The \( r \)-values and Recrystallized Textures of Ti-stabilized Low C, N-17% Cr Stainless Steel Sheets

By Tadashi SAWATANI, ** Kunihiko SHIMIZU, ** Tadashi NAKAYAMA ** and Masanori MIYOSHI ***

** Synopsis **

The effects of mill processing variables on the \( r \)-values and textures of Ti-stabilized low C, N-17% Cr stainless steels have been investigated. The results obtained are as follows:

1. The \( r \)-values in cold-rolled and annealed sheet is improved significantly by addition of Ti in 0.2 to 0.3 wt\%

2. The optimum \( r \)-value is obtained under the following conditions: hot-finishing temperature of hot rolling, annealing of hot-rolled sheet at 900°C with a rapid heating rate, cooling at a rate as fast as air cooling, cold reduction more than 80%, to be achieved either in single or in double rolling, dividing the reduction between 1st and 2nd stages 40%–60% in the latter case, with subsequent annealing, and annealing, both for intermediate and for final, at a temperature of 850°C.

3. When the desirable fine carbide-nitride precipitates are formed in the hot-rolled sheet under the above-mentioned processing conditions before cold reduction, they seem of help to develop a strong \( \{112\}\{110\} \) deformation texture in heavy cold reduction and a strong \( \{554\}\{225\} \) component in the recrystallized texture by suppressing the growth of the \( \{110\}\{001\} \) component resulting in annealed products with very high \( r \)-values.

** I. Introduction **

Many studies were made on improvement of deep drawability of low-C steel by addition of various carbide-forming elements, and as a result Ti-stabilized super-deep drawing steel sheets have been developed.1)

For possible application of Ti to low C, N ferritic stainless steels, the effects of processing conditions on the \( r \)-values and the recrystallized textures of Ti-stabilized low C, N-17% Cr stainless steel were investigated in the present study. As a result, it has been revealed that on addition of Ti a strong \( \{554\}\{225\} \) component is developed in the recrystallized texture of low C, N-17% Cr stainless steels, a texture which is greatly different from that in SUS430, thus resulting in a significant improvement of \( r \)-values.

** II. Experimental Procedures **

1. ** Materials **

For this investigation, four stainless steels were melted in a 150 kg vacuum induction furnace and cast into 45 kg ingots. The chemical composition of these steels are given in Table 1.

The ingots were reheated to approximately 1100°C and hot-rolled to 110 mm square billets. These billets were reheated to 1100°C and hot-rolled to 3.8 mm thick sheets.

The commercial hot-rolled stainless steel sheets were also 3.8 mm thick. Their chemical compositions are given in Table 2.

Plastic strain ratio measurements were made on JIS No. 13B sheet tensile specimens cut to 0°, 45° and 90° to the rolling direction and subjected to 15% elongation by means of a hard 10 t tensile tester.

The analysis of preferred orientations was conducted by the inverse pole figure technique and by the standard reflection pole figure technique with an automatic pole figure device and with Zr filtered Mo Ka radiation (40 kV and 16 mA). The specimens used for determining the relative intensity (with respect to a random specimen) of \( \{222\} \), \( \{211\} \), \( \{200\} \) and \( \{110\} \) planes lying parallel to the sheet surface were blanked out from sheets, surface-ground to the mid thickness, mechanically polished, and then finished by electrolytic polishing to remove disturbed metal.

For processing conditions, studies were made on the following variables: finishing temperature of hot rolling (890° and 780°C), annealing temperature of hot-rolled sheet (750° to 950°C), heating rate (0.05°C/s) and resulting in a significant improvement of \( r \)-values.

| Table 1. Chemical analyses of vacuum melted stainless steel sheets |
|-------------------|-------|-------|-------|-------|-------|-------|-------|-------|
| Samples | C  | Si  | Mn  | P  | S  | Cr  | Ti  | N  |
| VF-0% Ti | 0.004 | 0.03 | 0.05 | 0.013 | 0.002 | 16.4 | Tr  | 0.0058 |
| VF-0.2% Ti | 0.006 | 0.4  | 0.41 | 0.019 | 0.007 | 16.5 | 0.17 | 0.0037 |
| VF-0.4% Ti | 0.006 | 0.4  | 0.41 | 0.019 | 0.007 | 16.5 | 0.40 | 0.0038 |
| VF-0.6% Ti | 0.006 | 0.4  | 0.41 | 0.019 | 0.007 | 16.5 | 0.64 | 0.0040 |

