EFFECT OF COLD-REDUCTION ON THE PRESS-FORMABILITY OF ANNEALED ALUMINIUM SHEETS

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Abstract

The tensile properties of 1050-aluminium sheets cold-rolled to 20%, 50%, 80%, 90%, 95%, and 96.7%, annealed to full recrystallization, are examined. The 90% and 96.7% cold-rolled sheets are annealed at different annealing temperatures for one hour. Their tensile properties are also examined and compared with those of the sheet cold-rolled to 95% prior to annealing. The microscopic structure through thickness, and surface and mid-thickness textures are investigated for the 96.7% cold-reduced sheet annealed at different temperatures for one hour. r_{45}- and $\bar{r}$-values show characteristic variation with an increasing annealing temperature for the 90%, 95%, and 96.7% cold-rolled sheets; they show peak values for the partially recrystallized state. This variation is qualitatively explained in correlation with textures obtained by means of X-ray pole figures. Heavily cold-reduced sheets annealed to full recrystallization are recommended for the improvement of press-formability.

1. Introduction

In an earlier paper[1)], the effects of annealing conditions on the properties of 1050-aluminium sheets cold-rolled to 95% have been studied. It was concluded that the development of surface and mid-thickness textures of the (112) [11$\bar{1}$] and (123) [21$\bar{1}$] types is recommended for high r-values. The $\bar{r}$-, $\bar{n}$-, and the pure-stretch test values of the 95% cold-rolled sheet were reported to be higher than those of the 90% cold-rolled sheet, as both of them was in the full recrystallized condition. Therefore, in the present paper the role of cold-reduction, with an emphasis on a heavy cold reduction of 96.7%, in improving the press-formability of annealed sheets is to be investigated. In an attempt to clarify the effect of surface friction, a part of the heavily cold-rolled sheets (96.7%) is rolled with degreased rolls in two passes, about 10% and 25% respectively, thus reducing the thickness from 0.60mm. (of sheets previously cold-reduced to 95%) to about 0.38mm. The other part of these sheets is cold-rolled while applying mineral oil blended with oleic acid 1% as a lubricant, in one pass (about 35%). A back tension of about 14kg/mm^2 is applied to make the forward slip approximately zero. The tensile properties, microscopic structure through thickness, surface and mid-thickness textures

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are examined for the 96.7% cold-rolled sheets annealed at different temperatures for one hour. The tensile properties of the 20%, 50%, and 80% cold-rolled and fully recrystallized sheets (350°C X 1 hr.), and those of the 90% cold-rolled sheets annealed at different temperatures for one hour are also investigated.

The experimental analysis adopted in the present work have been described elsewhere[1].

2. The effect of prior cold-reduction on the tensile properties of the fully recrystallized sheets (350°C X 1 hr.):

Fig. 1 shows the variation of r-value with prior cold-reduction for the fully recrystallized specimens:

a) The r_0-value increases gradually from 20% reduction to 80%, then decreases gradually.

b) The r_{90}-value is relatively the same for the 20% and 50% reductions. It rises to a small peak at 80%, then decreases gradually becoming the least among the 0°, 45° and 90° directions.

c) The r_{45}-value decreases gradually up to 80%, then increases rapidly showing a very high value ($r_{45}=1.82$) for the 96.7 % reduction.

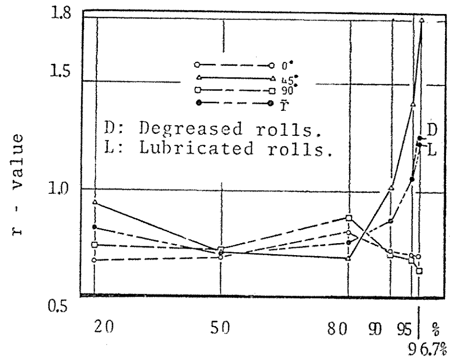


Fig. 1. Effect of cold-reduction prior to full recrystallization on r-value.

d) The $\bar{r}$-value shows the same tendency as that of the r_{45}-value but the $\bar{r}$-value of the 50% reduction is minimum among the other reductions.

e) A case of approximately earless condition appears for both the 50% and about 84% reductions, i. e., the r_0, r_{45}, and r_{90} are approximately equal (0.71 and 0.77 for the 50% and 84% reductions respectively).

f) Two distinguished regions can be observed, the first region from 50% up to about 84% reductions, while the second one for reductions higher than 90%. In the first region the r-value changes its order at some reduction between 50% and 80% (from $r_{90}>r_{45}>r_0$ to $r_{90}>r_0>r_{45}$), but a highest r_0-value at both 50% and 80% reductions was reported by Kawai et al.[2]. For 90%, the order of r-value changes to $r_{45}>r_0>r_{90}$ and remains unchanged for higher reductions.

