KAWASAKI STEEL TECHNICAL REPORT
No.9 (March 1984)

Controlling of Microstructure and Mechanical Properties Utilizing Deformation Resistance in Plate Rolling

Yoshiyuki Saito, Motomu Kimura, Michihiro Tanaka, Toshihiro Sekine, Kazuya Tsubota, Tomoo Tanaka

Synopsis :
Production scale rolling experiments were conducted in order to formulate the effect of rolling conditions on microstructure during rolling. On the basis of the experimental results the relation between microstructure and deformation resistance was obtained. The results are summarized as follows: (1) Grain size variation of austenite and kinetics of Nb (C,N) precipitation can be expressed by simple mathematical equations. These two factors are closely related to deformation resistance. (2) Strain accumulation in the low temperature austenite region and the austenite-to-ferrite transformation kinetics are estimated by deformation resistance. (3) Both ferrite grain refinement and ferrite strengthening parameters are closely related to tensile and impact properties of steels. The former parameter is determined by recrystallized austenite grain size and strain accumulated prior to transformation, and the latter by the sum of the product of fractional transformation and strain given at each rolling pass. The proper control of these two parameters makes the control of mechanical properties practicable.

The body can be viewed from the next page.

Controlling of Microstructure and Mechanical Properties Utilizing Deformation Resistance in Plate Rolling*

Yoshiyuki SAITO ** Motomu KIMURA ** Michihiro TANAKA **
Toshihiro SEKINE *** Kazuya TSUBOTA *** Tomoo TANAKA **

Production scale rolling experiments were conducted in order to formulate the effect of rolling conditions on microstructure during rolling. On the basis of the experimental results the relation between microstructure and deformation resistance was obtained. The results are summarized as follows:

(1) Grain size variation of austenite and kinetics of Nb(C,N) precipitation can be expressed by simple mathematical equations. These two factors are closely related to deformation resistance.

(2) Strain accumulation in the low temperature austenite region and the austenite-to-ferrite transformation kinetics are estimated by deformation resistance.

(3) Both ferrite grain refinement and ferrite strengthening parameters are closely related to tensile and impact properties of steels. The former parameter is determined by recrystallized austenite grain size and strain accumulated prior to transformation, and the latter by the sum of the product of fractional transformation and strain given at each rolling pass. The proper control of these two parameters makes the control of mechanical properties practicable.

1 Introduction

Spurred by the production of high-strength steel plates for large-diameter line pipe in the latter half of the 1960's, controlled rolling, one of the methods for controlling the mechanical properties utilizing microstructural changes during rolling, has made rapid progress and now occupies an important position in the field of thermomechanical treatment[1]. Although deformation resistance is used in hot rolling for controlling the gage and shape of products by predicting the rolling load, it is essentially a characteristic value of a steel by which microstructural changes associated with hot deformation is reflected. Therefore, it is necessary from the standpoint of microstructure control that the microstructure during deformation be correctly correlated with deformation resistance.

Principal microstructural changes during rolling are as follows:

(1) Grain refinement and grain growth by the recrystallization in the high temperature austenite region.
(2) Strain-induced precipitation of carbonitrides of microalloying elements such as Nb.
(3) Strain accumulation in the low temperature austenite region.
(4) Austenite–ferrite transformation.

Effects of these microstructure factors on deformation resistance have already been made clear by laboratory measurements using a hot deformation simulator[2,3]. However, scarcely any reports have so far been made on the relationship between microstructural changes and deformation resistance in practical rolling. Therefore, the authors have conducted a production-scale rolling experiment using the rolling mill in the No. 2 plate mill at Kawasaki Steel's Mizushima Works, analyzed rolling data, estimated microstructural changes during rolling by using a simple mathematical model, and attempted to correlate the microstructure during rolling with deformation resistance based on the knowledge obtained in the laboratory. Furthermore, they have examined the possibility of prediction of the mechanical properties utilizing

* Originally Published in *Kawasaki Steel Giho*, **15** (1983) 4, pp. 241–248
** Research Laboratories
*** Mizushima Works

deformation resistance from results of the production-scale rolling experiment.

2 Experimental Method

The experiment was conducted on continuously cast slabs of the chemical composition shown in **Table 1**. The Nb steel is a steel obtained by adding Nb to a steel of almost the same chemical composition as of the Si-Mn steel. Attention was paid to the effects of rolling conditions on the austenite grain size, strain accumulated, precipitates and kinetics of phase transformation during rolling, and 25 mm thick plates were produced from 240 mm thick slabs by varying the slab-reheating temperature, reduction per pass, rolling temperature range and finish rolling temperature. Especially in an experiment to investigate the effect of Nb on the microstructure and deformation resistance under the same deformation conditions, the composite slab shown in **Fig. 1** was used which was produced by welding an Nb steel slab section and an Si-Mn steel slab section placed in the rolling direction.

The entry and exit thicknesses, rolling load, motor speed and surface temperature during rolling were measured, and the mean deformation resistance, work strain by rolling, strain rate and average rolling temperature were determined by data processing. **Figure 2** shows an example of measurement of the rolling load of the composite slab. It is possible to clearly distinguish between the rolling load of the Nb steel and that of the Si-Mn steel and therefore, it is possible to clarify the effect of Nb on microstructural changes.

Furthermore, variations of austenite grain size, kinetics of strain-induced precipitation of Nb (C, N), strain accumulation inside austenite grains and austenite–ferrite transformation behavior were estimated from rolling data by using a simple mathematical mode land were correlated to deformation resistance.