<table>
<thead>
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<th>Materials</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ti</th>
<th>N</th>
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<td>Ti-NC, N-17% Cr</td>
<td>0.010</td>
<td>0.64</td>
<td>1.32</td>
<td>0.021</td>
<td>0.005</td>
<td>16.65</td>
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<td>LG, N-17% Cr</td>
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<td>0.39</td>
<td>1.32</td>
<td>0.017</td>
<td>0.010</td>
<td>16.50</td>
<td>Tr</td>
<td>0.006</td>
</tr>
</tbody>
</table>

** Hikari Works, Nippon Steel Corp., Oaza-Shimada, Hikari 743.
and 3°C/sec), cooling rate (water quenching, air cooling and furnace cooling), cold rolling reduction (30 to 92%), distribution of reduction (30%, 40%, 50%, 60%, 70% and 80%) for a total reduction of 82%, and temperatures of intermediate and final annealing (800° to 1000°C).

The standard single rolling process and the double cold rolling process are shown in Figs. 1 and 2, respectively. For the study of processing conditions, these standard processes were employed, changing the above-mentioned variables in the ranges shown in parentheses.

III. Results

1. Effects of Ti addition

1. The r-values

The effect of Ti addition on the r-values of low C, N-17%Cr stainless steel produced by the standard single cold reduction process is shown in Fig. 3. It will be seen that the addition of Ti improves the r-values of 17%Cr stainless steel significantly in the same manner as in carbon steels. The fact that the r-value becomes highest when the Ti content is about 0.2% corresponds to the finding that recrystallization in the steel sheet containing over 0.4% Ti cannot be completed by annealing at 850°C for two minutes as will be described later. If the final annealing temperature is raised, the r-values of the sheets containing Ti to higher percentages do increase but the grains become coarser, a situation which may lead to troubles such as occurrence of rough surface on press forming.

To obtain steel sheets with r-values which are desirable from the practical standpoint, therefore, the amount of Ti to be added should preferably be 0.2%.

2. Recrystallization Behavior

Figure 4 shows the results of study on changes in recrystallization percentage in the sheets produced by the standard single cold rolling process except for the final annealing temperature which was varied in the range from 550° to 900°C.

It will be seen that the recrystallization temperature is shifted to a higher range by addition of Ti, and that recrystallization cannot be completed at temperatures below 875°C when the Ti content exceeds 0.4%. This means that recrystallization is not completed by the final annealing (at 850°C) under the standard processing conditions. Studying the effect of Ti addition on recrystallization of iron, Okazaki et al. reported that recrystallization temperature was raised by the addition of Ti.

3. Textures

Figure 5 shows the {200} pole figures of the cold-rolled textures and recrystallized textures obtained at 850°C in the manufacture of sheets under the standard single cold rolling conditions except for the final annealing temperature. By comparing the cold-rolled textures of sheets with varying Ti contents, it will be observed that the {112} < 110 > texture is intensified when the Ti content is 0.17%, but that when the Ti content exceeds 0.4%, a fibrous structure with RD//110 > axis relationship and extending to the {001} < 110 > orientation is formed in addition to the {112} < 110 > texture. Even when Ti is not added,
cold-rolled textures which are similar to those are developed in sheets containing more than 0.4% Ti.

Although the data on incompletely recrystallized textures obtained at 750°C are not presented here, the main orientation was the {554}⟨225⟩, but many fibrous structures with RD/⟨110⟩ axis relationship were observed as auxiliary orientations in the sheets containing higher percentages of Ti.

In Ti-stabilized sheets annealed at 850°C, the {554}⟨225⟩ main texture becomes stronger, and an auxiliary texture that will be clearly defined later as {112}⟨110⟩ ± 15°ND remains in sheets of higher Ti contents as shown in Fig. 5. On the other hand, in sheets which are not added with Ti and annealed at 850°C, the main component is {554}⟨225⟩ but a very strong {110}⟨001⟩ auxiliary component is also observed.

To study those phenomena quantitatively, changes in relative intensity of the ⟨001⟩, ⟨112⟩, ⟨110⟩ and ⟨111⟩ planes with annealing temperatures were measured, the results of which are shown in Fig. 6. When annealed, the intensity of the ⟨001⟩ in sheets with a high Ti content is decreased as the temperature is raised, reflecting the delay of recrystallization due to Ti addition. When the annealing temperature exceeds 850°C, nearly the same intensity is obtained, regardless of Ti contents. The intensity of the ⟨112⟩ increases as the Ti content increases, but decreases as recrystallization proceeds. As can be seen from the pole figures, the ⟨110⟩ clearly shows the characteristics of Ti addition. All the sheets added with Ti show a very low intensity. The sheets which are not added with Ti show a high intensity when recrystallization begins, but this intensity decreases again as the annealing temperature rises.