Figs. 2-(a) and 2-(b) show the effect of prior cold-reduction on the n-value and the total natural strain ε_t respectively: From fig. 2-(a):

a) n_{45}-value increases slowly with an increasing cold-reduction prior to full recrystallization up to 95%, then decreases for the 96.7%. Both of the n_0- and $\bar{n}$-values vary in the same way as that of the n_{45}-value.

b) n_{90}-value decreases slowly with the increase of the cold-reduction up to 80%, then it increases to reach a maximum value for the 95%; it decreases at the 96.7% reduction.

c) The differences among the three directions are small, and the dependence of n-value on cold-reduction prior to annealing is relatively small.

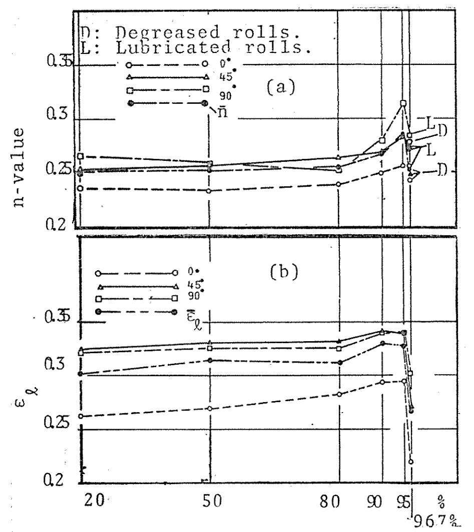


Fig. 2. Effect of cold-reduction prior to full recrystallization on both of n-value and total natural strain.

As it can be observed from fig. 2-(b), the variation of the total natural strain with cold-reduction prior to full recrystallization is likely the same as that of n-value.

As shown in fig. 3, the range of

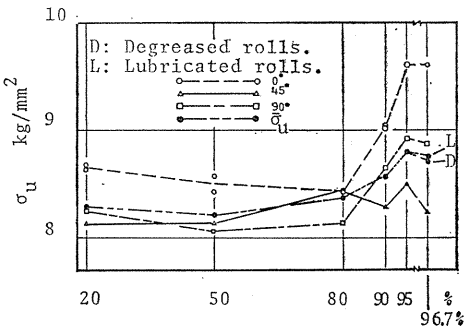


Fig. 3. Effect of cold-reduction prior to full recrystallization on the ultimate tensile strength σ_u.

variation of the ultimate tensile strength lies between 8 kg/mm² and 9 kg/mm². Therefore, the ultimate tensile strength (σ_u) seems to be approximately constant up to 80% reduction, then it increases up to 95% and remains unchanged for the 96.7 % reduction. The σ_{u-45} hardly changes after 80% reduction.

The role of higher reduction prior to full recrystallization has been clarified. A heavy cold-reduction (96.7%) prior to full recrystallization raises remarkably r-values, but slightly affects n-values, the total natural strain, and the ultimate tensile strength. The effect of annealing temperature on the properties of the 96.7 % cold-rolled sheets will be studied in the following chapter.

3. Properties of heavily cold-rolled specimens annealed at different temperatuers for one hour:

3. 1. Vicker's hardness and ultimate tensile strength:

Figs. 4 and 5 show the variation of the Vicker's hardness with annealing temperature for the 90% and 95%, and 96.7% cold-rolled specimens respectively. It can be observed that recrystallization commences at about 250°C and ends itself at about 300°C. The hardness values of the 96.7% cold rolled specimens with degreased rolls are slightly higher than those with lubricated rolls up to 263°C, but those obtained with the former procedure become lower after 275°C. The commence and end of recrystallization are to be confirmed from the tensile properties, and microscopic structure and texture results to be mentioned later.

The variation of the ultimate tensile strength with annealing temperature for the 90% and 96.7% cold-rolled specimens is likely the same as that of the 95% reduction[1]; i. e., the tensile strength decreases rapidly with an increasing annealing temperature, reaching a constant value after full recrystallization.