Table 1 Chemical composition of steels (wt %)

Steel	C	Si	Mn	P	S	Nb	Al
Nb	0.14	0.40	1.45	0.018	0.005	0.035	0.045
Si-Mn	0.14	0.36	1.40	0.022	0.006	—	0.034

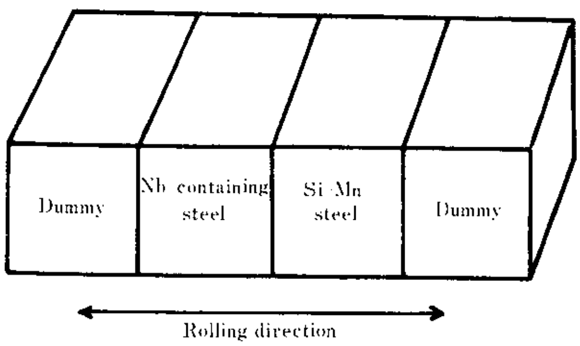


Fig. 1 Schematic illustration of composite slab

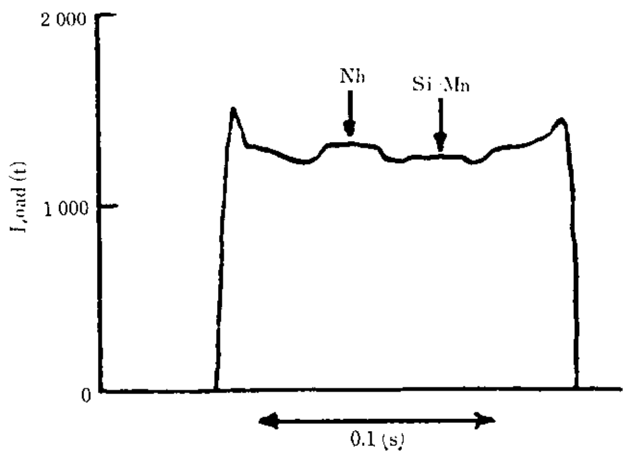


Fig. 2 An example of roll force for composite slab

After these rolling experiments, the microstructure of plates air-cooled to room temperature was examined under optical and electron microscopes, and the tensile test (JIS No. 4 test piece) and impact test (JIS No. 4 test piece) were conducted to investigate the mechanical properties.

3 Experiment Results and Discussion

Figure 3 shows an example of changes in the mean deformation resistance, k_m, strain and temperature in each pass of the rolling experiment on the composite slab. In the high-temperature range rolling after reheating to 1 150°C, the difference in k_m between the

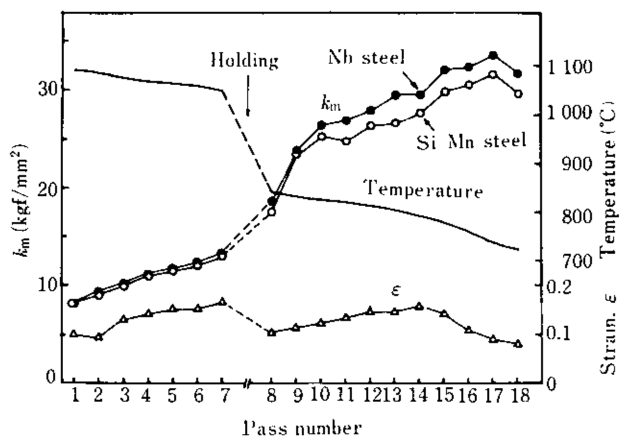


Fig. 3 Variations of mean deformation resistance, k_m, temperature and strain, ϵ, for composite slab during rolling

Nb and Si-Mn steels is small and the k_m of the Nb steel is only about 4% higher than that of the Si-Mn steel regardless of the rolling pass (temperature). It seems that strain has completely recovered between passes, because the difference in k_m between the two steel grades in this high temperature range can be explained by the solid-solution hardening of Nb[3], the strain-induced precipitation of Nb (C, N) carbonitrides does not seem to occur, as will be described later, and the rate of strain recovery is high in this temperature range[2,3]. This suggests that only the grain refinement by recrystallization needs to be considered as a microstructural change in the deformation in the low-temperature austenite region.

In contrast to this, the difference in k_m between the Nb steel and Si-Mn steel increases with increasing k_m in the deformation in the low-temperature austenite region after the holding for temperature control during rolling. This seems to be attributable to the effect of nonrecovery of strain between passes in the Si-Mn steel and the effect of strain-induced precipitation in the Nb steel. The effect of a surface temperature decrease to the austenite–ferrite dual phase region is observed in the decrease in k_m in the final pass.

An investigation is made into the relationship between changes in the above-mentioned microstructure factors and deformation resistance in the following.

3.1 Grain Refinement in High-Temperature Austenite Region

Sellars and Whiteman[4] proposed an empirical formula for estimating the austenite grain size after static recrystallization, and showed that the recrystallized austenite grain size, d_γ, can be approximated by the following equation:

$$d_\gamma = A''\cdot\epsilon^{-1}\cdot d_0^{1/2}\left[\frac{1}{B}\ln(Z/A)\right]^{-2/3} \cdots\cdots (1)$$

d_0: Initial austenite grain size
Z: Zener-Hollomon parameter[1]
ϵ: Strain
A, A'', B: Constants

Z is a function of temperature and strain rate, and if the grain size upon reheating is denoted by d_0, all the parameters in eq. (1) take known values and it is possible to calculate the d_γ in the first pass. Therefore, the grain size in multi-pass rolling can be estimated by repeating the procedure in which the d_0 in the next pass is calculated in consideration of grain growth and eq. (1) is used again[5].

As to the relationship between deformation resistance and grain size, the following has been made clear by laboratory studies using a hot deformation simulator[2,3]. That is to say, austenite grain refinement increases deformation resistance and a linear relationship is obtained by plotting the austenite grain size and deformation resistance on log-log graph paper. To quantitatively explain the relationship between the grain refinement and deformation resistance during rolling based on these experiment results, a parameter called the standard deformation resistance, k_m^c, is used. k_m^c is a calculated value of deformation resistance in a case where the austenite grain size corresponds to 150 μm. This is the deformation resistance obtained under the same deformation conditions as the rolling conditions in question by using a mathematical model on the basis of the hot deformation experiment, and the value is corrected with respect to the through-thickness temperature distribution. The effect of the grain size is reflected in the ratio of the mean deformation resistance, k_m, calculated from the rolling load to k_m^c; namely, k_m/k_m^c. Attention is paid to changes in this value.

