_{90° -value and the orientation density of $\{001\} \langle 110 \rangle$. The r_{90° -value decreased as the orientation density of $\{001\} \langle 110 \rangle$ increased, and the relationship between the orientation den-

Fig. 12. Texture of annealed sheet (coiling temperature: 652°C).

Fig. 13. Orientation distribution function of annealed sheet (coiling temperature: 652°C).

Fig. 14. Texture of annealed sheet (coiling temperature: 680°C).

Fig. 15. Orientation distribution function of annealed sheet (coiling temperature: 680°C).

Fig. 16. Relationship between r_{90° -value and orientation density of $\{001\} \langle 110 \rangle$.

sity of $\{001\} \langle 110 \rangle$ and the r_{90° -value was substantially the same with the coiling temperatures 652°C and 680°C.

4. Discussion

4.1. Microstructure of Hot-rolled Steel Sheet

As shown in Fig. 2, with the coiling temperature of 680°C, the grain size of the hot-rolled sheet increases in comparison with that with the coiling temperature of 652°C. It is thought that grain growth is promoted and the grain size becomes larger with the coiling temperature of 680°C because the cooling rate on the run-out table is slow and the material is kept at a high temperature after coiling.

As shown by Table 2, the precipitated Nb/total Nb ratio is almost the same, even if the coiling temperature changes. The precipitated B/total B ratio is also substantially the same at the different coiling temperatures.

Regarding the difference in the grain sizes of hot-rolled sheets, since there are no large differences in the amounts of precipitated Nb and precipitated B, it is thought that the difference in grain sizes is the result of grain growth due to holding at high temperature on the run-out table and after coiling in the case of the coiling temperature of 680°C.

4.2. Microstructure of Annealed Steel Sheet

With the coiling temperature of 652°C, unrecrystallized grains remain at the annealing temperatures of 700°C and 710°C, as shown in Fig. 3.

Because the amount of solid solution Nb does not change

even if the coiling temperature is decreased, as shown Table 2, it is thought that suppression of recrystallized grain growth occurs from some reasons other than solute drag by solid solution Nb segregation. As shown in Fig. 2, the crystal grain size of the hot-rolled sheet is finer with the coiling temperature of 652°C. Based on this fact, it is thought that grain refinement occurs as a result of growth of recrystallized grains from the grain boundary in the hot-rolled sheet, and nucleation of recrystallized grains increase.

As shown in Fig. 6, the r_{mean} -value, r_{0° -value, and r_{90° -value decrease when the annealing temperature decreases. Since the recrystallization rate decreases at the annealing temperature of 700°C and the unrecrystallized grains remain small, the r_{90° -value decreases greatly. It is thought that this is due to the high accumulation of the α -fiber at the annealing temperature of 700°C, and a larger orientation density of $\{001\} \langle 110 \rangle$ in that α -fiber.

If recrystallization has been completed, the r_{90° -value decreases as shown in Fig. 6 when the annealing temperature decreases. At the same time, the grain size also decreases, as shown in Fig. 7. When the annealing temperature decreases, the r_{90° -value decreases as shown in Fig. 8, even with the coiling temperature of 680°C, and simultaneously with this, the grain size also decreases as shown in Fig. 9.

As shown in Fig. 10, when the coiling temperature is low, the r_{90° -value decreases rapidly as the annealing temperature decreases. As shown in Fig. 2, the grain size of the hot-rolled steel sheet is smaller with the coiling temperature of 652°C in comparison with the high coiling temperature of 680°C, and recrystallization nucleation from the grain boundary increases in the first stage of recrystallization. Therefore, at temperatures near the recrystallization completion temperature, grain growth is suppressed by the adjacent recrystallized grain boundaries, and the grain size of the annealed sheet is smaller with the low coiling temperature. In contrast to this, when the annealing temperature is high, the difference of the grain size of the annealed steel sheets due to the difference of the coiling temperature becomes small because recrystallized grain growth is promoted. When the relationship between the grain size of the annealed steel sheets and the r_{90° -value is arranged, a correspondence as shown in Fig. 11 can be seen.

4.3. Texture of Annealed Steel Sheets

As shown in Fig. 13, with the coiling temperature of

652°C, the orientation density of $\{001\} \langle 110 \rangle$ in the annealed steel sheet is larger with lower annealing temperatures. This is thought to occur because the higher orientation density of $\{001\} \langle 110 \rangle$, which remains as a stable orientation during cold rolling, is also retained after annealing under a low annealing temperature condition.

It is thought that the r_{90° -value decreases due to the heightened orientation density of $\{001\} \langle 110 \rangle$ because $\{001\} \langle 110 \rangle$ is an orientation in which the r -value is low in all directions, and r_0° and r_{90° (0° and 90° directions) are especially low.⁸⁾

Moreover, as shown in Fig. 15, the orientation density of $\{001\} \langle 110 \rangle$ in the annealed steel sheet is larger with lower annealing temperatures, even with the coiling temperature of 680°C. As with the coiling temperature of 652°C, it is thought that the orientation density of $\{001\} \langle 110 \rangle$, which increases as a stable orientation during cold rolling, is also retained after annealing when the annealing temperature is low.