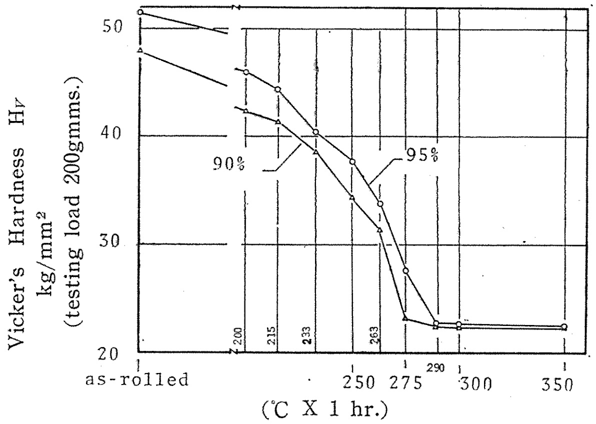


Fig. 4. Effect of annealing temperature on Vicker's hardness of the 90% & 95% cold-rolled sheets.

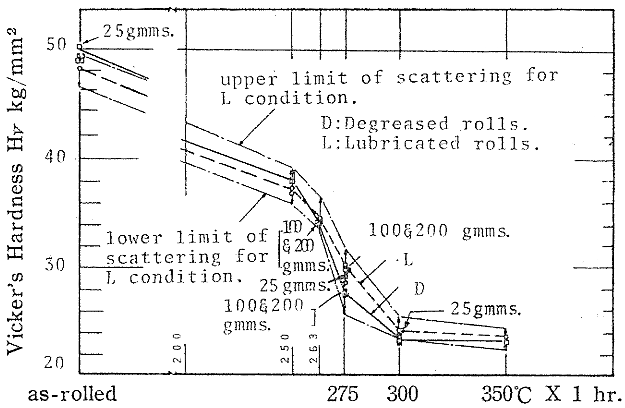


Fig. 5. Effect of annealing temperature on Vicker's hardness of the 96.7% cold-rolled sheet.

3. 2. The effect of annealing temperature on r-value of the 90% and 96.7% cold-rolled sheets:

They are shown in figs. 6, 7 and 8 respectively. The $\bar{r}$- and r_{45}-values of the 95% cold-rolled sheets are reproduced in fig. 8. From these figures the following can be noticed.

a) The variation of the r-values with an increasing annealing temperature for the 90%, 95% and 96.7% cold-reductions is qualitatively the same. The r_{45}-value is always highest among the r_0, r_{45} and r_{90} values, reaching a peak-value at 275℃. The $r_{45}>r_{90}>r_0$ order changes to $r_{45}>r_0>r_{90}$ after the 275℃ X 1 hr. condition [Fig. 6, 7 and 8; fig. 5 of reference no. 1)].

b) Up to 250℃, the r_{45}-values of the 95% and 96.7% reductions are nearly equal. As the temperature increases, the $\bar{r}$ and r_{45} of the 96.7% reduction become

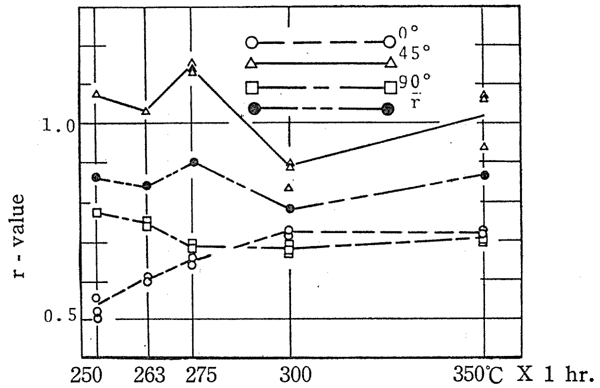


Fig. 6. Effect of annealing temperature on the r-value of the 90% cold-rolled sheet.

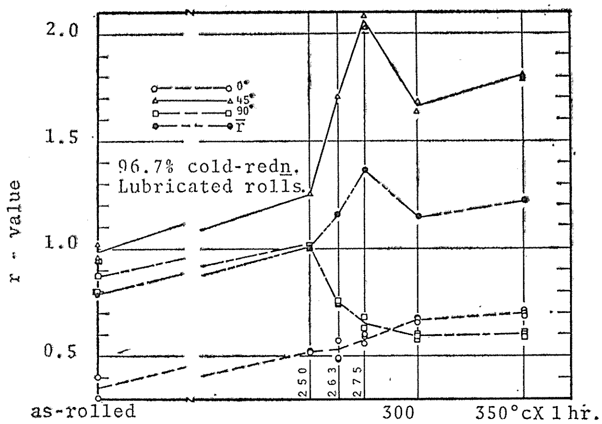


Fig. 7. Effect of annealing temperature on r-value.