Variations in austenite grain size in Si-Mn steels reheated to 1 150° and 1 250°C were simulated by using eq. (1). Simulation results, along with variations in the above-mentioned k_m/k_m^c, are shown in **Fig. 4**. Recrys-

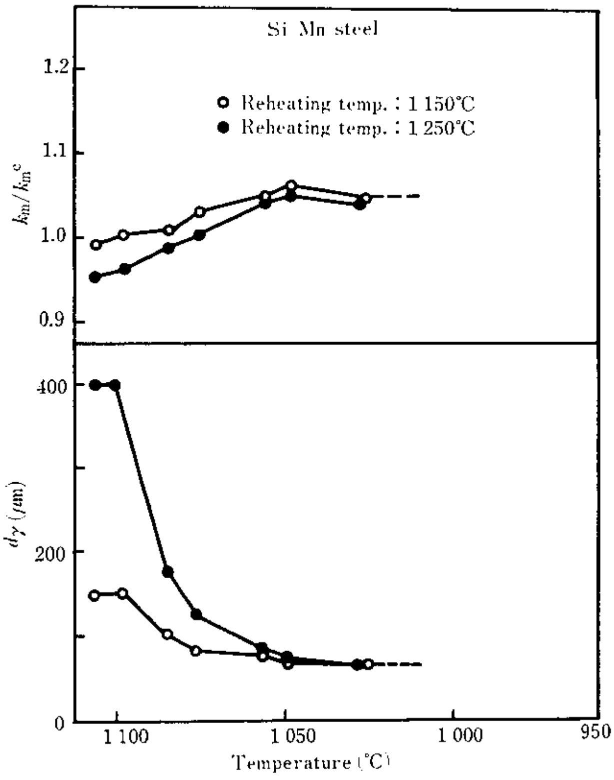


Fig. 4 Variations of austenite grain size, d_γ, and deformation resistance ratio, k_m/k_m^c, during rolling

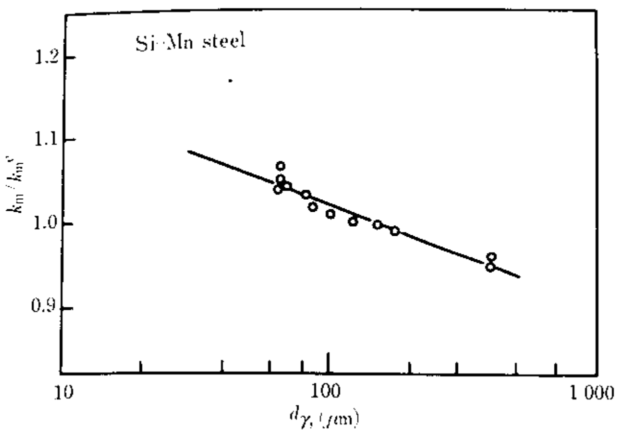


Fig. 5 Relation between deformation resistance ratio, k_m/k_m^c, and austenite grain size, d_γ, of Si-Mn steel

tallization results in grain refinement and the value of k_m/k_m^c increases. In the steel heated to 1 250°C, the austenite grain size of 400 μm upon reheating is refined and becomes finally about 65 μm, reaching the same level as the steel heated to 1 150°C. Also the value of k_m/k_m^c is as low as 0.95 after the first pass, but it is 1.04 after the sixth pass, the same level as the steel heated to 1 150°C.

Figure 5 shows the relationship between the austenite grain size and k_m/k_m^c of the Si-Mn steels. There is a close relation between k_m/k_m^c and austenite grain size and this result agrees with the result of the experiment using the hot deformation simulator[2,3]. Therefore, the austenite grain size can be estimated from variations in deformation resistance if the rolling load and surface temperature can be accurately measured and deformation resistance can be accurately predicted.

3.2 Strain-induced Precipitation of Nb Carbonitrides

In Nb steels, fine Nb (C, N) precipitates are formed during rolling; these precipitates play an important role in the retardation of recrystallization. The Becker-Döring classical nucleation theory[6] was used to describe the precipitation process of Nb (C, N) during rolling by a simple mathematical model.

The rate of nucleation per unit volume, J, can be described by the following equation:

$$J = N \cdot \beta^* \cdot Z \cdot \exp(\Delta G^*/kT)\exp(-\tau/t) \quad \cdots (2)$$

N: Number of nucleation sites per unit volume

β^*: Number of atoms reaching the critical nucleus surface per unit time

Z: Zeldvitch factor

ΔG^*: Gibbs free energy upon forming the critical nucleus

τ: Incubation period for steady-state nucleation

k: Boltzmann constant

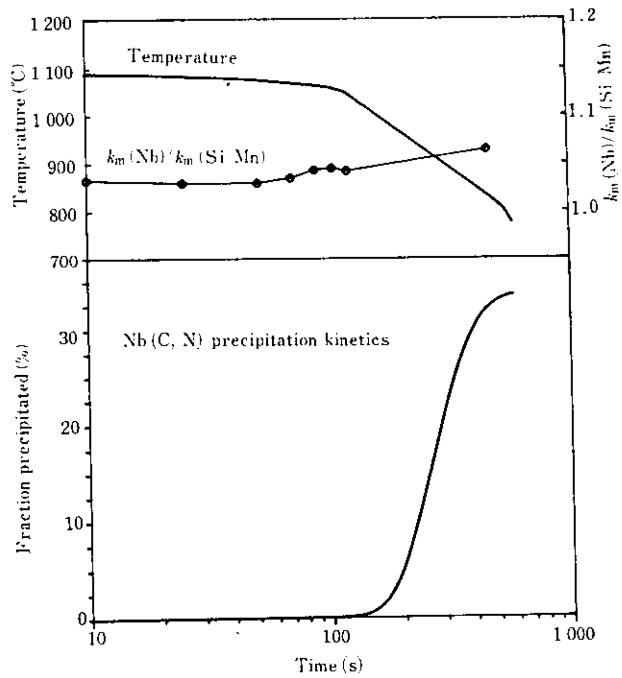
T: Temperature

t: Time

The parameters contained in eq. **(2)**, β^*, Z, ΔG^* and τ are functions of the surface energy of precipitates, σ, and the diffusion coefficient of Nb in austenite, D. In addition to σ and D, the number of nucleation sites, N, is an unknown parameter. By varying these three parameters, the precipitation process changes greatly in the above-mentioned model. The values of N, σ and D were determined so that the best agreement with the reported experiment result[7] could be obtained[8]. Furthermore, to express the strain-induced precipitation process by a formula, the effect of deformation was incorporated in the above-mentioned three parameters, N, σ and D. A model of the growth of precipitates was developed in consideration of an interface-controlled reaction for the initial period of precipitation and a diffusion-controlled reaction for the latter period.

