Change in Earing of Low-carbon Aluminum-killed Steel Sheets with Hot- and Cold-rolling Conditions

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Experiments have been conducted to investigate the effect of hot- and cold-rolling conditions on earing. It was shown that the earing of cold-rolled and annealed sheets increases with an increase in cold-rolling reduction. On the other hand, the earing decreases with a finishing temperature below Ar3 temperature in hot rolling, the effect of the finishing temperature below Ar3 being minimal in connection with a hot-rolling reduction. The earing increases as the hot-rolling reduction increases and a finishing temperature below Ar3 decreases. With a lower cooling temperature, a deformed structure remains in hot-rolled band and the earing is increased. These increases or decreases in earing depend on the growth or suppression of 45° earing arising from the texture of RD//<110>±20°. The texture development is affected by the initial texture and initial grain size before cold-rolling, and the earing is controlled by the effect of a balance between the same.

KEY WORDS: cold rolled product; low carbon steel; crystal plasticity; texture; recrystallization; earing.

1. Introduction

Recently in the manufacture of steel two-piece cans made through a drawing process, thinner sheets are used to reduce the amount of material used for one can. To produce thinner sheets, in the manufacturing of steel sheets, high cold-rolling reduction (>90%) is applied. As a result of this heavy cold-rolling, planar plastic anisotropy increases. It is commonly known that steel sheets have planar anisotropy in regard to their plastic deformation behavior and form ears on drawn cylinders. Earing is undesirable in can manufacturing as it causes a waste of material and manufacturing troubles. To produce thinner sheets in the same cold-rolling reduction, a decrease in the thickness of hot-rolled band might be one effective way. However, an excessive decrease in the thickness of hot-rolled bands leads to a decline in hot-working productivity. So it is necessary to suppress the earing in the same cold-rolling reduction by controlling other process factors.

The increase in earing with an increase in cold-rolling reduction is caused by the development of the texture of the near α-fiber (RD//<110>) which induces ears on drawn cups situated at ±45° to the sheet rolling direction. To suppress the earing, it is necessary to suppress the development of the α-fiber or enhance the texture which induces 0/90° earing. To reduce the α-fiber after annealing, it is effective to raise the annealing temperature. However, this causes troubles in a continuous annealing process because a thin strip is easily buckled by small stress variations. This investigation was carried out to ascertain the effects of hot-rolling conditions on avoiding the above difficulties.

2. Materials and Processing

The chemical composition of the low-carbon steel is given in Table 1. Slabs 40 mm thick, 200 mm wide, 250 mm long were reheated at temperatures of 1 200°C and 1 050°C for one hour. The slabs reheated to 1 200°C were hot-rolled at the finishing temperature (FT) of 900°C. The slabs reheated to 1 050°C were hot-rolled at the FT of 750, 800 or 850°C. The FT of 900°C is in γ-phase, and the FT of 800°C and 750°C are in α+γ-phase. Regarding the sheets hot-rolled at the FT below 850°C, the hot-rolling reduction in the temperature region between FT150°C and FT(αHR) was changed from 80% to 95%, and all hot-rolling previous to the temperature dropping to FT150°C was done at a temperature above 900°C. The finishing thickness was between 3.0 mm and 1.5 mm to result in an equal thickness after cold-rolling of the various reductions mentioned later. All hot-rolling was carried out on two stands tandem mill in 5 or 6 passes. The hot bands were rapidly cooled by spraying water, and then held at 700 or 550°C for one hour followed by cooling to room temperature in the furnace as a simulation of the coiling process. The hot bands were cold-rolled to the thickness of 0.19 mm with various reductions 87% to 94%. The cold-rolled sheets were subsequently annealed at 720°C for 60 sec and cooled to 400°C and then over-aged at 400°C for 120 sec. The annealed sheets were cold-rolled again by a 5% reduc-

Table 1. Chemical composition of sample. (mass %)

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Al</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.03</td>
<td>0.01</td>
<td>0.13</td>
<td>0.009</td>
<td>0.012</td>
<td>0.066</td>
<td>0.0024</td>
</tr>
</tbody>
</table>
tion to 0.181 mm thick. As a result, the total cold-rolling re-
duction became between 88 and 94%. Hereinafter in this
report, the cold-rolling reduction (CR) mentioned will be
referring to the total cold-rolling reduction combining the
cold-rolling reduction before and after annealing.