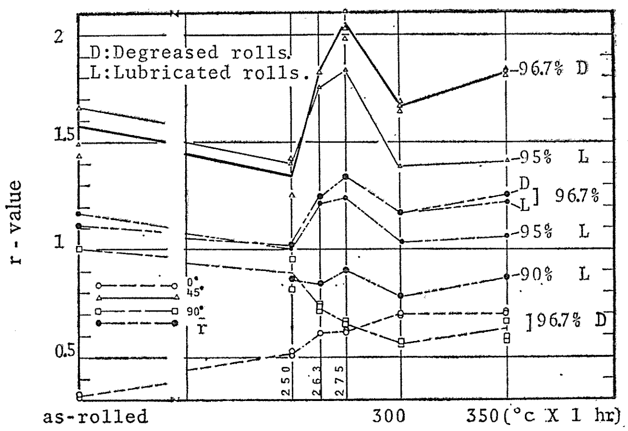


Fig. 8. Effect of annealing temperature on r-value.

larger than those of the 95% one. The largest difference is for the fully recrystallized condition. At 350℃ the $\bar{r}$-value of 96.7% reduction with degreased rolls is slightly larger than that with lubricated rolls [fig. 8]. The $\bar{r}$- and r_{45}-values of the 90% reduction are always least among the three cold-reductions.

c) The r_0-value increases gradually with the increase of annealing temperature up to full recrystallization where it remains constant. It shows a step increase at 250℃ [figs. 6, 7 and 8].

d) The r_{90}-value decreases with an increasing annealing temperature reaching a constant value after full recrystallization.

e) The r_0- and r_{90}-values are nearly equal among the 90%, 95% and 96.7% cold-reductions at the corresponding annealing temperatures.

3. 3. The n-value:

As reported for the 95% cold-rolled sheet[1], the n-value increases rapidly as soon as recrystallization commences reaching a maximum constant value after full recrystallization. The differences among the n_0-, n_{45}-, and n_{90}-values are relatively small as shown in figs. 9, 10 and 11.

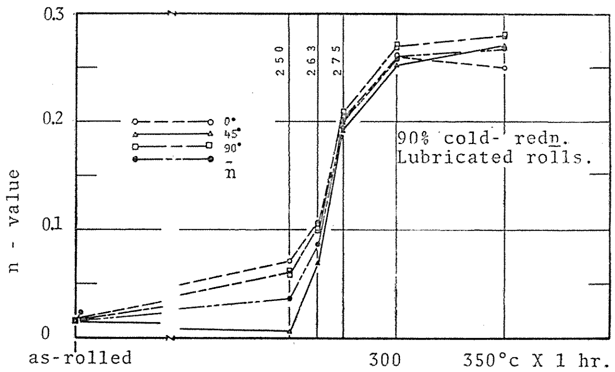


Fig. 9. Effect of annealing temperature on n-value,

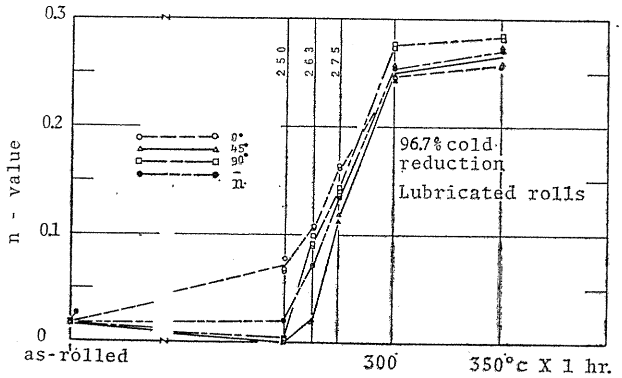


Fig. 10. Effect of annealing temperature on n-value.

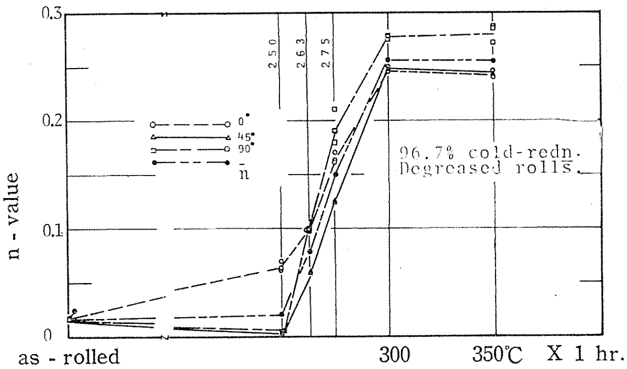


Fig. 11. Effect of annealing temperature on n-value.