The precipitation process of Nb (C, N) in the Nb steel was simulated by using the above-mentioned model in composite slab rolling after reheating to 1 250°C. **Figure 6** shows changes in the amount of Nb (C, N) precipitates during rolling together with the surface temperature and the deformation resistance ratio of the Nb steel and Si-Mn steel. In the deformation in the high-temperature austenite region, Nb (C, N) scarcely precipitates and precipitation proceeds abruptly during the interruption for waiting for a temperature decrease. Also the deformation resistance ratio is almost constant at about 1.03 in the high-temperature austenite region. In the pass after the interruption, however, this ratio increases to 1.06, showing the effect of the progress of precipitation during the interruption. This reveals that an increase in the amount of precipitates leads to an increase in deformation resistance.

Based on an experiment using a hot deformation simulator, the authors have already reported that the contribution of Nb (C, N) precipitates formed by strain-induced precipitation to deformation resistance is about three times as great as that of the Nb in solution[3]. Almost the same result was also obtained in this experiment and it was confirmed that a change in the precipitation process is closely related to deformation resistance.



k_m (Nb) : Deformation resistance for Nb steel
k_m (Si-Mn) : Deformation resistance for Si-Mn steel

Fig. 6 Effect of Nb (C,N) precipitation kinetics estimated by computer simulation on deformation resistance ratio, k_m (Nb)/k_m (Si-Mn)

3.3 Strain Accumulation in Low-Temperature Austenite Region and Its Effect on Ferrite Grain Size

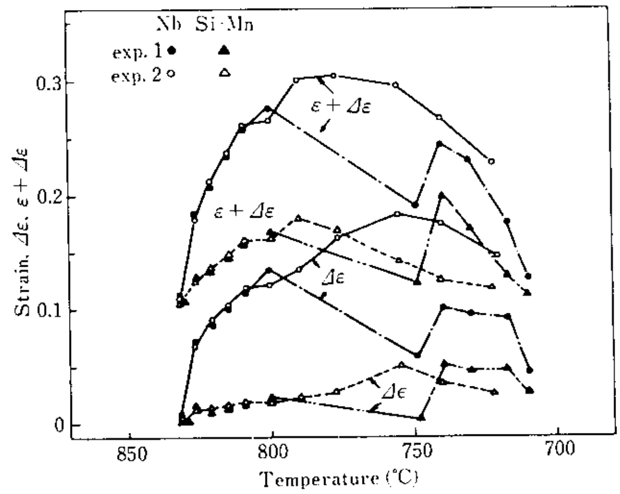
In the rolling in the low-temperature austenite region, strain accumulates within grains and as a result, deformation resistance increases. The strain accumulated in each pass during rolling, $\Delta\epsilon$, is calculated as a function of the observed mean deformation resistance, $k_m^{(obs)}$, and the strain, ϵ, of the pass in question by the following equation:

$$\Delta\epsilon = [(k_m^{(obs)}/k_m^{(o)})^{1/n} - 1]\cdot\epsilon \quad \cdots\cdots\cdots\cdots(3)$$

$k_m^{(o)}$: Calculated value of deformation resistance for which the effect of strain accumulation is neglected

n: Strain hardening coefficient

The strain accumulated in the low-temperature austenite region was calculated by using eq. **(3)**. Two sets of composite slab were rolled in different non-recrystallization regions. **Figure** 7 shows changes in strain accumulated during rolling, $\Delta\epsilon$, and effective strain, $\epsilon + \Delta\epsilon$. In the Nb steel, $\Delta\epsilon$ increases abruptly with decreasing rolling temperature, whereas this increase is moderate in the Si-Mn steel. A comparison is made between the two kinds of rolling conditions for these



exp. 1 : By rolling schedule with interruption prior to transformation
exp. 2 : By continuous rolling schedule

Fig. 7 Variation of strain accumulated, $\Delta\epsilon$, and effective strain, $\epsilon + \Delta\epsilon$, during rolling

steels. Since the rolling conditions are the same at temperatures above 800°C, the strain accumulation behavior is naturally almost the same. However, the value of $\Delta\epsilon$ varies greatly depending on whether rolling is carried out again after an interruption (experiment 1) or is continued without interruption (experiment 2). At temperatures below 740°C, the value of $\Delta\epsilon$ tends to decrease with decreasing temperature. This seems to be due to austenite-ferrite deformation.

As will be described later, the strain accumulated just before phase transformation, $\Delta\epsilon_t$, has a great effect on austenite-ferrite deformation and is an important factor when the control of the ferrite grain size is considered. To know $\Delta\epsilon_t$, it is necessary to know the austenite-ferrite transformation temperature, Ar_3, first. Ar_3 is estimated here by an indirect method[9] utilizing the Fourier equation of heat conduction. As transformation proceeds, thermal constants such as specific heat and thermal conductivity change discontinuously and latent heat is generated. If these changes in thermal constants are ignored in temperature calculation, the surface temperature difference between the calculated temperature, T_c, and the observed temperature, T_o, increases with decreasing temperature below a certain level, as shown in **Fig. 8**. This is because latent heat is ignored. The temperature at which the curve showing the value of T_c-T_o deviates from zero is denoted by Ar_3.

Figure 9 shows schematically how to estimate the strain accumulated just before phase transformation, $\Delta\epsilon_t$, using the above-mentioned results. It is supposed that transformation occurs during the rolling between

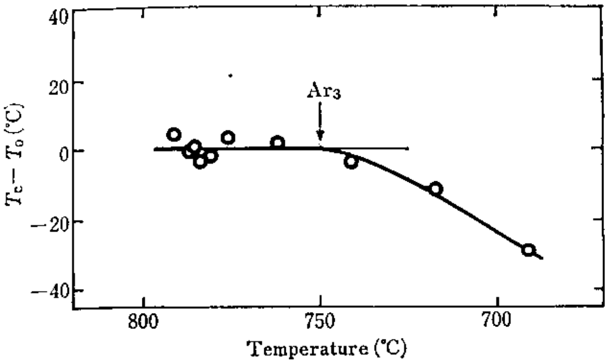


Fig. 8 Austenite to ferrite transformation temperature, Ar_3, estimated by disagreement between observed T_o and calculated T_c temperatures of steel surface