3. Experimental Methods

Examination of microstructures was carried out at the
stage of hot-rolling and re-cold-rolling using optical mi-
croscopy on a polished and etched cross section of thick-
ess to reveal the grain size. The earing in deep drawing
tests for the re-cold-rolled sheets was measured on cups
drawn with a 30 mm dia. flat-bottomed punch from 54 mm
dia. blanks lubricated with oil. Three cupping tests were
conducted to establish each experimental point. The cup
height was measured optically at 720 points around the pe-
riphery of the cup. The raw data was modified so that the
profile was symmetrical in the rolling direction and a direc-
tion perpendicular to it. The percentage of earing was then
calculated as an ‘earing index’ using the equation

\[
\text{Earing index} = \frac{(H_{\text{max}} - H_{\text{min}})}{H_{\text{min}}}
\]

where \(H_{\text{max}}\) and \(H_{\text{min}}\) are the highest and lowest heights of
the cup edge.

Textures on the hot-rolled, cold-rolled and re-cold-rolled
sheets were determined. Specimens of 70 \text{mm} in thickness
for X-ray analysis were prepared from the mid-thickness
position in each sheet. A complete (200) pole figure was
obtained by utilizing a combination of the reflection and
transmission methods, and then detailed studies of the tex-
ture were carried out by means of a three-dimensional
analysis based on the vector method.\textsuperscript{7} As a reference of ex-
ression, fundamental orientations are shown in Fig. 1.

Some of the cup profiles were calculated for an analysis
based on an experimental texture or an ideal texture by
using the theoretical model.\textsuperscript{8}

4. Results and Observations

4.1. Effect of Hot- and Cold-rolling Conditions on
Earing Behavior

Figure 2a) shows the relationship between CR and ear-
ing index of the sheets hot-rolled at various FT. The earing
index indicates a minimum earing at the CR of about 90 %,
and increases with an increase in the CR above 90 % for all
FT. Regarding the effect of FT, the sheets hot-rolled at the
FT of 900°C which are finish-rolled in \(\alpha\text{+}\gamma\)-phase show larger
earing than that of the sheets hot-rolled at the FT of 800 or
750°C which are finish-rolled in \(\alpha\text{+}\gamma\)-phase. Figure 2b)
shows the same relationship as that shown in Fig. 2a) for
the sheets of various coiling temperatures (CT). It can be
seen by comparing Fig. 2b) with Fig. 2a) that a decrease in
CT results in an increase in earing upon CR increasing.

Figure 3a) shows the effect of FT on the earing of the
sheets hot-rolled with various \(\alpha\text{HR}\). The earing decreases
with the decrease in FT for the sheets with 80 % \(\alpha\text{HR}\).
Compared with this, the earing increases in the region of
FT below 800°C for the sheets with more than 86 % \(\alpha\text{HR}\).
This result shows that a heavy hot-rolling in
\(\alpha\text{+}\gamma\)-phase
might increase earing in a case of comparatively low FT.
This effect is evident in a case of lower CT as shown in
Fig. 3b).

The change in earing with a change in hot- and/or cold-
rolling conditions is due to the change of 45° earing regard-
less of these conditions. Some of these changes are seen by
comparing the cup profiles in Figs. 4a) and 4b) with each
other. In the higher region of CR, all cup profiles indicate
obvious 45° earing. At this stage, the 45° earing is large in
the sheets with the FT of 900°C. The sheet finish-rolled in
\(\alpha\text{+}\gamma\)-phase which shows small 45° earing in the higher re-
gion of CR shows a 0/90° earing in the lower region of CR,
so that the growth of 45° earing was suppressed with an in-
crease in CR. The effects of \(\alpha\text{HR}\) and CT are similar to
those of FT and CR. The change in earing by an increase in
\(\alpha\text{HR}\) or a decrease in CT is also caused by the growth of
45° earing as shown in Fig. 4b).

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Fig. 1. Expression of fundamental orientations.

Fig. 2. Effect of cold-rolling reduction on earing index. a): CT700, b): CT550
4.2. Effect of Hot- and Cold-rolling Condition on the Microstructure

The optical microstructures of hot bands showed significant variations depending on hot-rolling conditions. Typical examples of the optical microstructures are shown in Fig. 5. Decreasing FT below the Ar3, at a higher CT (700°C), results in a great increase in grain size. In the case of a lower CT (550°C), a deformed structure remains in the central layer in the thickness of the sheets below 800°C FT. Although the photographs are not shown because the results show the same tendencies as the previous work,9) with a decreasing FT or an increasing αHR in the α+γ-phase, the grain size is reduced slightly at a higher CT (700°C) and the fraction of the deformed structure increases at a lower CT (550°C).

Although the grain size varied markedly depending on the hot-rolling conditions, the grain size of annealed cold-rolled sheets did not vary markedly, except in the case of the sheets hot-rolled in γ-phase and coiled at a lower temperature (550°C) which shows a relatively fine microstructure. Some of these microstructures are shown in Fig. 6. The difference in grain size caused by the difference in the FT, αHR, CR and CT for the sheets with the FT in α+γ-phase is about 5 μm at the most, while on the other hand, the effect of the CT on the sheets with the FT in γ-phase is over 10 μm. Only in the case where the sheets have a fine grain, which is the case reheated at higher temperature (1200°C) and coiled at lower temperature (550°C), the interpretation of the earing behavior needs to consider the ef-
The effects of grain growth in annealing. The discussion about the results in such a situation will be omitted hereafter in this paper and discussed in another future paper to focus the discussion on just the phenomena in hot- and cold-rolling process.