The characteristic variation of the r_{45}-value with an increasing annealing temperature is also obtained for both the 90% and 96.7% as well as for the 95% reduction previously reported[1]. The effect of an increasing cold-reduction prior to annealing is to raise the r_{45}- and $\bar{r}$-values remarkably after 263℃. But the differences between the peak r_{45}- and $\bar{r}$-values appearing at 275℃ and those at full recrystallization are lowered for the 96.7% cold-reduction. The r_{45}- and $\bar{r}$-values of the 96.7% cold-reduced sheets with degreased rolls and those with lubricated ones are nearly equal at the different annealing temperatures, but they are slightly larger at 350℃ for the degreased rolls-condition. This indicates that the heavier cold-reduction is suggested to be the primary factor, while the effect of higher friction (degreased rolls-condition) is a secondary one as only two final passes (to bring the thickness from 0.60 down to 0.38mms.) are carried out with degreased rolls. This point is to be investigated later. A microstructure examination through the thickness, and texture of both the surface and mid-thickness layers of the 96.7% cold-reduced sheet are to be studied to throw some light on the charateristic variation of r-value.

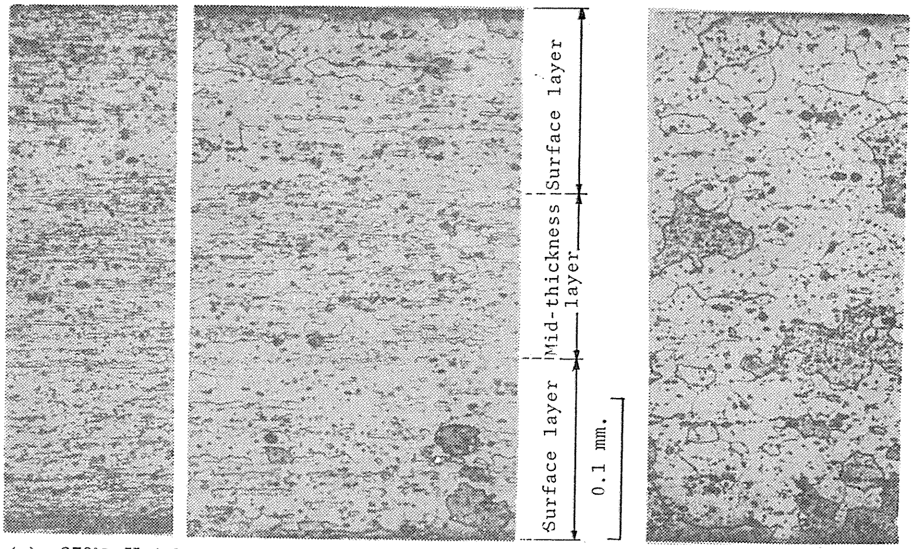
With respect to the effects of annealing temperatures on the Vicker's hardness, the ultimate tensile strength, and n-values, similar results have been often reported.

In view of the results mentioned above, a heavily cold-rolled sheet annealed to full recrystallization, acquiring both high r- and high n-values, is to be recommended for the improvement of press-formability. This is more or less different from the results of Grimes et al.[3], in which heavily cold-reduced sheet annealed to maximuum recovery, and those of Kawai et al.[2], in which heavily cold-reduced sheet annealed to partial recrystallization, give the greatest drawability.

3. 4. *Microscopic structure and Textures examination*:

As mentioned above, the characteristic variation of r-value according to the annealing conditions is to be clarified. In order to understand the mechanism by which the variation of r-value takes place, microscopic structure through thickness, and textures of both the surface and mid-thickness layers will be examined.

Plate 1 shows the microscopic structure through the thickness of the 96.7%



(a) 250℃ X 1 hr. (b) 275℃ X 1 hr. (c) 350℃ X 1 hr.