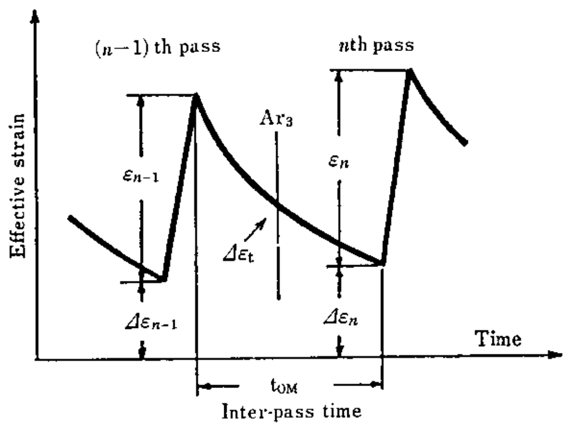


Fig. 9 Schematic illustration of estimating strain, $\Delta\epsilon_t$, accumulated prior to transformation

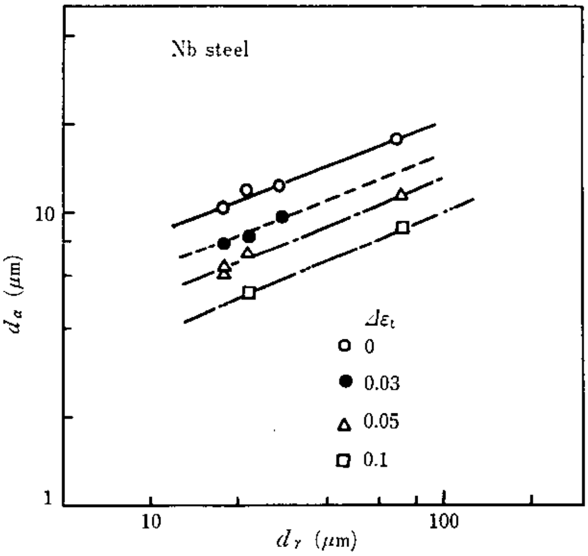


Fig. 10 Effect of recrystallized austenite grain size, d_γ, and strain, $\Delta\epsilon_t$, accumulated prior to transformation on ferrite grain size, d_α of Nb steel cooled at 0.2°C/s

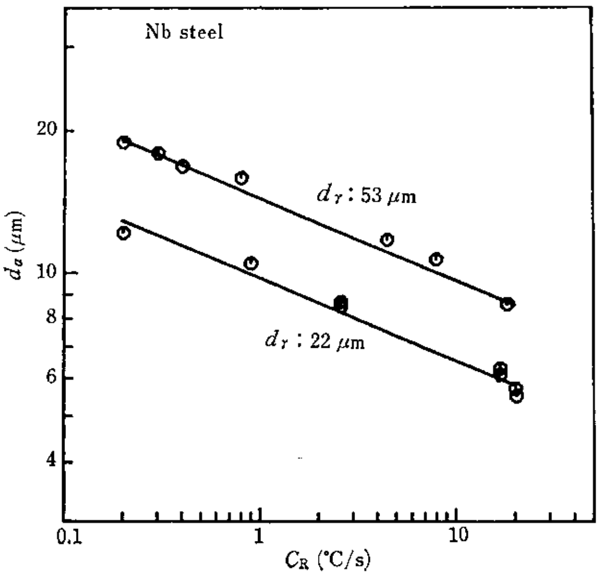


Fig. 11 Effect of cooling rate, C_R, on ferrite grain size, d_α, of steel transformed from recrystallized austenite where $\Delta\epsilon_t$ is zero

the $(n - 1)$th pass and nth pass. The curve showing the kinetics of strain recovery, $f(T, t, \epsilon_P)$, can be described as a function of temperature, T, interruption time, t, and prestrain, ϵ_P, by the following equation:

$$f(T, t, \epsilon_P) = \frac{C_2 \cdot \epsilon_P}{(C_1\epsilon_P + C_2)\exp[C_2 \cdot t \cdot \exp(-Q/T)] - C_1\epsilon_P} \quad \cdots (4)$$

where, C_1, C_2 and Q are constants. T and ϵ_P are known, and if Ar_3 is known, the time to transformation, t, can be determined and $\Delta\epsilon_t$ can be calculated by using eq. **(4)**.

There is a close relationship between the strain accumulated just before transformation, $\Delta\epsilon_t$, and the ferrite grain size. In **Fig. 10**, the effect of recrystallized austenite grain size, d_γ, on the ferrite grain size, d_α, at a cooling rate of 0.2°C/s is plotted against an arbitrary $\Delta\epsilon_t$. When d_γ is the same, the larger $\Delta\epsilon_t$, the smaller d_α.

Figure 11 shows the effect of the cooling rate, C_R, on d_α for d_γ of 22 μm and 53 μm. In this experiment, $\Delta\epsilon_t$ is zero and this shows transformation from completely recrystallized austenite. In a case where d_γ is the same, d_α becomes approximately 2/3 when C_R becomes tenfold.

From the experiment data, the effects of the recrystallized austenite grain size, d_γ, cooling rate, C_R, and strain accumulated just before phase transformation,

$\Delta\epsilon_t$, on the ferrite grain size, d_α, is given by the following equation:

$$\ln d_\alpha = 0.92 + 0.44 \ln d_\gamma - 0.17 \ln C_R - 0.88 \tanh(10 \cdot \Delta\epsilon_t) \quad \cdots\cdots\cdots\cdots (5)$$

The curved surface in **Fig. 12** shows results of calculation of the effects of d_α and $\Delta\epsilon_t$ on d_α at C_R of 0.2°C/s from eq. **(5)**. The straight line parallel to Z-axis (d_α) shows observed values used for forming eq. **(5)**.

Thus it is possible to measure the recrystallized grain size by the method described in Paragraph 3.1, calculate the strain accumulated just before phase transformation based on the above-mentioned method, and estimate the ferrite grain size from eq. **(5)**. Since it is possible to know the austenite grain size and strain accumulated in each pass from changes in deformation resistance, it is also possible to obtain such a ferrite grain size as may be necessary for meeting the mechanical properties of steels, by checking deviations from targets and modifying rolling schedules as required.

