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A New Process for Manufacturing Deep-Drawing Cold-Rolled Steel Sheets from Extra-Low-Carbon Steels

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Synopsis :
For developing a new process of manufacturing deep-drawing cold-rolled steel sheets, effects of chemical composition and hot-rolling conditions on mechanical properties of extra-low-carbon steel sheets have been investigated. The results obtained are given below: (1) In low C content less than 0.002%, resistance to aging can be obtained without overaging treatment in continuous annealing. However, improvement of deep-drawability by lowering C content is small because planar anisotropy of mechanical properties is extremely large. (2) A small addition of Ti or Nb effectively decreases the planar anisotropy and gives good deep-drawability. (3) Lowering a slab reheatig temperature below 1100℃ in such steels provides good deep-drawability even for hot-rolling with the finishing temperature below Ar3 and the coiling temperature below 600℃. This is noticeable in Ti-added extra-low-carbon steels. (4) On the basis of the above findings, a new process consisting of hot-rolling in the low temperature range and continuous annealing without overaging treatment using extra-low-carbon steels has been developed for producing deep-drawing cold-rolled steel sheets.

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A New Process for Manufacturing Deep-Drawing Cold-Rolled Steel Sheets from Extra-Low-Carbon Steels*1

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For developing a new process of manufacturing deep-drawing cold-rolled steel sheets, effects of chemical composition and hot-rolling conditions on mechanical properties of extra-low-carbon steel sheets have been investigated. The results obtained are given below:

(1) *In low C content less than 0.002%, resistance to aging can be obtained without overaging treatment in continuous annealing. However, improvement of deep-drawability by lowering C content is small because planar anisotropy of mechanical properties is extremely large.*

(2) *A small addition of Ti or Nb effectively decreases the planar anisotropy and gives good deep-drawability.*

(3) *Lowering a slab reheatig temperature below 1 100°C in such steels provides good deep-drawability even for hot-rolling with the finishing temperature below Ar_3 and the coiling temperature below 600°C. This is noticeable in Ti-added extra-low-carbon steels.*

(4) *On the basis of the above findings, a new process consisting of hot-rolling in the low temperature range and continuous annealing without overaging treatment using extra-low-carbon steels has been developed for producing deep-drawing cold-rolled steel sheets.*

1 Introduction

Not only because of their high gage accuracy and beautiful surface appearance, but because of their good formability, large amounts of cold-rolled steel sheets are used in a wide variety of applications. Pressed automobile panels are a representative example of their forming applications. Cold-rolled steel sheets are used as stock material in producing various types of surface-treated steel sheets that have been produced in increasingly large amounts in recent years.

The formability of steel sheets substantially governs their formability after surface treatment, and is, in turn, closely related to their mechanical properties. In general, low yield strength (*YS*) and high elongation (*El*) improve stretchability, and the higher the Lankford value (*r*-value), the better the deep-drawability. Solute carbon and nitrogen remaining in steel sheets cause not only the deterioration of mechanical properties due to strain aging, but also a non-conformance called stretcher strain during press forming. Therefore, cold-rolled steel sheets for forming must possess ① high ductility, ② high *r*-values, and ③ a good anti-aging property. Steel sheets that meet these properties are generally called deep-drawing quality (DDQ) steel sheet.

At present, steel sheets of this type are manufactured from low-carbon Al-killed steels of about 0.05% C. A recent progress in steelmaking techniques, however, has made it economically possible to refine extra-low-carbon steels with C contents of 0.005% or less. It has recently become clear that, using these extra-low-carbon steels, deep-drawing steel sheet can be manufactured more economically than has been achieved to date with the conventional process using low-carbon steels.

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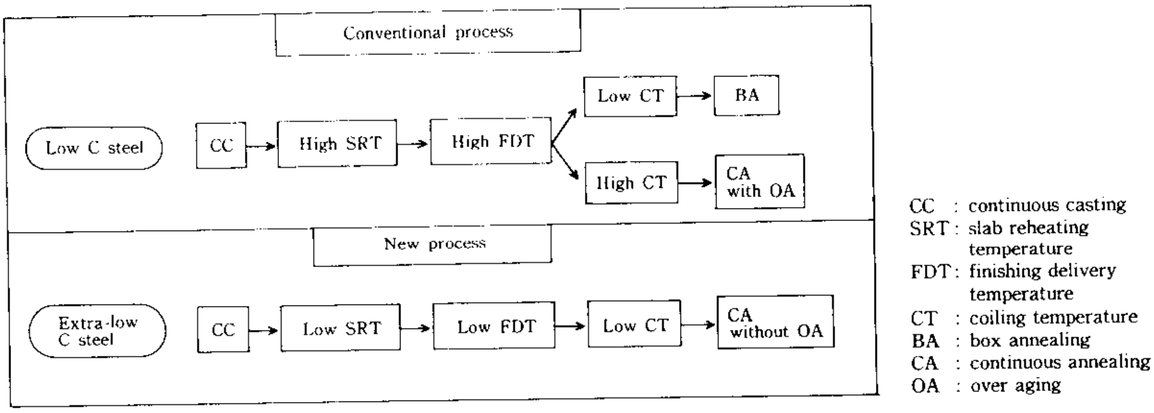


Fig. 1 Comparison of a conventional process and a new process for producing deep-drawing cold-rolled steel sheets

This report describes a new process for manufacturing deep-drawing cold-rolled steel sheets from extra-low-carbon steels, with particular attention to metallurgical aspects.