Plate. 1. Microscopic structure through thickness of the 96.7% cold-rolled sheet (degreased rolls).

cold-rolled sheet annealed at different annealing temperatures. No recrystallized grains appear in the surface layer of the 250℃ X 1 hr. condition. The recrystallized grains appear in the surface layer of the 275℃ X 1 hr. condition, and a sandwitch-like structure seems to be existing. The 300℃ X 1 hr. and the 350℃ X 1 hr. annealed specimens are in the fully recrystallized state. The depth of the surface layer compared to that of the mid-thickness layer is greater for the 96.7% cold-reduction than for the 95% cold-reduction in case of specimens annealed at 275℃ for one hour [plate 1; and plate 1 of reference no. 1)].

Sets of {111} and {200} pole figures of the surface and mid-thickness layers of the as-cold-rolled, partially recrystallized, and fully recrystallized specimens cold-rolled to 96.7%, with degreased rolls are reproduced in figs. 12 and 13 respectively. Table 1 summarizes the textures developed.

The presence of the sandwitch-like structure can also be noticed by texture examinations. Following the same way mentioned in a previous paper[1)], the mechanism by which the characteristic variation of r-value takes place can be revealed.

Making reference to texture results of both Hosford and Backofen[4)] and Gokyu et al.[5)] the variation of r-value can be qualitatively correlated with that of the texture.

As it was noted above, fig. 8, and fig 5 of reference no. 1), the r-values of the 95% cold-rolled sheet are nearly equal to those of the 96.7% cold-rolled ones; but, the r_{45}- and $\bar{r}$-values of the 96.7% rolled sheets are remarkably higher for the partially and fully recrystallized conditions. Comparing the texture results of the two cold-reduced conditions, [table 1 and figs. 12, 13 - table 4 and figs 13, 14 of reference no. 1)], the as-rolled textures of the surface and mid-thickness layers