The ⟨111⟩ exhibits a complex behavior. In sheets added with 0.17% Ti, the intensity increases slightly when recrystallization begins, but decreases to the minimum value when the annealing temperature is between 750° and 775°C. This intensity increases again until the temperature reaches 800°C, but is saturated at temperatures above 800°C. In the sheets added with 0.64% Ti, the intensity decreases until the annealing temperature reaches 700° to 750°C. From this point on, the intensity increases rapidly as the temperature rises, but is not saturated until the temperature reaches 900°C. In the sheets which are not added with Ti, the intensity decreases as recrystallization begins, but does not change at all at 700° to 900°C.

In the sheets which are not added with Ti, ⟨110⟩ grains increase with the start of recrystallization at the expense of grains in other orientations. In the sheets added with Ti, however, the recrystallization of ⟨110⟩ grains is suppressed by fine precipitates, and ⟨111⟩ grains, which are easy to recrystallize next to the ⟨110⟩ grains, are developed, encroaching on other components, at slightly higher temperatures. Fine precipitates seem to obstruct the growth of ⟨001⟩ recrystallizing nuclei or ⟨110⟩ recrystallized grains, thus promoting the growth of ⟨111⟩ recrystallized texture.

2. **Effect of Finishing Temperature of Hot Rolling**

1. The r-values

The effect of finishing temperature of hot rolling

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**Research Article**

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**Fig. 5.** The (200) pole figures of cold-rolled textures and recrystallized textures of Ti-stabilized low C, N-17%Cr stainless steel sheets. (Other variables based on the ICR standard processing condition.)

**Fig. 6.** Effect of Ti on the pole intensity of the recrystallization texture of low C, N-17%Cr stainless steel at various isothermal annealing temperatures. (Other variables based on the ICR standard processing condition, soaking time: 2 min.)

**Fig. 7.** Effect of finishing temperatures of hot rolling on the average r-value of Ti-stabilized low C, N-17%Cr stainless steel. (Other variables based on the ICR standard processing condition.)
on the $r$-values of Ti-stabilized low C, N–17% Cr stainless steel was investigated using the commercial hot-rolled sheets which were manufactured by two different processes.

The results are given in Fig. 7. The $r$-values of all the sheets which are not added with Ti are so low that they are little affected by the finishing temperature of hot rolling, while the $r$-values of Ti-stabilized sheets are high and increase with decreasing finishing temperature of hot rolling.

2. Textures

Figure 8 shows the effect of finishing temperature of hot rolling on the textures at the midsection of as-hot-rolled, annealed and cold-rolled, and annealed commercial steel sheets. It will be seen that no effect of finishing temperature of hot rolling is observed in the relative intensity of plane reflection of as-hot-rolled and annealed sheets, but the relative intensity of the [111] of the cold-rolled and annealed sheets finished at lower temperature is increased, revealing the effect of finishing temperature of hot rolling.

3. Effect of Annealing Conditions of Hot-rolled Sheets

1. The $r$-values

The effect of annealing temperature, heating rate and cooling rate of hot-rolled sheets on the $r$-values of Ti-stabilized low C, N–17% Cr stainless steel was studied. These sheets were produced under the standard single cold rolling conditions except for the above-mentioned variables.

The effect of annealing temperature of hot-rolled sheet on the $r$-value is shown in Fig. 9. As temperature rises from 750°C, the $r$-values increase slightly, reaching the maximum at 900°C, and then decrease again beyond 950°C, at which precipitates tend to coagulate and grains to grow.

The effect of heating rate of hot-rolled sheet on the $r$-value is shown in Fig. 10. The heating rate is shown in terms of the average rate of temperature rise from room temperature to 850°C. In Ti-stabilized sheets, the $r$-value increases with increasing heating rate.

The effect of cooling rate after annealing of hot-rolled sheet on the $r$-value is shown in Fig. 11. The effect of cooling rate is far greater as compared with those of the other two variables described above. In the case of water quenching in particular, the $r$-value becomes lower and the in-plane anisotropy is changed from V shape to inverted V shape.