2 Comparison between Conventional and New Processes

Figure 1 schematically shows a comparison between the conventional and new manufacturing processes for deep-drawing cold-rolled steel sheets. In the conventional process, use of low-carbon Al-killed steels as material requires reheating of continuously cast slabs to high slab reheating temperatures (SRT) of 1 200°C or above. This is because it is necessary,

(1) to secure hot-rolling finishing delivery temperatures (FDT) above the Ar_3 transformation temperature (about 850°),

(2) to keep AlN in solution in the stage of the hot coil when box annealing is conducted.

These two requirements, (1) and (2) above, must be met to achieve the deep-drawability indicated by high *r*-values in cold-rolled steel sheets. Needless to say, vast amounts of energy are required to reheat slabs to such high temperatures, and there are accompanying problems such as decrease in yield and deterioration of surface properties due to high-temperature oxidation.

In recent years, continuous annealing has been increasingly applied to the conventional DDQ steel manufacturing process to improve productivity and product uniformity. (At Kawasaki Steel, both Chiba and Mizushima Works are equipped with KM-CAL continuous annealing lines.) To produce deep-drawing cold-rolled steel sheets from low-carbon steels by continuous annealing, it is generally necessary,

(1) to coil the strip at high temperatures (about 700°C) after hot rolling,

(2) to conduct overaging in the continuous annealing line.

High-temperature coiling is conducted to facilitate the growth of recrystallized grains during rapid-heating continuous annealing; and overaging aims at securing the anti-aging property by precipitating solute carbon as Fe_3C. However, high-tempeature coiling after hot rolling poses problems, such as deterioration in removing scale of hot-rolled steel sheets.

The foregoing are the key metallurgical points and problems in the conventional manufacturing process when deep-drawing cold-rolled steel sheets are produced from low-carbon Al-killed steels.

Recent progress in steelmaking techniques, especially

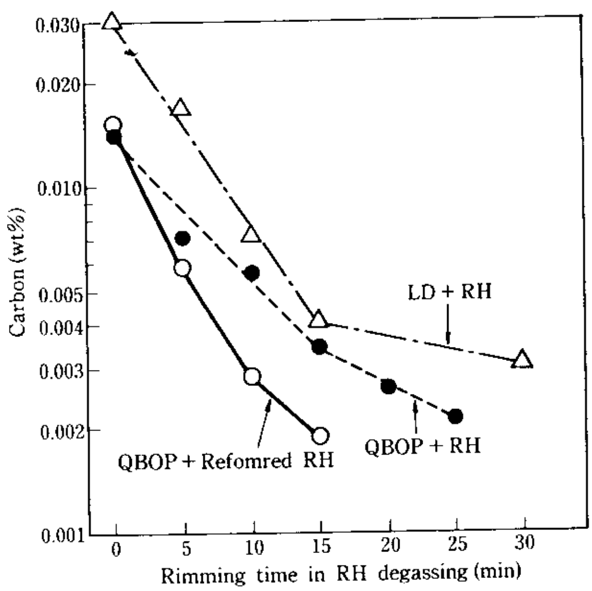


Fig. 2 C content of RH-degassed steels plotted against rimming time in RH-degassing

degassing-refining techniques, is remarkable, and it has now become possible to economically produce extra-low-carbon steels with C contents of 0.005% or less. **Figure 2** shows the relationship between decarburization time and C content in the RH degassing process when various refining processes are combined with RH degassing.[1] By a combined use of the bottom-blown converter (Q-BOP) and modified RH degassing equipment, a stable, economical production of extra-low-carbon steels with an average C content of 0.002%, in a greatly reduced time, has now become possible.[2] If such extra-low-carbon steels are used as material, cold-rolled steel sheets for forming can be produced by the new manufacturing process shown in Fig. 1. The new process is comprised of low-temperature reheating, low-temperature hot rolling, low-temperature coiling, and continuous annealing with a simple heat cycle. This new process eliminates all the problems of the conventional process.

3 Effect of C Content and Alloying Elements on Mechanical Properties

In general, a decrease in C content brings about an increase in the ductility and r-value of steel sheets. Furthermore, an overaging treatment to obtain the anti-aging property during continuous annealing may become unnecessary if C content can be lowered sufficiently near to its limit. **Figure 3** shows the effect of C content on the mechanical properties of extra-low-carbon steel sheets. The materials for these sheets were small vacuum-melted steel ingots with a composition of 0.02% Si–0.15% Mn–0.01% S–0.04% Al–0.003% N, not containing special alloying elements such as Nb and Ti. Hot rolling (SRT 1 250°C, FDT 880°C), cold rolling (rolling reduction: 79%) and annealing (soaking: 830°C for 40 s; without overaging) were conducted in the laboratory. Even if overaging is not conducted, the aging index AI (7.5% pre-straining; aging at 100°C for 30 min) can be lowered to 30 MPa or less by lowering the C content to 0.002% or less, thereby virtually securing the anti-aging property. Although elongation (El) and the r-value improve with decreasing C content, the amounts of increase are small in spite of the great change in the C content (from 0.01 to 0.001%). This is because the planar anisotropy of El and r-value (ΔEl and Δr) increases with decreasing C content. In Fig. 3, the letters L, D and T denote the values of these properties at angles of 0°, 45°, and 90°, respectively, to the rolling direction. $\overline{El}$, ΔEl, $\bar{r}$ and Δr were calculated by the following equations:

$$\overline{El} = \frac{El_L + El_T + 2El_D}{4} \qquad (1)$$

$$\Delta \overline{El} = \frac{El_L + El_T - 2El_D}{2} \qquad (2)$$

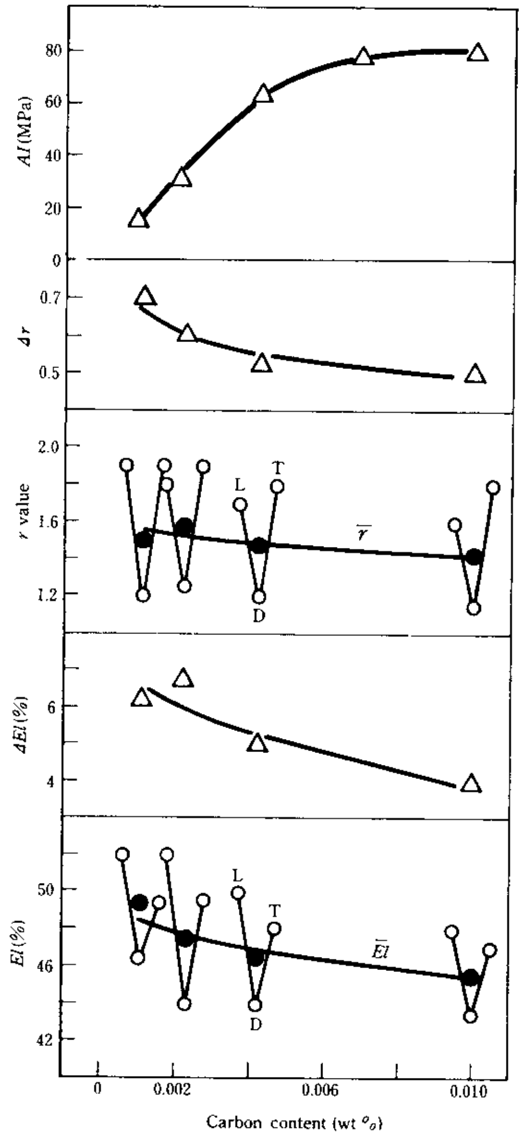


Fig. 3 Effect of C content on mechanical properties of cold-rolled and continuous-annealed steel sheets

$$\bar{r} = \frac{r_L + r_T + 2r_D}{4} \qquad (3)$$

$$\Delta r = \frac{r_L + r_T - 2r_D}{2} \qquad (4)$$

It is apparent that in spite of a decrease in C content, the values in D direction (45°) are low. This shows that the planar anisotropy is large.

Figure 4 shows the effect of alloying elements on the planar anisotropy of 0.002% C–0.04% Al steels to which special alloying elements such as Nb and Ti are added, the contents of other elements and the experimental conditions being the same as with the steel shown in Fig. 3. In Ti-added steels, almost all S and N combine

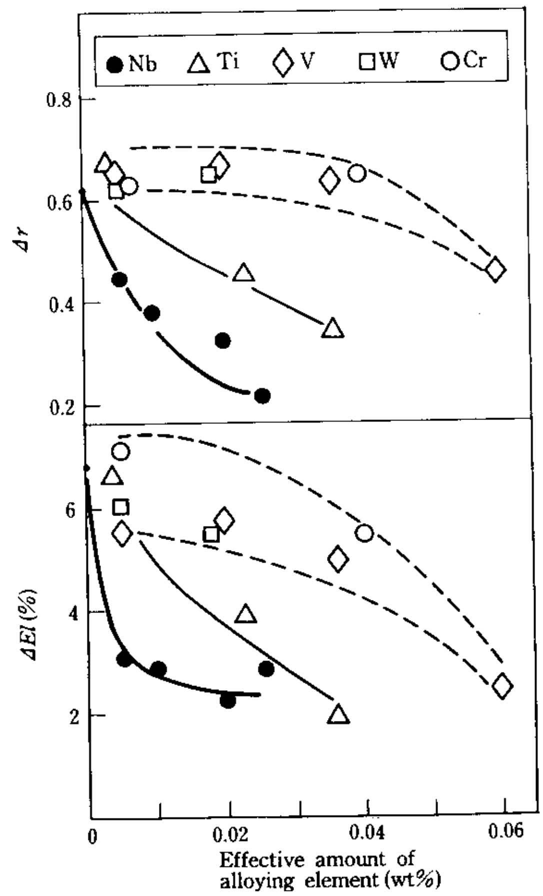


Fig. 4 Effect of alloying elements on planar anisotropy of mechanical properties of cold-rolled and continuous-annealed steel sheets (C = 0.002%)