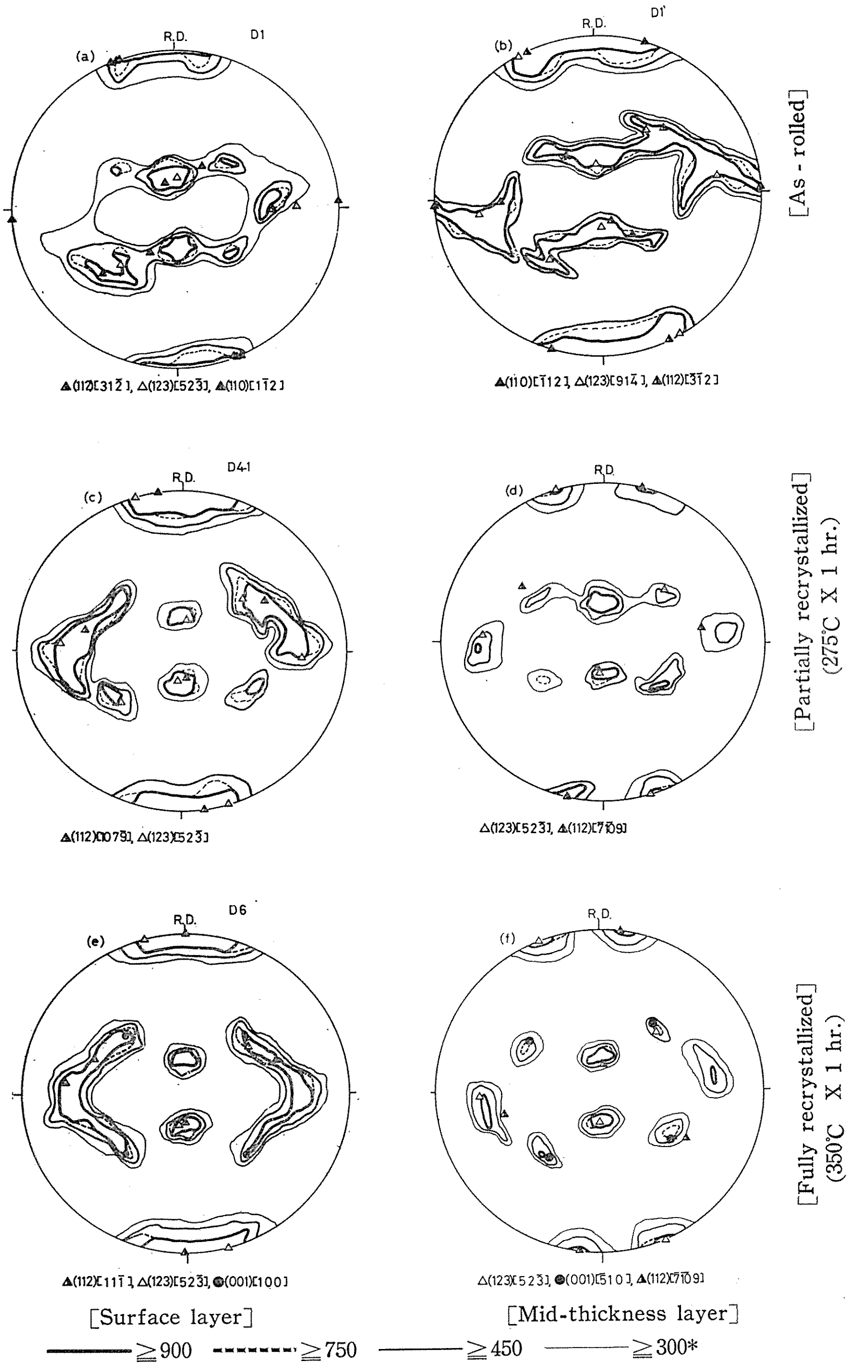


Fig. 12. {111} Pole figures at both surface and mid-thickness layers of the 96.7% cold-rolled sheet.
* : Intensities in arbitrary units.