As shown in Fig. 16, the relationship between the r_{90° -value and the orientation density of $\{001\} \langle 110 \rangle$ is almost the same regardless of the coiling temperature. Thus, it is thought that an increase in the orientation density of $\{001\} \langle 110 \rangle$ strongly influences the decrease of the r_{90° -value.

Next, Fig. 17 shows the α -fiber and the γ -fiber with the different coiling temperatures of 652°C and 680°C under the annealing temperature condition of 720°C. The orientation density of $\{001\} \langle 110 \rangle$ is higher with the coiling temperature of 652°C than with the coiling temperature of 680°C.

As shown in Figs. 7 and 9, when compared at the annealing temperature of 720°C, the grain size of the annealed sheet is small and grain growth is suppressed with the coiling temperature of 652°C.

Figure 18 shows the α -fiber and the γ -fiber under the annealing temperature condition of 730°C for the different coiling temperatures of 652°C and 680°C. The orientation density of $\{001\} \langle 110 \rangle$ is almost the same with the coiling temperatures of 652°C and 680°C. This is thought to show that the influence of the coiling temperature has become small because the influence of the subsequent grain growth has become larger than the influence of the initial nucleation rate at the annealing temperature 730°C, and grain growth is saturated.

Figure 19 shows the α -fiber and the γ -fiber at the similar grain size of the annealed steel sheet. A grain size of 7.6 μm to 7.7 μm is achieved in the annealed sheet at the annealing temperature of 720°C when the coiling temperature is 652°C and at the annealing temperature of 700°C when the coiling temperature is 680°C.

The orientation density of $\{001\} \langle 110 \rangle$ is almost the same when compared at the similar grain size. In contrast, when the orientation density of $\{111\} \langle 112 \rangle$ is compared at the similar grain size, the orientation density is higher with the higher coiling temperature. In the Nb- and B-added extra low-carbon steel, it is thought that the orientation density of $\{111\} \langle 112 \rangle$ increases with the higher coiling temperature as a result of formation of grains of $\{111\} \langle 110 \rangle$ and $\{111\} \langle 112 \rangle$, which have fast recrystallization

Fig. 17. Orientation distribution function of annealed sheet at annealing temperature of 720°C (1/2 layer).

Fig. 18. Orientation distribution function of annealed sheet at annealing temperature of 730°C (1/2 layer).

Fig. 19. Orientation distribution functions of annealed sheets with similar grain sizes (1/2 layer).

kinetics.

It has been reported that recrystallization occurs easily and the recrystallization orientation of $\{111\}$ increases when the grain size before rolling is refined.⁹⁾ However, in the neighborhood of the recrystallization completion temperature in the present study, the grain size of the annealed sheets decrease when the coiling temperature is low, which is different from the result in the above-mentioned report. On the other hand, when the coiling temperature is low, it has been reported that recrystallization and grain growth are suppressed by refinement of precipitates.¹⁰⁾ Moreover, it has also been reported the r -value of annealed steel sheet is improved by adequate precipitation of NbC in hot-rolled sheets.¹¹⁾ Because the amounts of precipitated Nb and precipitated B are the same in the steel concerned, as shown in Table 2, differences in the morphology or precipitate size are also conceivable. However, the influence of the morphology or precipitate size will be left as a topic for future study.

Although the r_{90° -value was explained by the density of the $\{111\}$ plane in the present research, here, the influence of the $\{111\}$ plane on the r_{90° -value will be described. In Fig. 19, when the crystal grain size is substantially the same, the density of the $\{111\}$ plane is higher with the high coiling temperature. As shown in Fig. 19, in comparison with the coiling temperature of 652°C and annealing temperature of 720°C, the r_{90° -value is 0.02 larger with the coiling temperature of 680°C and annealing temperature of 700°C, and only a slight influence of the density of the $\{111\}$ plane is observed. Thus, it is thought that the influence of $\{111\}$ on the r_{90° -value, which is the focus of the present research, is small, and the r_0 -value and r_{90° -value (r -values of 0° and 90° directions) are reduced by an increase in the density of $\{001\} \langle 110 \rangle$.¹²⁾

As shown in Figs. 15 and 17, in the Nb- and B-added extra low-carbon steel, the orientation density of $\{001\} \langle 110 \rangle$ increases when a lower annealing temperature is

used, and as a result, the r_{90° -value (r -value of 90° direction) decreases.

5. Conclusion

(1) In the Nb- and B-added extra low-carbon steel, the grain size is refined by manufacturing at a low annealing temperature, and simultaneously with this, the orientation density of $\{001\} \langle 110 \rangle$, which is the stable orientation after cold rolling, increases and the r_{90° -value decreases in the annealed steel sheet.

(2) In the Nb- and B-added extra low-carbon steel, the coiling temperature influences the behavior of the decrease in the r_{90° -value. In particular, when a low coiling temperature is used, the r_{90° -value decreases rapidly as the annealing temperature decreases.

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