At present, it is very difficult to explain the effect of annealing conditions of hot-rolled sheets on the $r$-value in a systematic manner. It seems that the temperature and heating rate will have an effect on the $r$-values as fine Ti(C, N) precipitates existing in the hot-rolled sheet are coagulated under these conditions causing changes of the recrystallized texture after cold rolling in the same manner as the finishing temperature of hot rolling does on the recrystallized texture. In the future, study will be made on the conditions of precipitates existing in the annealed and hot-rolled sheets and cold-rolled sheets, including the effect of finishing temperature of hot rolling, from the above-mentioned standpoint.

2. Textures

On annealing conditions of hot-rolled sheets, the cooling rate which showed a remarkable effect was studied using the {200} pole figures, the results of which are shown in Fig. 12. The main orientation in the cold-rolled textures is the {112}{<110>} for all the cooling rates. In the case of water quenching, however, the fibrous structure with an RD/<110> axis relationship extending to the {001}{<110>} is observed as the auxiliary component. In the recrys-
significant when the cold reduction exceeds 60%, is saturated more or less at about 80% cold reduction, and is then improved slightly until the ratio reaches 90%. Unlike Al-killed steels, the Ti-stabilized carbon steel shows a tendency that the cold reduction at which the r-value becomes maximum is shifted to a higher reduction range.

The in-plane anisotropy of r-value is V-shaped with $r_{50'}<r_{60'}<r_{90'}$ until the ratio of cold reduction reaches 85%. However, the anisotropy is changed to the linear shape of $r_6<r_{50'}<r_{90'}$ when the cold reduction reaches 90%. As a result, $r_{50'}$ increases and Jr decreases with increasing cold reduction.

2. Textures

Figures 14 (a) to (d) show the results of study of the effect of cold reduction on the [200] pole figures of cold-rolled textures and recrystallized textures. When the cold reduction is 30%, a weak accumulation toward the {554}<225> orientation is observed. At 50% of cold reduction, the accumulation toward the {554}<225> + {111}<110> orientation becomes slightly stronger. At 82% of cold reduction, the accumulation toward the {112}<110> orientation becomes stronger, and this becomes the main orientation. When the cold reduction is 92%, the main orientation is {112}<110>, but a fibrous texture with RD//<110> axis relationship and extending to the {100}<110> orientation is observed as the auxiliary component.

The [200] pole figures of the recrystallized textures in these sheets are also shown in Figs. 14 (e) to (h). When the cold reduction is 30%, a random texture having no specific accumulation is formed. When the cold reduction is 50%, a weak doughnut-like recrystallized texture with ND//<111> relationship

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4. Effect of Cold Reduction

1. The r-values

Changes in r-values of Ti-stabilized low C, N-17%Cr stainless steel under the standard single cold rolling conditions, except for the cold reduction which was varied from 30 to 90%, were studied. The results are shown in Fig. 13. The r-value is improved

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Fig. 11. Effect of cooling conditions after the annealing of hot-rolled sheet on the r-values of commercial Ti-stabilized low C, N-17%Cr stainless steel sheet (The 1CR standard processing)

Fig. 13. Effect of cold reduction on the r-values of single cold rolling of commercial Ti-stabilized low C, N-17%Cr stainless steel sheet (Other variables based on the 1CR standard processing condition.)

tallized texture developed at any cooling rate, the main orientation is {554}<225>. In the case of water quenching only, however, {112}<110>$\pm 15^\circ$ND is observed as the auxiliary orientation. As will be described later, similar recrystallized texture is obtained in a case when the cold reduction is higher than 90% under the standard single cold rolling conditions.

When the hot-rolled sheet is quenched with water after annealing, the recrystallized textures are shifted to those developed by heavier reductions through the cold-rolled textures. This may be explained by the effect of the lattice distortion remaining in the hot-rolled sheet. It is considered that the effect of cooling rate will be manifested as the low r-values through the changes of recrystallized textures. However, the r-values of 92% cold reduction sheet, which develops nearly the same recrystallised textures as will be described later, are not deteriorated so much. Quantitative study on this point will be necessary in the future.

4. Effect of Cold Reduction

1. The r-values

Changes in r-values of Ti-stabilized low C, N-17%Cr stainless steel under the standard single cold rolling conditions, except for the cold reduction which was varied from 30 to 90%, were studied. The results are shown in Fig. 13. The r-value is improved
is observed. When the cold reduction is 82%, a strong accumulation toward the \{554\}<225> orientation is observed. At 92%, the main orientations are \{554\}<225>, but a weak \{112\}<110>±15°ND orientation was observed when the hot-rolled sheet was quenched with water after annealing, is observed as the auxiliary component. The \{112\}<110>±15°ND orientation was also observed by Goodenow and Hold\(^3\) as the auxiliary orientation in the recrystallized textures when a Ti-stabilized C steel was given a cold reduction of more than 90%.