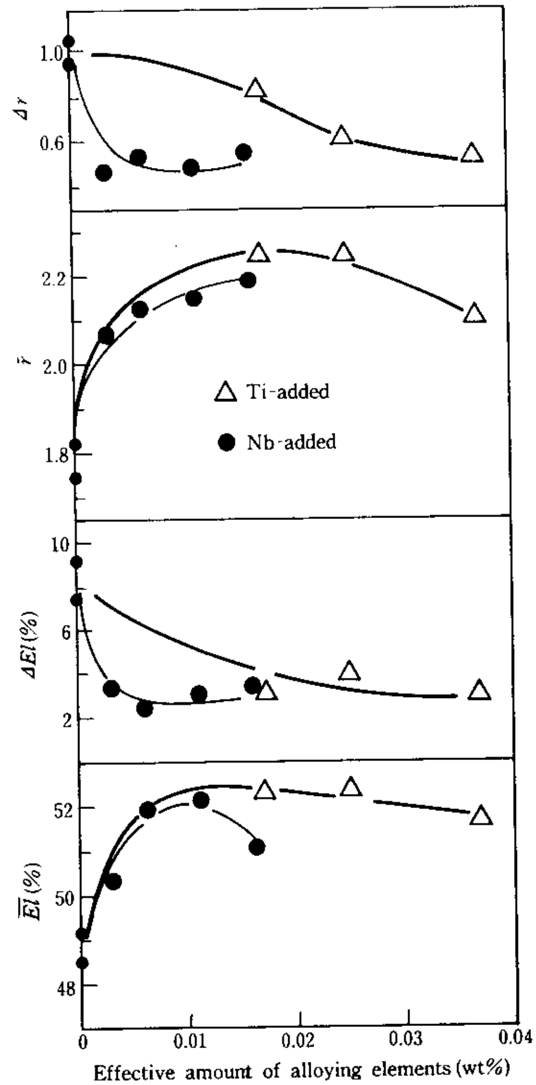


Fig. 5 Effect of Ti and Nb contents on mechanical properties of commercially produced extra-low-carbon steel sheets (C = 0.002%)

with Ti; therefore, the effective amount of Ti (Ti*) was calculated by the following equation:

$$\mathrm{Ti}^*(\%) = \mathrm{Ti}(\%) - \frac{48}{32}\mathrm{S}(\%) - \frac{48}{14}\mathrm{N}(\%) \cdots\cdots (5)$$

In steels to which special alloying elements other than Ti are added, S combines with Mn, and N combines with Al; therefore, the entire amounts of these alloying elements were regarded as effective. Nb and Ti are effective in reducing the planar anisotropy of *El* and *r*-value. The effect of Nb is especially noticeable.

Based on the above-mentioned results, steel sheets were made by way of trial in a mill from steels with a basic composition of 0.002% C-0.02% Si-0.06 to 0.15% Mn-0.01% P-0.01% S-0.03 to 0.06% Al-0.002% N, to which Nb and Ti were added. **Figure 5** shows the mechanical properties of these steel sheets. Hot rolling was conducted at an SRT of 1 220°C, an FDT of 880°C, and a coiling temperature (CT) of 700°C. In extra-low-carbon steels which do not contain Nb or Ti, the planar anisotropy (ΔEl and Δr) of *El* and *r*-value is very large and their means ($\overline{El}$ and $\bar{r}$) are low. In contrast to this, addition of a slight amount of Nb or Ti considerably reduces the planar anisotropy of *El* and *r*-value and increases their means. Nb is more effective than Ti in reducing planar anisotropy and, in Ti-added steels the values of $\overline{El}$ and $\bar{r}$ themselves are superior to those in Nb-added steels.

The planar anisotropy of *r*-value and *El* is closely related to the recrystallization texture of annealed steel sheets.[3,4] The {hk0}⟨001⟩ orientation is known to be a texture which reduces these properties at an angle of about 45° (D, in Fig. 3 above) to the rolling direction. The extra-low-carbon steels without Nb and Ti used in this experiment showed stronger intensity in {110} ⟨001⟩ neighboring orientations than the Nb-added steels and Ti-added steels.[5] The recrystallization texture of cold-rolled and annealed steel sheets is greatly affected by the properties of the hot-rolled mother sheets. **Figure 6** shows the ferrite grain size number and aging index of

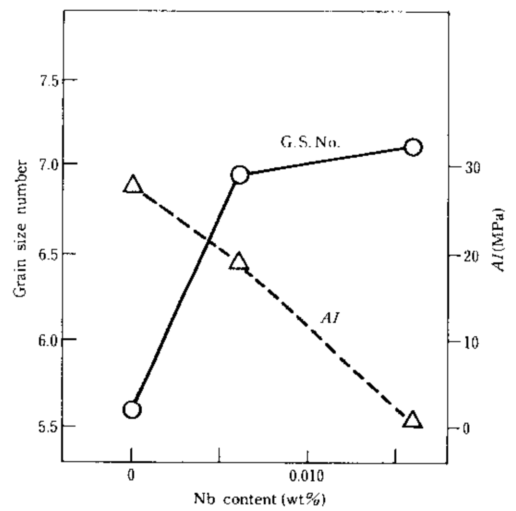


Fig. 6 Grain size number and aging indices of hot bands plotted against Nb content