4.3. Effect of Hot- and Cold-rolling Conditions on the Texture

The textures of re-cold-rolled sheets, which affect the earing behavior directly, are shown in Fig. 7. Some of the
5. Discussion

5.1. Relation between the Earing Behavior and the Texture

As mentioned above, a characteristic of earing behavior is the growth or suppression of 45° ear. It was generally confirmed qualitatively that the accumulation of α-fiber results in the enhance of 45° earring. However, the texture observed near α-fiber in this experiment was slanted by 20° in the planar angle from the α-fiber. Moreover an obvious decrease in ND/[111] or an increase in the {133}, {035} or inner orientations in a unit stereographic triangle were observed to be the effects of FT. On the other hand, the ear is not located at just 45° as it is shifted to 90/270° by about 10° so the trough at 0/180° is wider than that at 90/270°. Furthermore, small ear was observed at 0/180° in some cases.

To clarify the relation between the earing behavior and the texture, the earing caused by a partial texture is calculated using the earing prediction model. Figure 8 shows the partial textures used in the calculation and Figure 9 shows the results of the calculated earing from each texture. The calculated earing by α-fiber cannot explain the characteristics of the experimental earing. On the other hand, the results by RD/[110] express the characteristics of the experimental earing. The extension of RD/[110] to {111}/112 emphasizes the characteristics of the measured earing. The effect of the near {110}-texture works so as to increase 0/90° earring that suppresses 45° earring. As a result, 45° earring with the FT below Ar3 is suppressed due to the suppression of RD/[110] and the increase in the inner orientation in a unit stereographic triangle.

It is confirmed by using the earing prediction model that the actual earing behavior is affected by the various components of texture as mentioned above. Some examples of the calculated earing are shown in Figure 12, and they show the characteristics of the experimental earing shown in Figure 4 as well. Figures 13a and 13b show the effects of various parameters by the calculation corresponding to Figures 2 and 3. These figures also represent the characteristics of the measured earing behavior as well, whereby it is proved that the earing behavior is due to the peculiar changes in textures mentioned above.
5.2. The Development of the Texture Suppressing the Earing

The hot- and cold-rolling texture is measured to ascertain the mechanism for changing the texture affecting the earing behavior. Figure 14 shows the typical cold-rolling textures. Upon increasing CR, the \( \alpha \)-fiber increases remarkably, as shown in Fig. 15a, to a maximum of \{114\}–\{116\} in \( \alpha \)-fiber. Figure 15b shows the effect of FT on cold-rolling texture. The \{114\}–\{116\} in \( \alpha \)-fiber increases with the decrease in the FT below Ar3, as in the case of the...
increase in CR mentioned above. It is commonly known that cold-rolled \{112\} is the origin of annealed \{111\} because these orientations have a special relation of a rotation angle ranged from 25° to 36° around a common \{110\} axis. Applying this relation to the present experimental results, it can be considered that the components of RD//\{110\}±20° and \{114\}–\{116\} have the same relation as \{111\} and \{112\} have. To make sure this supposition, a calculation of crystal rotation was performed. Although there are 12 equivalent crystal rotations about the \{110\} axes, specific \{110\} axes and direction of rotation is chosen in the actual recrystallization to increase the \{111\} component in deformed \{112\} matrix. Many studies are being performed for clarifying the mechanism of such a variant selection and for defining the rotation angle around the axis. In the present discussion, the selection is supposed to be inevitable and the rotation angle is supposed to be 30°. To be concrete, for deformed \{112\} matrix, +30° rotation around \{011\} axis and −30° rotation around \{101\} axis are selected. \{111\} and \{112\} component are developed in annealing texture. For the deformed \{116\} matrix which was the increasing component in the cold-rolling texture as the effect of CR and FT as shown in Fig. 15, by the +30° rotation around \{011\} axis, \{326\} should be developed. This orientation have only a slight difference in orientation by 8° from \{112\} orientation which is the rotated \{112\} around ND by +20° and on RD//\{110\}±20°.

By another rotation, −30° around \{101\} axis, \{116\} rotate to \{236\} which deviates slightly from \{112\} on RD//\{110\}±20° in the same relation as above. That is to say, RD//\{110\}±20° in annealing texture is formed from \{114\}–\{116\} in cold-rolling texture, as shown schematically in Fig. 16.