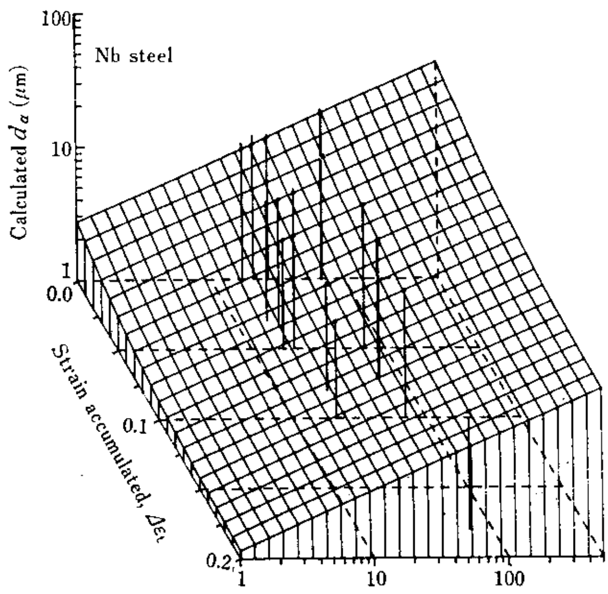


Fig. 12 Calculated ferrite grain size, d_α, compared with observed ones of Nb steel

3.4 Mechanism of Austenite-Ferrite Transformation

The purpose of rolling in the austenite-ferrite dual-phase region is to increase strength by strengthening ferrite grains. This is accomplished by the deformation of transformed ferrite grains and formation of substructures within grains. It is necessary for the quantification of the effect of rolling in the dual-phase region to know the fractional transformation in each pass and the amount of strain accumulated in ferrite.

The fractional transformation, R, depends on chemical composition, rolling condition, cooling rate, etc. However, since it is difficult to express R by a simple equation, R is estimated by an indirect method using deformation resistance.

To investigate the relationship between the deformation resistance and fractional transformation in the dual-phase region, an experiment was conducted by using a hot deformation simulator[10]. The Si-Mn steel was heated to 950°C, cooled to 750°C and isothermally held at this temperature. The kinetics of transformation during the isothermal holding was measured from variations in thermal expansion, and flow stresses were measured by deformation. **Figure 13** shows a plot of these relations. In this figure, flow stress decreases with increasing fractional transformation. From this, it is found that the deformation resistance in the dual-phase region can be described by the mixed law of deformation resistance of austenite and ferrite. In the dual-phase region, there is strain recovery associated with austenite-ferrite deformation in addition to a reduction in dislocation density caused by the recovery in austenite and ferrite grains[10]. Therefore, a term expressing the strain recovery associated with transformation is added to the conventional formula describing the strain recovery process[9], and the kinetics of recovery in the dual-phase region is estimated from the modified formula.

Figure 14 shows a flow for estimating the fractional

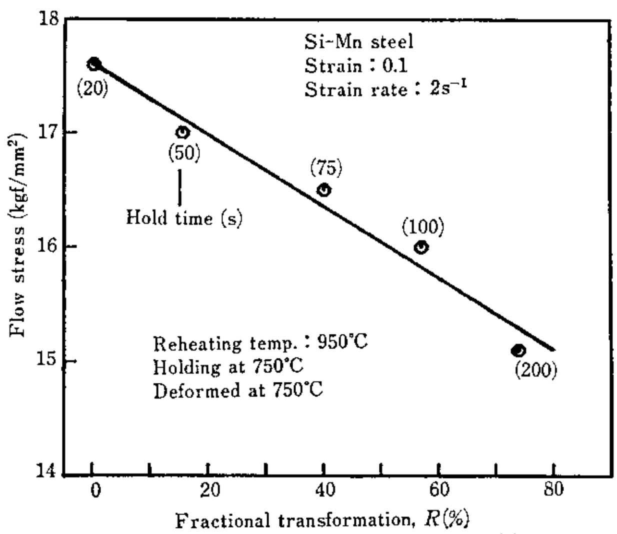


Fig. 13 Variation of flow stress of Si-Mn steel with fractional transformation

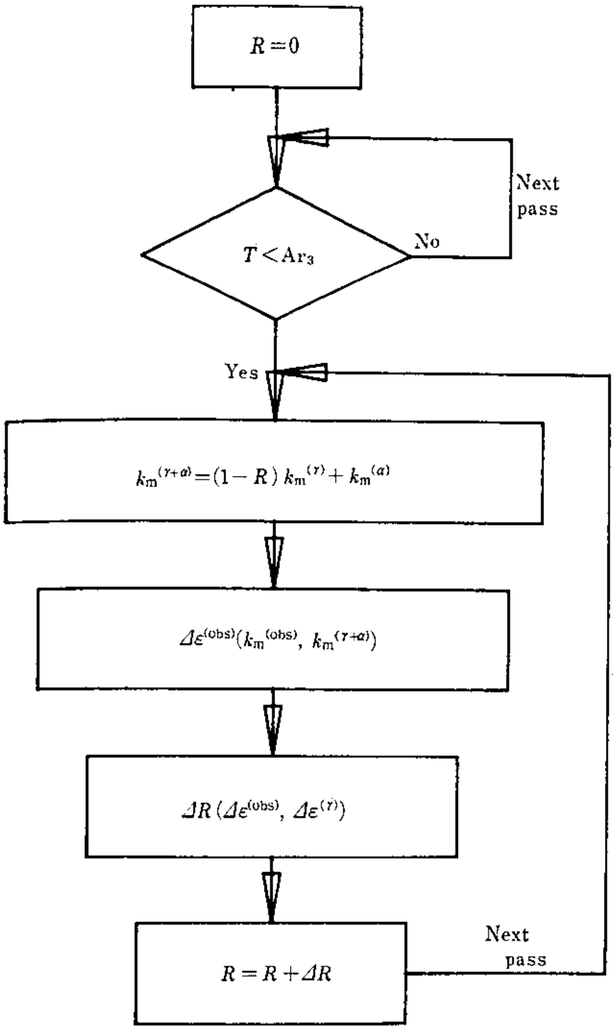


Fig. 14 Flow chart for estimating fractional transformation in austenite-ferrite dual phase region