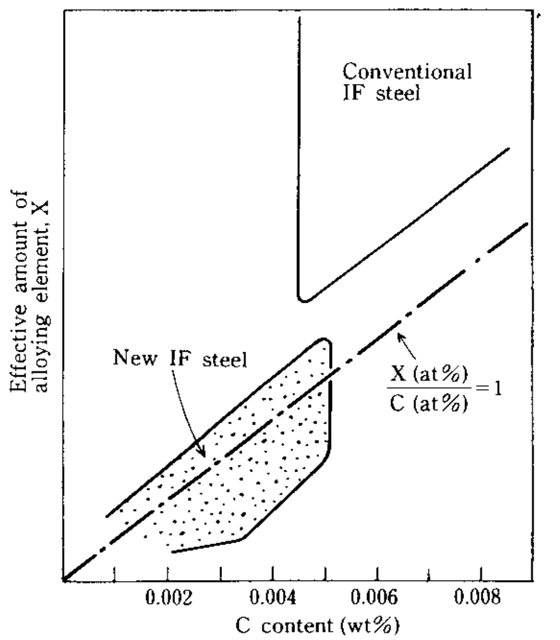


Fig. 7 Situation of a new type interstitial-free steel sheet

hot-rolled steel sheets of the Nb-added steels shown in Fig. 5 (measured by the same method as with annealed steel sheets) as a function of the Nb content.[5] The addition of Nb results in a smaller ferrite grain size and a decrease in the amount of solute C. (N is fixed as AlN because these steel sheets were coiled at a high temperature.) In general, the development of {110}⟨001⟩ neighboring orientations during recrystallization is inhibited when the mother sheets for cold rolling (here hot-rolled steel sheets) are fine-grained and have only low levels of solute C.[6,7] For this reason, the planar anisotropy of *El* and *r*-value of cold-rolled and annealed steel sheets is reduced by addition of Nb or Ti.

Figure 7 schematically shows a comparison between the above-mentioned extra-low-carbon steels to which a trace amount of Nb or Ti is added and the conventional interstitial-free steels (IF steels). Because the C content of conventional IF steels is between 0.005% and 0.010%, it was necessary to add Ti,[8] Nb,[9,10] etc. in amounts which are stoichometrically equivalent to or larger than the C content, or additionally, the N content (in the figure, X(at%)/C(at%) = 1). This is because the mechanical properties deteriorate substantially if these amounts are smaller than the equivalents. In conventional IF steels, high *r*-values can be obtained because C (or N) is fixed as stable carbides (or nitrides) at the hot-rolled stage. However, addition of excessive alloying elements resusits in the deterioration of ductility (especially in Nb-added steels) and has an adverse effect on surface properties. In addition, as a matter of course the manufacturing cost is high.

In contrast, the C content of the above-mentioned extra-low-carbon steels (referred to as new IF steel in Fig. 7) is as low as 0.005% or less; therefore, excellent mechanical properties can be obtained by adding small amounts of Nb and Ti. (X(at%)/C(at%) is near or less than 1.) In extra-low-carbon steels, the amounts of solute C and N are very small even after reheating for the purpose of recrystallization during annealing. Therefore, overaging in the cooling process to improve the anti-aging property is unnecessary.

4 Effects of Hot Rolling Conditions on Mechanical Properties of Extra-Low-Carbon Cold-Rolled Steel Sheets

In addition to cold rolling and annealing conditions, hot rolling conditions are important for the control of the mechanical properties of cold-rolled steel sheets. In particular, the finishing delivery temperature (FDT) and coiling temperature (CT) have heretofore been considered important. In the above-mentioned Nb- or Ti-added extra-low-carbon steels, however, carbonitrides, etc., are formed even in the temperature region of the austenite (γ) phase; therefore, the thermo-mechanical history before the completion of hot rolling also has a great effect on mechanical properties.[11,12]

Figure 8 shows the relationship between the slab-reheating temperature prior to hot rolling and the mechanical properties after cold rolling and annealing of Nb- or Ti-added extra-low-carbon steel sheets.[5] The materials are small vacuum-melted ingots with the same basic composition as in the steel in Fig. 3. Hot rolling (FDT: 880°C), cold rolling (rolling reduction: 79%) and annealing (soaking: 830°C for 40 s) were conducted in the laboratory. Mechanical properties improved to the extent that the slab-reheating temperature was lowered.