To study the above-mentioned results quantitatively, the relative intensities of typical planes lying parallel to the sheet surface at the midsection were measured. Figure 15 shows the relationships between r-values and relative intensity ratios of \{111\} and \{001\} planes and between r\(_{\text{rel}}\) values and reflection intensity of \{112\} plane. Both relationships agree well with each other and with the results obtained so far.\(^4\)

5. Effect of Distribution of Reduction in Double Cold Rolling

1. The r-values

The effect of the distribution of reduction on r-values for a Ti-stabilized low C, N-17% Cr stainless steel subjected to double cold rolling is shown in Fig. 16. For a total reduction of 82%, the distribution of reduction between the 1st and 2nd stages was varied from 30%-70%, 40%-60%, 50%-50% to 70%-30%. In this case, the maximum r-value of 1.82 was obtained with the 40%-60% combination, and the minimum value of 1.48 with 70%-30%.

The in-plane anisotropy of r-values of sheets subjected to double cold rolling is the V-shape of r\(_{\text{rel}}\)< r\(_{0.0}\)< r\(_{90}\) for any distribution of reduction.

![Fig. 14. Effect of cold reduction on the (200) pole figures of cold-rolled textures and recrystallized textures of commercial Ti-stabilized low C, N-17% Cr stainless steel sheet (Other variables based on the ICR standard processing condition, Ti=0.34%).](image)

![Fig. 15. Relationships between the average r-value and the relative intensity ratio, and between the r\(_{\text{rel}}\) value and \{112\] intensity of commercial Ti-stabilized low C, N-17% Cr stainless steel sheet (Other variables based on the ICR standard processing condition.](image)

2. Textures

The \{200\} pole figures of sheets cold-rolled in two stages under different distributions of reduction with subsequent annealing are shown in Fig. 17. With 30%-70% distribution of reduction, the main orientation is the strong \{554\}<225>, but it seems that a very weak accumulation to \{112\}<110>±15°ND exists as the auxiliary component. When the distribution of reduction is 40%-60%, a strong accumulation to \{554\}<225> orientation is observed. When reduction is distributed 50%-50%, a doughnut-like recrystallized texture with ND//\{111\} relationship is obtained. Typical doughnut-like texture is formed at 70%-30% distribution of reduction.

To study the effect of the distribution of reduction on the textures, changes in textures caused by double cold reduction were measured, using the cold-rolled and annealed sheets in which a strong \{554\}<225> type recrystallized texture is developed by 1st stage...
cold rolling of 70% reduction. The results of this measurement are shown in Fig. 18.

When the 2nd reduction is 30% of the total, the strong \(\{554\}<225>\) type texture still remains. When annealed under this condition, a random recrystallized texture is obtained. When the 2nd reduction is increased to 50%, the \(\{554\}<225>\)+\(\{111\}<110>\) texture is obtained which is changed to a doughnut-like recrystallized texture when annealed. When the 2nd reduction is 80%, the main orientation is changed to \(\{112\}<110>\). When annealed under this condition, the strong \(\{554\}<225>\) recrystallized texture is developed again.

Combining these results with the results of single cold rolling, it may be said that the maximum \(r\)-value is obtained by the optimum combination of the 1st reduction with the 2nd reduction at which a cold-rolled texture with \(\{112\}<110>\) as the main orientation is obtained, and that the \(r\)-value is decreased when a cold-rolled texture containing components other than \(\{112\}<110>\) is developed.

6. The \(r\)-values of Intermediate and Final Annealing Temperatures in Double Cold Rolling

Figure 19 shows the effect of various intermediate annealing temperatures on \(r\)-values under the standard double rolling conditions. The \(r\)-value reaches maximum when the intermediate annealing temperature is 850°C, but decreases at higher temperatures. When the intermediate annealing temperature exceeds 950°C, the grain size is abruptly increased.

The effects of various final annealing temperatures on \(r\)-values under the standard double rolling conditions are shown in Fig. 20. The \(r\)-value is improved as the final annealing temperature rises. When this temperature exceeds 950°C, however, grains become coarse.

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**Fig. 16.** Effect of the distribution of reduction between 1st and 2nd stages on the \(r\)-value of after the 2nd cold rolling and subsequent annealing of commercial Ti-stabilized low C, N-17% Cr stainless steel sheet (Other variables based on the 2CR standard processing condition; Total reduction: 82%).