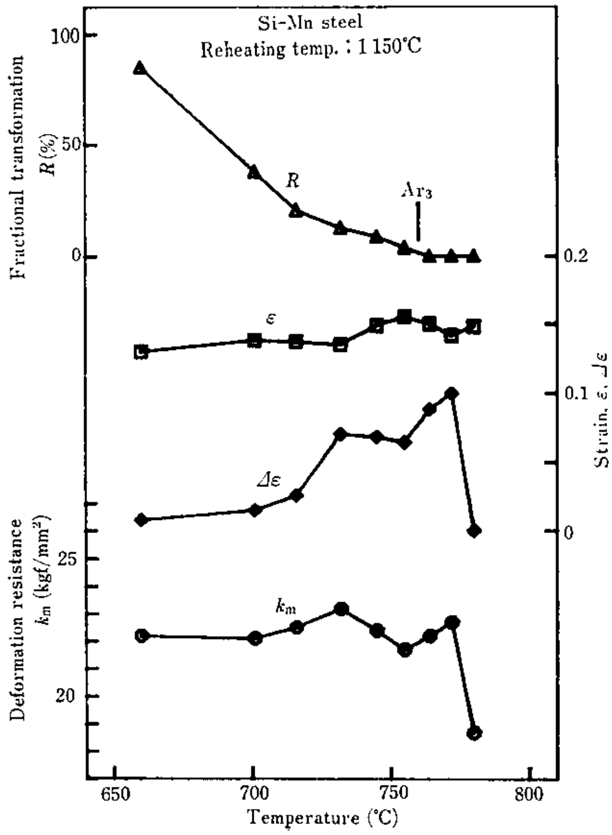


Fig. 15 An example of rolling data analysis in austenite-ferrite dual phase region

transformation utilizing deformation resistance based on the above-mentioned experiment results. First, the deformation resistance in the dual-phase region, $k_m^{(\gamma+\alpha)}$, is expressed by the mixed law of the deformation resistance of austenite and ferrite, $k_m^{(\gamma)}$ and $k_m^{(\alpha)}$, respectively. Then, the strain accumulated in the dual-phase region, $\Delta\epsilon^{(obs)}$, is calculated from the observed mean deformation resistance, $k_m^{(obs)}$, and the value calculated from the above-mentioned method, $k_m^{(\gamma+\alpha)}$. Since variations in the fractional transformation during a pass interval, ΔR, can be described as a function of the strain accumulated determined from observed values, $\Delta\epsilon^{(obs)}$, and the strain accumulated determined by ignoring transformation, $\Delta\epsilon^{(\gamma)}$[10], it is possible to estimate R between passes. R in each pass is determined by repeating the above-mentioned procedure, starting with $R = 0$, until rolling is completed.

The deformation resistance, fractional transformation and strain accumulated during rolling are estimated by the above-mentioned method of data analysis. The Si-Mn steel was reheated to 1 150°C and was rolled in the non-recrystallization austenite region and dual-phase region after rolling in the high-temperature region. **Figure 15** shows the relationship between the deformation resistance, fractional transformation and strain accumulated and the rolling temperature in this case. In the non-recrystallization austenite region, deformation resistance increases with decreasing temperature. In the temperature region below Ar_3, the rate of increase in deformation resistance decreases and deformation resistance tends to decrease as the temperature decreases. This is the combined result of an increase in ferrite of lower deformation resistance and the strain recovery associated with austenite-ferrite transformation.

Thus it is possible to estimate the fractional transformation and the strain accumulated in ferrite during the rolling in the dual-phase region, and the effect of rolling in the dual-phase region can be expressed by a formula using a ferrite strengthening parameter, which will be described in the following section.

4 Correlation between Microstructural Changes during Rolling and Strength and Toughness

The preceding section described that microstructural changes during rolling can be described by a simple mathematical model and that deformation resistance is closely related to changes in microstructure factors. Therefore, it is possible to predict microstructural changes during rolling and control the mechanical properties by measuring the deformation resistance in each pass.

Attention was paid to ferrite grain refinement and strengthening from the standpoint of control of strength and toughness of rolled products, and an attempt was made to control the mechanical properties by using the results described in the preceding section.

If the ferrite grain size is denoted by d, as is well known, the yield strength of polycrystals increases in proportion to $d^{-1/2}$ [11], and the Charpy ductile-brittle transition temperature decreases in proportion to $d^{-1/2}$ [12]. The refinement of ferrite grains thus increases both strength and toughness. The ferrite grain size, d_α, can be expressed by eq. **(5)** as a function of the recrystallized austenite grain size, d_γ, strain accumulated just before phase transformation, $\Delta\epsilon_t$, and cooling rate, C_R. $d^{-1/2}$ is proportional to the ferrite grain refinement parameter, P_{GR}, described below if the cooling rate is constant.

$$P_{GR} = d_\gamma^{-0.22} \exp[0.44 \tanh(10 \cdot \Delta\epsilon_t)] \cdots\cdots (6)$$

Figure 16 shows the relationship between the Charpy toughness and brittleness and transition temperature and P_{GR} of 25 mm thick Nb and Si-Mn steel plates of different values of d_γ and $\Delta\epsilon_t$, which were produced by varying the reheating temperature, non-recrystallization region and rolling temperature region in rolling with an amount of deformation in the dual-phase region. This figure reveals that the improvement of impact properties by controlled rolling can be described by P_{GR} regardless of steel grades. In this experiment, a clear relation was not obtained between strength and P_{GR}. Strength is affected by the solid-solution hardening and precipitation hardening by alloying elements, and dislocation hardening in addition to the grain size. Since in this experiment reheating and rolling conditions are greatly different, the effects of hardening factors other than the grain size are considered inconstant. It seems that this is the reason why the above-mentioned results were obtained.

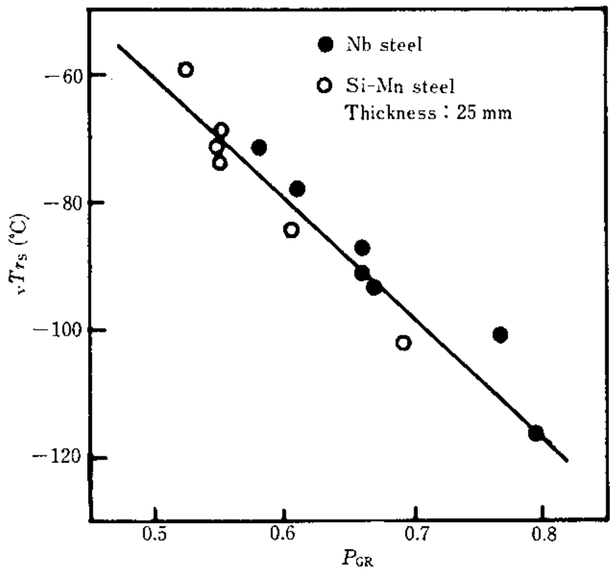


Fig. 16 Effect of grain refinement parameter, P_{GR}, on Charpy transition temperature, $_vTr_S$, in controlled rolled steel