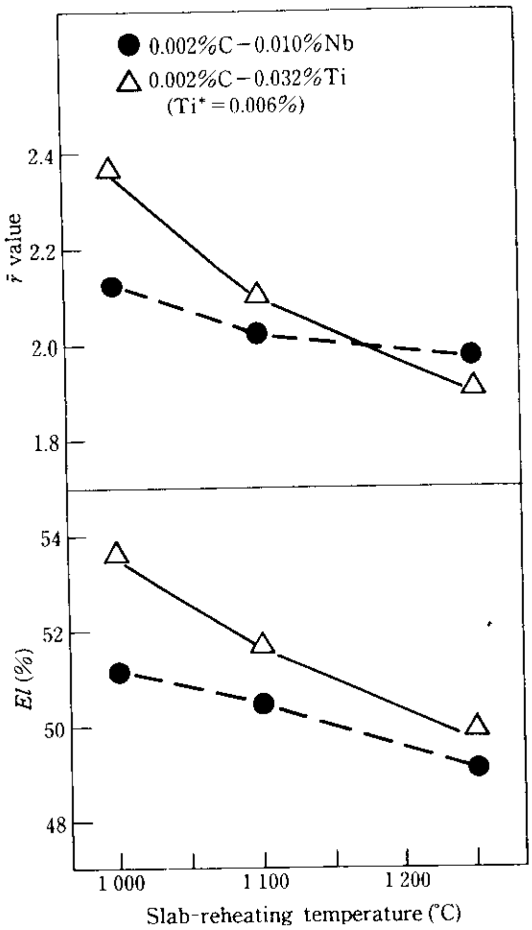


Fig. 8 Effect of slab-reheating temperature on mechanical properties of Ti- and Nb-added extra-low-carbon steel sheets

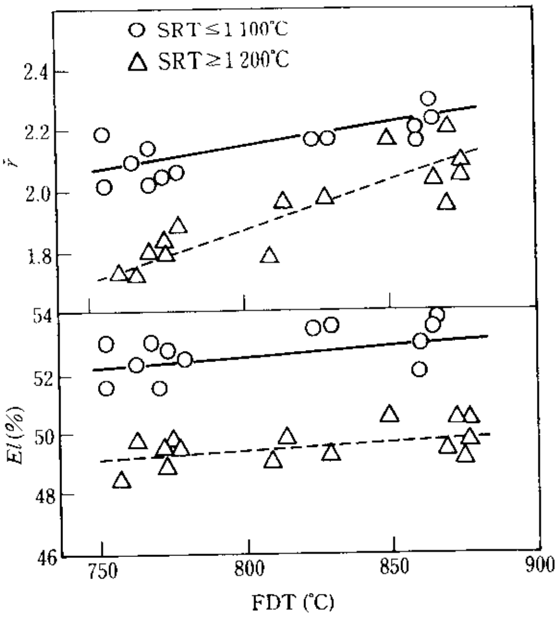


Fig. 9 Influences of slab-reheating temperature (SRT) and finishing delivery temperature (FDT) in hot-rolling process on mechanical properties of commercially produced Ti-added extra-low-carbon steel sheets.

Especially in the extra-low temperature region below 1 100°C, improvement of mechanical properties is noticeable, with this tendency stronger in Ti-added steels than in Nb-added steels.

Figure 9 shows the relationship between mechanical properties and the finishing delivery temperature (FDT) in the hot rolling process for Ti-added extra-low-carbon steel sheets made by way of trial in a mill from Ti-added steels (0.002% C-0.01% Si-0.06% Mn-0.01% P-0.01% S-0.06% Al-0.002% N-0.06% Ti). Two slab reheating temperatures (SRT), about 1 200°C and 1 100 to 1 050°C, were used, and the strip was coiled at low temperatures between 550 and 600°C after hot rolling. After cold rolling (rate of reduction: 75%), continuous annealing without overaging was conducted at a soaking temperature of 820°C. Mechanical properties improved with low-temperature slab-reheating, as was also observed in the laboratory. Particulary noteworthy is the fact that excellent properties can be obtained by low-temperature reheating even when the finishing delivery temperature is lower than the Ar_3 transformation temperature (about 850°C). Furthermore, a comparison with the Ti-added steel sheets coiled at a high temperature (Fig. 5) reveals that mechanical properties equal or superior to those obtained by high-temperature coiling can be obtained by low-temperature slab-reheating and coiling.

Using the laboratory materials shown in Fig. 8, amounts of precipitates in steel sheets reheated to 1 000 and 1 250°C were investigated. **Figure 10** shows these amounts relative to those obtained after hot rolling.[5] When low-temperature reheating is conducted, the amounts of AlN and MnS precipitates in Nb-added steel sheets increase, whereas NbC is not detected. On the other hand, the amounts of Ti(C, N) and TiS precipitates in Ti-added steel sheets reheated to low temperatures are almost equal to those in hot-rolled sheets. This means that these precipitates exist in almost their entire final quantities before hot rolling.

Photo 1 shows a typical example of precipitates in a Ti-added extra-low-carbon hot-rolled sheet. These were examined using the electron diffraction technique and diverse X-ray spectroscopy. The precipitate in Photo 1(a) was identified as Ti(C, N), and that in Photo 1(b) as TiS. It is not certain whether these precipitates existed before reheating or were formed by low-temperature reheating. A comparison with the precipitates in Nb-added steel sheets reveals that the precipitates in Ti-added steel sheets are coarser in size and are more sparsely distributed. Generally, in the recrystallization annealing process and especially during continuous annealing