**Fig. 17.** Effect of the distribution of reduction between 1st and 2nd stages on the (200) pole figures of recrystallized textures of commercial Ti-stabilized low C, N-17% Cr stainless steel sheet (Other variables based on the 2CR standard processing condition, Ti=0.34%; Total reduction: 82%).

**Fig. 18.** Effect of 2nd stage cold reduction on the (200) pole figures of 2nd stage cold-rolled and recrystallized Ti-stabilized low C, N-17% Cr stainless steel sheets in which a strong \(\{554\}<225>\) type recrystallization texture is developed by 1st stage cold rolling and annealing (Other variables based on the 2CR standard processing condition, Ti=0.34%).
Effect of intermediate annealing temperatures on the average r-value and the grain size after the 2nd cold rolling and subsequent annealing of commercial Ti-stabilized low C, N-17% Cr stainless steel sheet (Other variables based on the 2CR standard processing condition.)

Effect of final annealing temperature on the average r-value of the 2nd cold rolling and subsequent annealing of commercial Ti-stabilized low C, N-17% Cr stainless steel sheet (Other variables based on the 2CR standard processing condition.)

IV. Discussion

1. Effect of Ti Addition on Recrystallized Textures

1. Textures of Hot-rolled Sheets

The hot-rolled and annealed textures of Ti-stabilized low C, N-17% Cr stainless steel, low C, N-17% Cr stainless steel and SUS430 at their midsections are shown in Fig. 21. As compared with SUS-430, the as-hot-rolled sheets show a marked increase in {001} and {111} components when their C and N contents are decreased. If Ti is added to these sheets, the {001} component is decreased remarkably, while that of {111} remains unchanged. When annealed under this condition, both orientation densities are decreased. As compared with the other two grades of sheets, the Ti-stabilized sheet is characterized by more abundant {111} orientation grains and less abundant {001} grains. As will be described later, the improvement of r-values by the addition of Ti can be explained mainly by the recrystallized textures developed after cold reduction. Moreover, the above-mentioned feature of hot-rolled and annealed texture is considered to be one of the secondary factors for the improvement of r-value.

Although the finishing temperature of hot rolling has little effect on the hot-rolled and annealed textures as shown in Fig. 8, the {111} orientation in the recrystallized texture of the sheets finished at low temperature is increased and its r-value is improved after cold reduction. The reason for this may be that in the sheet finished at low temperature, the precipitates existing before cold reduction are turned into more desirable distribution of finer precipitates as described previously in explaining the effect of annealing of hot-rolled sheet and the effect of intermediate annealing temperature.

2. Cold-rolled Textures

The changes in textures of hot-rolled and annealed sheet, having relatively random recrystallized textures, with cold reduction are shown in Fig. 14. Examination of these results according to the texture-forming model developed by Matsuo et al.7 reveals that the {554}⟨225⟩ texture is developed by rotation toward the stable orientation because of the uniform deformation when the random texture is given with an about

30% cold reduction, and then the {111}⟨110⟩ texture is developed by rotation and dispersion toward the unstable orientation because of unequal deformation when about 50% cold reduction is given. When this texture is given with an about 80% cold reduction, a strong {112}⟨110⟩ texture is developed by rotation produced from the {111}⟨110⟩ orientation. When a cold reduction as high as about 90% is given, the {001}⟨110⟩ texture is developed by rotation from the {112}⟨110⟩ toward the stable orientation, resulting in a fibrous structure with RD//⟨110⟩ axis relationship.

This process of formation of cold-rolled texture is apparent in Figs. 18 (a) to (c) which shows the effect of cold reduction on the cold-rolled texture of the sheets with a strong {554}⟨225⟩ type recrystallized texture. In their study of Ti-stabilized C steels, Goodenow and Held report that the addition of Ti makes no difference in the formation of cold-rolled textures. This is nearly the same with 17% Cr stainless steels. From the phenomenon standpoint, the effect of Ti addition is observed clearly in the recrystallized textures.