Next, the effect of the rolling in the austenite-ferrite dual-phase region is quantitatively determined. The effect of the rolling in the dual-phase region is evaluated by the amount of strain introduced in ferrite. The amount of strain introduced in ferrite is expressed by a ferrite strengthening parameter, P_F, described by the sum of the products of fractional transformation and strain in each pass, as given by the following equation:

$$P_F = \sum_{i=1}^{N} \epsilon_i \cdot R_i \prod_{j=i}^{N} \lambda_j \cdots\cdots (7)$$

where, N is the total pass number. The fraction of unrecovered strain, λ_j, between the $(j-1)$th pass and the jth pass was introduced in eq. (7) in consideration of the effect of recovery in ferrite. R_F was varied by changing the amount of deformation in the dual-phase region and rolling temperature in the rolling of an Nb steel slab with ferrite grain sizes of 5.3 to 5.7 μm. **Figure 17** shows the relationship between P_F and ten-

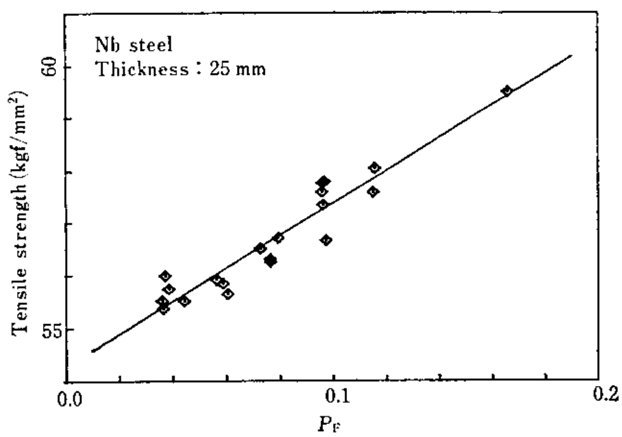


Fig. 17 Effect of ferrite strengthening parameter, P_F, on tensile strength of Nb steel

sile strength in this case. P_F is proportional to tensile strength; this suggests that tensile strength can be controlled by controlling the value of P_F.

Thus it was shown that the ferrite grain refinement parameter, P_{GR}, and ferrite strengthening parameter, P_F, are closely related to the strength and toughness of rolled products. The authors intend to accumulate data on microstructural changes during rolling and mechanical properties by making further analyses and to establish techniques for controlling on-line the mechanical properties of steel plates.

5 Conclusions

To express the effect of rolling conditions on microstructural changes at high temperatures during rolling and clarify the relationship between the microstructure at high temperatures and deformation resistance and the relationship between this microstructure and the mechanical properties after cooling to room temperature, a rolling experiment was carried out by using a plate mill and the following results were obtained:

(1) Changes in the austenite grain size can be described by a simple equation as a function of rolling temperature, strain and strain rate. Deformation resistance increases as the austenite grain size becomes refined. Therefore, the austenite grain size can be estimated from changes in deformation resistance.

(2) The precipitation process of Nb (C, N) can be described by a classical nucleation theory. The deformation resistance ratio of Nb and Si-Mn steels under the same deformation conditions increases due to strain-induced precipitation, and changes in deformation resistance are closely related to the kinetics of precipitation.

(3) The kinetics of strain accumulation in the low-temperature austenite region can be estimated from changes in deformation resistance. The strain accumulated just before phase transformation has a great effect on the behavior of austenite-ferrite transformation. It is an important factor that determines the ferrite grain size, together with the recrystallized austenite grain size and cooling rate.

(4) From changes in deformation resistance it is possible to estimate fractional transformation and strain accumulated in each pass in the rolling in the austenite-ferrite dual-phase region. By using these two values, it is possible to quantitatively determine the effect on strength of the rolling in the dual-phase region.

(5) The ferrite grain refinement parameter, which is proportional to (ferrite grain size)$^{-1/2}$, and the ferrite strengthening parameter, which is expressed by the sum of the products of fractional transformation and strain in each pass of rolling in the dual-phase region, are closely related to the strength and toughness of rolled products. The mechanical properties can be controlled by controlling these two parameters.

References

1) High Temperature Deformation Committee of Joint Society on Iron and Steel Basic Research: "Basic Techniques of Controlled Rolling and Its Development", (1980), [ISIJ]
2) C. Ouchi: ibid., pp. 67–82
3) Y. Saito, T. Enami, T. Tanaka: "Metallurgy of Metal Working in Elevated Temperatures", High Temperature Deformation Committee of Joint Society on Iron and Steel Basic Research, (1982), pp. 198–206
4) Sellars and Whiteman: "Recrystallization and Grain Growth in Hot Rolling", *Metal Science*, **13** (1979), pp. 187–194
5) M. Saeki, Y. Sakamoto, M. Nishida, T. Tanaka, T. Aoyagi, S. Takizawa: *Tetsu-to-Hagané*, **67** (1981) 13, S1155
6) H.I. Aaronson and J.K. Lee: "Lecture on the Theory of Phase Transformation", (1975), pp. 83–115 [ASM]
7) H. Watanabe: "Precipitation Kinetics of Columbium Nitride in Austenite of High Strength Low-Alloy Steel", University of Michigan, (1975)
8) Y. Saito, M. Kimura et al.: *Tetsu-to-Hagané*, **68** (1982) 12, S1386
9) Y. Saito, N. Koshizuka, C. Shiga et al.: "Advanced controlled rolling techniques for manufacture of high strength, high toughness steel plates at 5 500 mm plate mill", *Proc. of International Conference on rolling*, Tokyo, Japan, (1980) pp. 1 063–1 074, [ISIJ]
10) Y. Saito, M. Tanaka, T. Sekine, H. Nishizaki: *Tetsu-to-Hagané*, **69** (1983) 5, S604
11) N.J. Petch: The cleavage strength of polycrystals", *JISI*, **174** (1953), pp. 25–28
12) N.J. Petch: "Fracture", (1959), pp. 54–67 [MIT press]