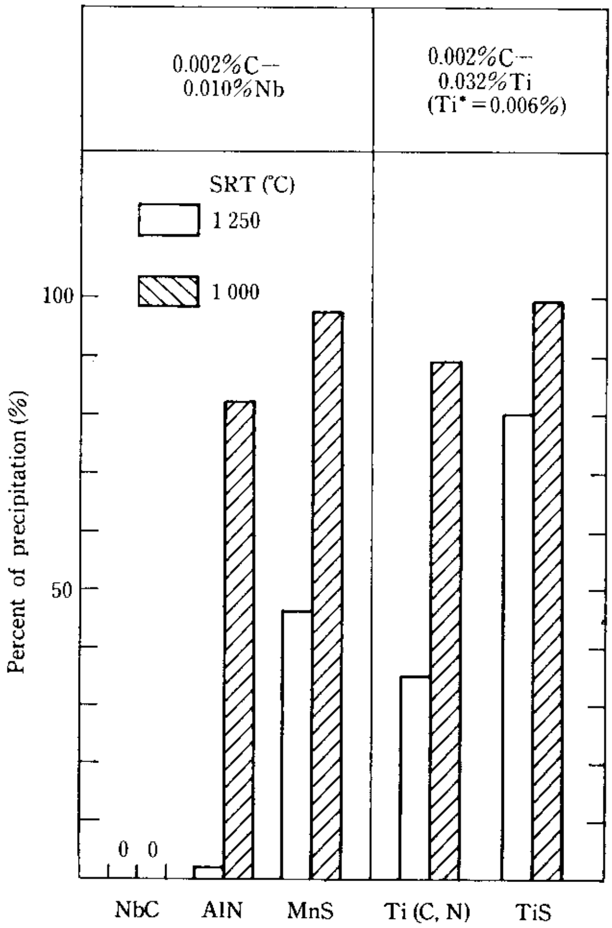


Fig. 10 Percentage of precipitation in reheated and water-quenched sheets to that in hot-rolled sheets (SRT: Slab-reheating temperature)

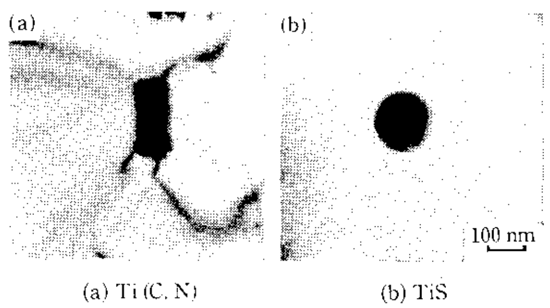


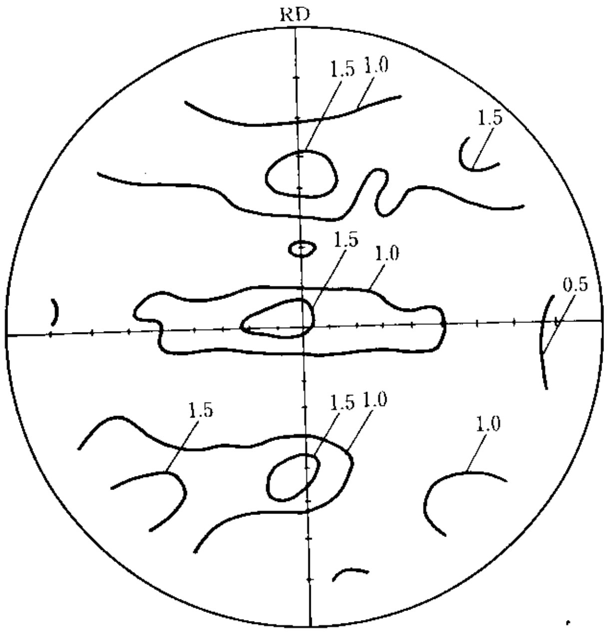
Photo 1 Transmission electron micrographs showing the morphology of precipitates in a Ti-added extra-low-carbon hot band

with rapid heating, coarse precipitates are advantageous in terms of mechanical properties, facilitating rapid grain growth. Because carbonitrides and sulfides precipitate in a higher temperature region in Ti-added steels than in Nb-added steels, these precipitates can be made coarse by low-temperature reheating. This seems to be the reason that the effect of low-temperature reheating is great in Ti-added steels.

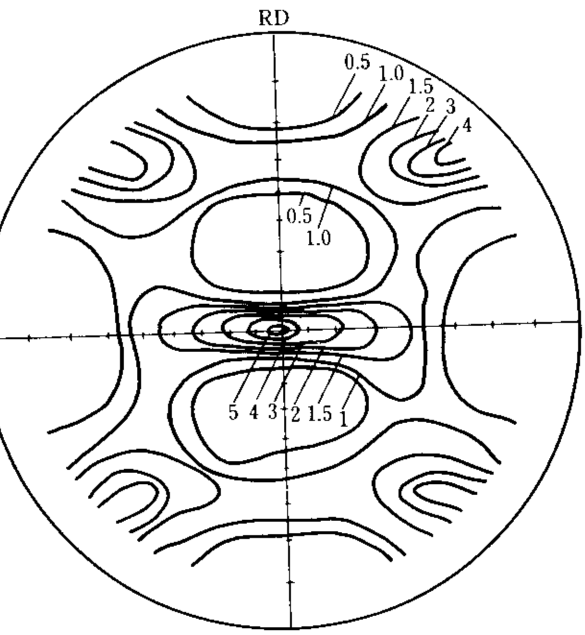
The relationship between low-temperature hot rolling (FDT < Ar_3) and deep-drawability will now be discussed. To produce cold-rolled steel sheets excellent in deep-drawability (high r-values), the general practice has been to finish hot rolling at temperatures above the Ar_3 transformation temperature. This is because a marked $\{100\}\langle 011\rangle$ texture is formed on the $^1/_2$ thickness portion of the hot-rolled strip when working is conducted in the α-phase below the Ar_3 point. This $\{100\}\langle 011\rangle$ texture cause deterioration of deep-drawability after cold-rolling and recrystallization.