3. Recrystallized Textures

Changes in the cold-rolled and recrystallized textures of Ti-stabilized 17% Cr stainless steel with cold reduction are summarized in Fig. 22. When the cold reduction is about 30%, recrystallization in specific orientations does not occur. With about 50% cold reduction, a doughnut-like texture is developed such that the {554}⟨225⟩+⟨111⟩⟨110⟩ texture as conceived in cold-rolled texture is recrystallized as it is. At 80% of cold reduction, the ⟨112⟩⟨110⟩ type cold-rolled texture is developed, and it seems that recrys...
tallization into the \( \{554\}<225> \) orientation which is at a rotational angle of 35° about the \( \{110\} \) axis proceeds rapidly. This point will be discussed in more detail later. When the cold reduction reaches 90%, the rotation of crystals proceeds up to the \( \{001\}<110> \) orientation. When recrystallized under this condition, it seems that the slowly recrystallizing \( \{001\} \) \( \{110\} \) grains are eroded out, but the \( \{112\}<100> \) grains which are more rapidly recrystallized and exist in a larger quantity remaining to become the auxiliary component in addition to the \( \{554\}<225> \) main component.

One of the effects of Ti addition on recrystallized textures is the elimination of the strong \( \{110\}<001> \) component which is observed in SUS430. Davison\(^6\) studied this effect on Ti-stabilized 18%Cr-2%Mo stainless steels in great detail and confirmed that the development of \( \{110\} \) component was not observed at all. The \( \{110\} \) components can be recrystallized most easily, and it is said that the \( \{110\}<001> \) component is recrystallized from the \( \{111\}<112> \) (near \( \{554\}<225> \)) component which is at a rotational angle of 35° about the \( \{110\} \) axis.\(^9\)

Based on the results of analysis of three-dimensional crystal orientations, Matsu et al.\(^7\) showed that the \( \{110\}<001> \) orientation is the one in which the release of distortion is suppressed most significantly. Assuming that two grains, oriented respectively \( \{110\}<001> \) and \( \{111\}<112> \), are joined with a simple tilt boundary, which is necessarily consisted of edge dislocations from the crystal geometry, and considering that the rising motion of edge dislocation is suppressed by precipitates, they concluded that the combination and disappearance of simple tilt boundaries are strongly suppressed by the AIN precipitating with the progress of recrystallization, resulting in the suppression of nucleation of \( \{110\}<001> \). It may then be considered that the suppression of the \( \{110\}<001> \) component by Ti addition as reported herein is attributable also to the same effect as described above, except it is derived by the presence of fine Ti(C, N) precipitates.

The second effect of Ti addition is that a strong \( \{554\}<225> \) recrystallized texture can be obtained. Akisue\(^8\) reported that, if the cold reduction is high and a great many \( \{112\}<110> \) grains exist when fine Nb precipitates are present in Nb-stabilized C steel, the subgrains formed in a distortion region which is being rotated away from the \( \{554\}<225> \) orientation toward the \( \{112\}<110> \), controls the whole recrystallized texture, resulting in a strong \( \{554\}<225> \) recrystallized texture. If this can be applied to Ti-stabilized low C, N-17%Cr stainless steels, the results of present experiment that a strong \( \{554\}<225> \) recrystallized texture can be obtained only when the rotation toward the \( \{112\}<110> \) orientation becomes significant in the cold-rolled texture mean that the increase in the \( \{112\}<110> \) component in the cold-rolled matrix results in an increase of distortion region reported by Akisue and can be interpreted that recrystallization into the \( \{554\}<225> \) component occurs starting from the distortion region having a high energy.

Terasaki et al.\(^1\) reported that in Ti-stabilized C steel, in situ recrystallization occurs preferentially because of the presence of fine precipitates, and that the \( \{110\} \) component which is not abundant in the cold-rolled matrix is absorbed with the progress of the recrystallization of the \( \{111\} \) grains which are present abundantly and are recrystallized next easily to the \( \{110\} \) grains, thus resulting in the development of the \( \{554\}<225> \) recrystallized texture which is characteristic of Ti addition. Miyagi and Watanabe\(^2\) held the same view in studying Cu-stabilized 17%Cr stainless steels.

According to the results of present experiment that the characteristic \( \{554\}<225> \) recrystallized texture is obtained after the \( \{112\}<110> \) component has become the main texture of the cold-rolled matrix, the Akisue's assumption of a region with a high energy such as the distortion region offering the first site of recrystallization is more reasonable than the view that abundant \( \{111\}<112> \) grains present in the cold-rolled matrix are recrystallized in situ. Based on the study of Ti-stabilized ultra-low C steel, Matsuoka and Takahashi\(^3\) pointed out the importance of changes in the binding force of dislocation and grain boundary as the result of coagulation of precipitates and grain coarsening with the progress of annealing. In the present experiment, this effect should be considered to be small because annealing was done at 850°C and for only two minutes.