In the case of the effect of CR, it can be considered that the accumulation to α-fiber is simply caused by the progress in the crystal rotation with the increase in the cold-rolling reduction. However, the change in texture

Fig. 14. Typical cold-rolling textures of sheets subjected to different conditions.
a): FT900-CR94, b): FT800-CR91.4

Fig. 15. Change of cold-rolling texture in different conditions.
a): Effect of CR / (FT900-αHR0-CT700-CR94.0)-(FT900-αHR0-CT700-CR91.4)
b): Effect of FT / (FT800-αHR80-CT700-CR91.4)-(FT900-αHR0-CT700-CR91.4)

Fig. 16. Schematic explanation of crystal rotation in cold-rolling texture and corresponding change of annealing texture.
with FT is considered to be caused by other mechanisms as well. Another remarkable change with a decrease in FT is a great decrease in $\gamma$-fiber shown in Fig. 15b).

The sheets hot-rolled at the FT below Ar3 have strong $\alpha$-fiber texture, especially $\{116\}$. $\{110\}$, compared with that hot-rolled at the FT above Ar3, as shown in Fig. 17. Although $\gamma$-fiber is a stable component in cold-rolling texture, the accumulation of it is suppressed because of the previous accumulation of $\alpha$-fiber before cold-rolling. Considering the cold-rolling texture only, it can be thought that RD/$(110)\pm 20^\circ$ would increase in the annealing texture of the sheet hot-rolled at the FT below Ar3 in view of the discussion above. However, this is not the case. This result indicates the importance of taking into consideration of the effect of nucleation of recrystallisation. The sheets hot-rolled at the FT below Ar3 showed a large grain size as mentioned in the previous Sec. 4.2. Supposing that grains recrystallised at grain boundaries tend to have RD/$(110)\pm 20^\circ$ orientations, based on the fact that grains recrystallised at grain boundaries have $\{111\}$ orientations,16,17 in view of the above discussion which said they have a similar relation to the cold-rolling texture except for the inclining to the transverse direction, the coarsening of grain in hot-rolled bands could suppress the development of RD/$(110)\pm 20^\circ$ in annealing. Moreover, it is well known that the grain size of hot band affects the annealing texture strongly, for example, a large grain results in an increase in $\{110\}$(001) in annealing.16 Considering the change of annealing texture shown in Figs. 8b) and 9 in which the near $\{110\}$(001) as $\{133\}$, $\{035\}$ or the inner orientations in the unit stereographic triangle increase, this effect could contribute to a decrease of RD/$(110)\pm 20^\circ$. Besides, the effect of initial grain size on crystal rotation is considerable. It is reported that a large grain size retards the crystal rotation by cold-rolling.16 The fact that the near $\{110\}$-orientation, which usually disappears through cold-rolling, remains weak in several cases might be explained by this effect. To enable a quantitative discussion to take place on this subject, a more precise and limited experiment are needed, as is a microscopic observation using a transmission electron microscope (TEM) or electron back-scattering pattern (EBSP) to clarify the nuclei of recrystallisation.

The effect of initial texture and initial grain size on the development of texture affecting the earing behavior concerning the FT mentioned above can be described schematically as shown in Fig. 18. Two effects have the opposite influence on each other, the grain size effect is dominant in the case of the FT in $\gamma$-phase so the earing is large, on the other hand, the initial texture effect is dominant in the case...
of a low FT and high αHR to excess so the earing is large. These effects cancel each other in the case of proper FT and αHR so the earing is suppressed.

6. Conclusion

The earing behavior of low-carbon steel sheets has been investigated to clarify the effect of hot- and cold-rolling conditions on earing.

(1) The earing increases with the increase in CR above 90%. In this CR region, the earing is suppressed with the FT in α+γ-phase compared with the FT in γ-phase. However, even in the condition hot-rolled at the FT in α+γ-phase, the earing is enlarged with a lower FT and higher αHR to excess.

(2) The growth of earing is due to the growth of 45° ears shifted to a 90° direction by about 10° having narrow trough at 90/270° and wide trough at 0/180°. This earing was proved to arise from a texture with RD//k_{110}l_{620}° orientations by using a mathematical earing prediction model. Using this model, the earing behavior is well explained by the change of the texture.

(3) An analysis shows that RD//(110)±20° in annealing texture is enlarged by the accumulation of the {114}–{116}(110) in cold-rolling texture as well known fact that the {111}(112) in annealing texture is enlarged by the {112}(110) in cold-rolling texture. An increase in CR and αHR enhances the formation of the {114}–{116}(110) in cold-rolling texture and as a consequence, the formation of RD//(110)±20° in annealing texture.

(4) In the sheet hot-rolled at the FT in α+γ-phase compared with the sheet hot-rolled at FT in γ-phase, RD//k_{110}l_{620}° in annealing texture decreases although the {114}–{116}(110) in cold-rolling texture increases. This phenomenon is explained by the effect of the balance between the initial texture and the initial grain size.

REFERENCES