Figure 11 shows (200) pole figures on the $^1/_2$ thickness portion of hot-rolled steel sheets with finishing delivery temperatures above and below the Ar_3 transformation temperature shown in Fig. 9. The marked $\{100\}\langle 011\rangle$ texture is not observed in steel sheets hot rolled at high finishing delivery temperatures. In contrast, a marked $\{100\}\langle 011\rangle$ texture is formed in hot-rolled sheets when hot rolling is completed below the Ar_3 point, and it is not essentially different from the texture so far reported in low-carbon steels. The textures of hot-rolled sheets shown in Fig. 11 scarcely changed by changes in slab-reheating temperature. The foregoing suggests that change in the texture of hot-rolled steel sheets is not the reason that high r-values can be obtained even in steel sheets rolled at a low finishing delivery temperature (<Ar_3) with extra-low-carbon steel reheated to low temperatures. In other words, even if low-temperature reheating is conducted, when low-temperature hot-rolling is employed, the texture of hot-rolled steel sheets will have an orientation unfavorable to good r-values in cold-rolled and annealed steel sheets. At present, this phenomenon is thought to result from a change in the distribution of precipitates in hot-rolled steel sheets resulting from low-temperature reheating. However, clarification of the mechanism is a problem awaiting solution.

Figure 12 shows schematically the thermo-mechanical history of this new process from continuous casting to coiling after hot rolling when the above-mentioned extra-low-carbon steels are used as material. The conventional process, in which continuous casting is conducted using low-carbon Al-killed steels as the material, is included in the figure for comparison. The energy-saving effect and a yield increase due to low-temperature reheating are clear; these are very advantageous for continuous casting-hot charge rolling and continuous casting-hot direct rolling (CC-DR). The slab is hot rolled after being reheated to a low temperature. Low finishing delivery temperatures below the Ar_3 transformation point are sufficient and low coiling temperatures below 600°C are also acceptable. The rate of pickling improves because this low-temperature rolling and low-temperature coiling reduce the amount of scale formed on hot-rolled steel strips. In general, the lower the temperature,



(a) SRT1 050°C, FDT880°C, CT550°C



(b) SRT1 050°C, FDT770°C, CT550°C

Fig. 11 (200) pole figures showing the effect of finishing delivery temperature (FDT) in hot-rolling process on textures of hot bands in a Ti-added extra-low-carbon steel

the larger the flow stress in hot rolling. When a comparison of the flow stress is made between the γ-phase and α-phae at the same temperature, it is found that the α-phase shows a lower flow stress and that the increase in flow stress due to low-temperature hot rolling is relatively small.

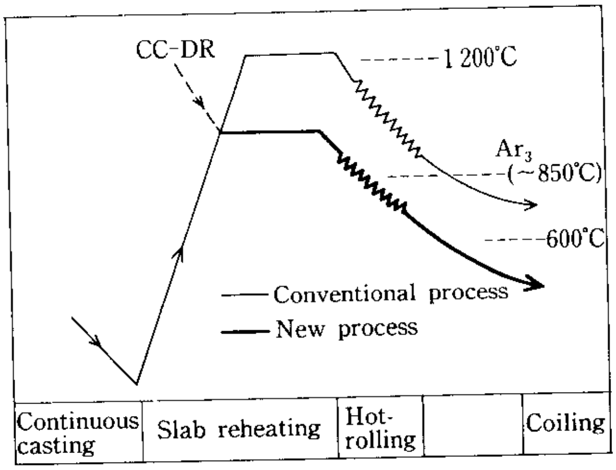


Fig. 12 Schematic illustration of thermo-mechanical history in a new process

5 Conclusions

A new process for deep-drawing cold-rolled steel sheets using extra-low-carbon steels was described, especially in its metallurgical aspect. The main points can be summarized as follows:

(1) The anti-aging property can be obtained by continuous annealing without overaging at C contents of 0.002% or less. However, the mechanical properties do not improve markedly because the planar anisotropy of these properties is large.

(2) The addition of a small amount of Nb or Ti is effective in reducing this planar anisotropy and allowing excellent properties to be obtained. Steels of this type are new, and differ from conventional interstitial-free steels.

(3) In steels of this type, the lower the slab-reheating temperature, the better the mechanical properties. This tendency is especially noticeable in Ti-added steels, in which excellent properties can be obtained even at finishing delivery temperatures below the Ar_3 transformation point and at low coiling temperatures.

(4) When the above-mentioned new extra-low-carbon steels are used as material, deep-drawing cold-rolled steel sheets can be produced by a new process comprising low-temperature reheating, low-temperature hot rolling, low-temperature coiling, and continuous annealing without overaging.

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