On the basis of the above-described discussion, the effect of Ti addition on low C, N-17%Cr stainless steel can be understood as follows. Namely, a strong \( \{112\}<110> \) cold-rolled texture can be developed at a certain high cold reduction by forming desirable fine Ti(C, N) precipitates before cold rolling. In recrystallization annealing, the fine precipitates suppress the recrystallization into the \( \{110\}<001> \) texture, whereby a strong \( \{554\}<225> \) type recrystallized texture is preferentially formed. As a result, the \( r \)-values are improved significantly.

In the future, studies on the desirable grain size and distribution of Ti(C, N) precipitates and the mechanism in which these precipitates show the dependence on orientation in suppressing recrystallization will have to be done.

2. Effect of Ti Addition on \( r \)-values
The effect of Ti addition on \( r \)-values of low C, N-17%Cr stainless steel has been investigated, and it has been clarified that stainless steels with remarkably high \( r \)-values can be obtained by addition of Ti in the same manner as in C steels.

Concerning the processing variables which affect \( r \)-values, the addition of Ti has the following effects.

(1) The recrystallization temperature is shifted to a higher range.

(2) In the recrystallized texture of hot-rolled sheet, the \( \{111\} \) component is slightly increased but the \( \{001\} \) component is decreased.

(3) The \( r \)-value is improved with decreasing finishing temperature of hot rolling, but this effect is derived through the increase in the \( \{111\} \) component in cold-
(4) The higher the heating rate for annealing of hot-rolled sheet, the better the r-values. For cooling rate, air cooling is better than water quenching and furnace cooling.

(5) If the annealing temperature of hot-rolled sheet or the intermediate annealing temperature in the double cold rolling process exceeds 950°C, precipitates become coarse and grains grow excessively, resulting in a decrease in r-values.

(6) The r-value is improved as the cold reduction is increased.

It seems that these experimental results give support to the view that fine precipitates existing before cold rolling make a great contribution to the improvement of r-values, more precisely to the formation of recrystallized texture which is desirable for the improvement of r-values. Since this investigation was designed to aim at the study of effects of processing conditions on r-values and textures from the phenomenological standpoint, however, the experimental conditions were not such as to single out the matrix purifying effects resulting from the formation of Ti carbides or the solid solution Ti effects which are said to affect r-values. Accordingly, the discussion of each of these effects is outside the scope of this report.

The in-plane anisotropy of r-values will be discussed briefly. Hitherto, many studies, including a theoretical study, have considered that the V-shaped in-plane anisotropy of \(r_{45} < r_{90} < r_{0}\) is obtained in SUS304 because of the influence of the \(\{110\}<001>\) texture. Using Ti-stabilized 18%Cr-2%Mo steels, Davison made a qualitative study to determine the reason why the V-shaped in-plane anisotropy is obtained even if there is no \(\{110\}<001>\) component at all. And Jongenbugor et al. made a quantitative study to clarify such a possibility theoretically. According to the present results of Ti-stabilized low C, N-17%Cr stainless steel on the (200) pole figures, the V-shaped in-plane anisotropy is obtained even if there is no \(\{110\}<001>\) component at all. A theoretical study of this point is being considered.

V. Conclusion

As a result of the study of the effects of processing conditions on r-values and recrystallized textures of Ti-stabilized low C, N-17%Cr stainless steel, the processing conditions to improve r-values may be summarized as follows.

(1) The finishing temperature of hot rolling should be low, the annealing temperature of hot-rolled sheet should be 900°C at which significant grain growth is not initiated, the heating rate should be high and the cooling rate should be as fast as air cooling. Although r-values are improved with increasing final annealing temperature, this temperature should preferably be 850°C to forestall problems arising from grain coarsening. The desirable cold reductions are ones that are higher than 80%, which may be achieved either in single or in double rolling, in the latter case the distribution of reduction between the two stages should preferably be 40%-60%. This steel is characterized by the fact that the r-values obtained by single cold reduction are not inferior to those obtained by double cold reduction, and that the Jr-value is smaller under single cold rolling with a higher cold reduction than in double cold rolling.

(2) The desirable amount of Ti to be added should be about 0.2%. As the recrystallization temperature is shifted to a higher range by addition of Ti, however, the addition of an excessive amount of Ti should be avoided.

(3) When the desirable fine Ti(C,N) precipitates are formed under the above-mentioned processing conditions before the cold reduction, these precipitates help to develop a strong \(\{112\}<110>\) component by the heavy cold reduction and a strong \(\{554\}<225>\) component in the recrystallized texture by suppressing the growth of \(\{110\}<001>\) component, thus resulting in significant improvement of r-values.

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