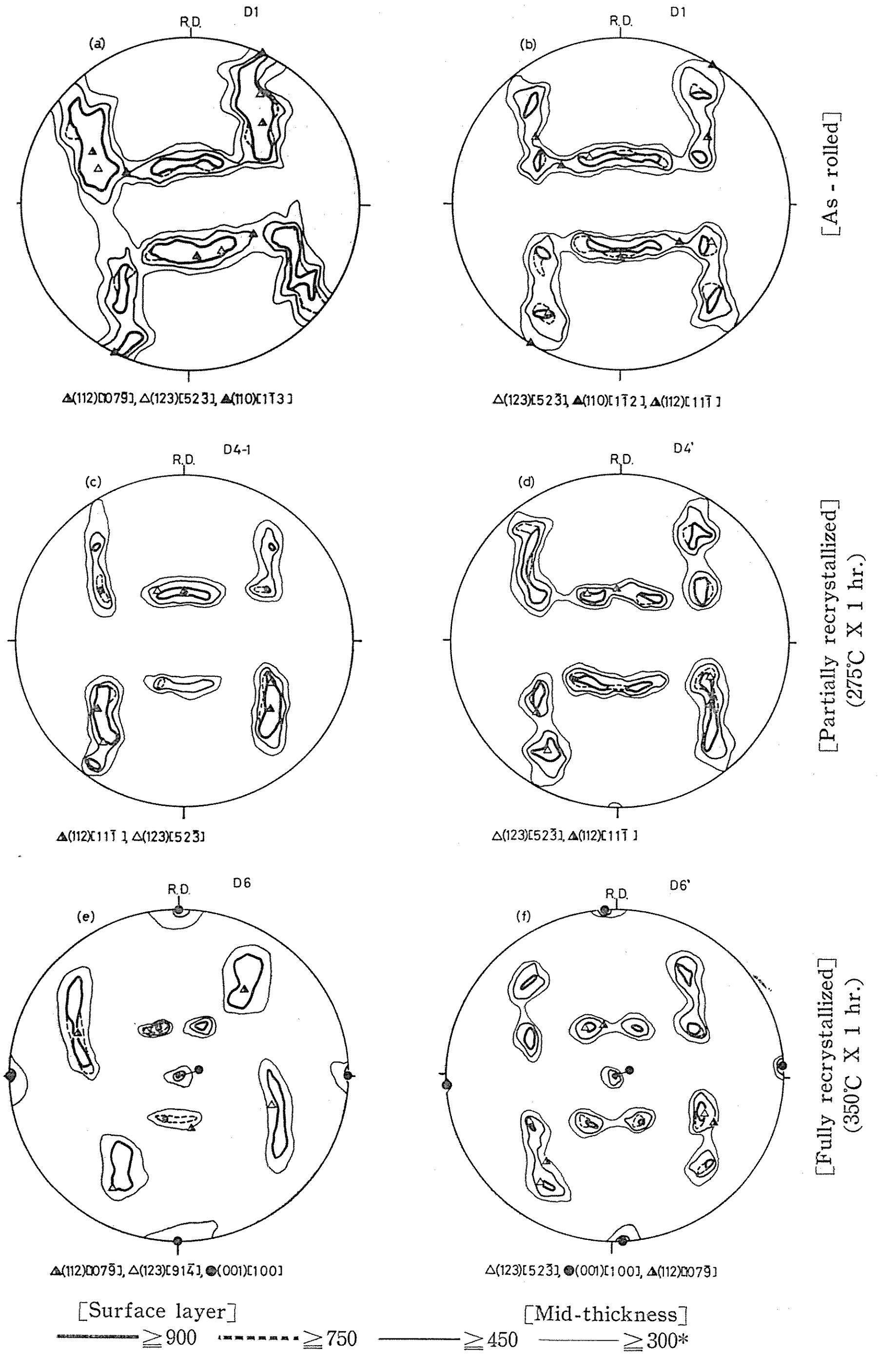


Fig. 13. {200} Pole figures at both surface and mid-thickness layers of the 96.7% cold-rolled sheet.

* : Intensities in arbitrary units.

Table. 1. Surface and mid-thickness textures of the 96.7% cold-rolled sheet.

	Surface layer	Mid-thickness layer
As cold-rolled.	1 (112)[11$\bar{1}$] (n.t.) 1' (123)[21$\bar{1}$] (n.t.) 3 (110)[1$\bar{1}$2]	1 (112)[11$\bar{1}$] (n.t.) 2 (123)[21$\bar{1}$] (n.t.) 1' (110)[$\bar{1}$12]
Partially recrystallized (275°c X 1 hr.)	1 (112)[11$\bar{1}$] (n.t.) 1' (123)[21$\bar{1}$] (n.t.)	2 (112)[11$\bar{1}$] (n.t.) 1 (123)[21$\bar{1}$] (n.t.)
Fully recrystallized (350°c X 1 hr.)	1 (112)[11$\bar{1}$] 2 (123)[21$\bar{1}$] (n.t.) 2' (001)[100]	1 (112)[11$\bar{1}$] (n.t.) 3' (123)[21$\bar{1}$] (n.t.) 1' (001)[$\bar{1}$00] (n.t.)

N.B.: a) (n.t.) : near to.
b) numbers indicate intensity order, e.g., 1 is of highest intensity.

are approximately the same. For the partial annealing condition, the (110) [$\bar{1}$12] component is absent in the 96.7% reduced sheet. The intensity of the (001) [100] component is relatively lower for the 96.7% than for the 95% cold-rolled sheets in the fully recrystallized condition. In this way, the improvement of the r-values for the 96.7% heavily cold-rolled sheet compared to those of the 95% cold-rolled one in both the partially and fully recrystallized conditions, can be qualitatively explained.

4. Conclusions

1) A remarkable increase in r_{45}- and $\bar{r}$-values is obtained with heavily cold-rolled sheets annealed to full recrystallization (350℃ X 1 hr.). The $\bar{r}$-value of the 50% cold-rolled sheet is minimum among the other cold-rolled sheets annealed to full recrystallization.

2) For the fully recrystallized condition, the r-value changes its order at some reduction between 50% and 80% (from $r_{90}>r_{45}>r_0$ to $r_{90}>r_0>r_{45}$). For the 90% reduction, the order of r-value changes to $r_{45}>r_0>r_{90}$ and remains unchanged for higher reductions. A case of approximately earless condition appers for both 50% and about 84% cold-reductions, for which r-values in the 0°, 45°, and 90° directions are approximately equal.

3) The n-values are slightly dependent on cold-reduction prior to full recrystallization. The differences between n-values at 0°, 45°, and 90° directions are small for any prior cold-reduction.

4) For the heavy cold-reductions 90%, 95%, and 96.7%, the r_{45} and $\bar{r}$-values show a characteristic variation with an increasing annealing temperature. They reach peak values for the partially recrystallized condition (275℃ X 1 hr.). The r_{45}-value is always highest at any annealing temperature.

5) The differences between peak r_{45}-and $\bar{r}$-values of the 96.7% cold-rolled sheets at partial recrystallization condition, and those at full recrystallization are lowered compared with other heavy cold reductions. Also, the r_{45}- and $\bar{r}$-values of the 96.7% cold-rolled sheets fully recrystallized are slightly higher for the degreased rolls-condition than for the lubricated rolls (mineral oils blended with oleic acid 1 %)- condition.

6) The variation of r-value with an increasing annealing temperature is qualitatively explained in correlation with textures obtained by means of pole figures.

7) A heavily cold-rolled sheet annealed to full recrystallization, acquiring both high r- and high n-values, is to be recommended for the improvement of press-formability. While the role of high surface friction, during cold-rolling, in developing high r-values of finished sheets remains to be clarified.

5. References

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