Effect of Dislocation Density in an Unrecrystallized Part of Austenite on Growth Rate of Recrystallizing Grain

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The growth rate of recrystallizing austenite grains of Si–Mn steels and Nb added steels after hot deformation was investigated by measurement of the fraction of recrystallized austenite and recrystallized austenite grain size. The fraction of recrystallized austenite (X_{cr}) at which the mechanism of recrystallization changed from nucleation and growth (NG) to site saturation (SS) was formulated as a function of Nb concentration and deformation conditions. According to the increase in deformation temperature and strain, X_{cr} increases while the increase in Nb in solution decreases X_{cr} .

The growth rate of recrystallizing austenite was also formulated as a function of strain energy (F_v) and Nb concentration. The growth rate decreases rapidly after deformation due to the decrease in F_v . The growth rate also decreases Nb addition.

KEY WORDS: austenite; dislocation density; recovery; recrystallization; growth rate; grain size; Nb; formulation; high strength steel; nucleation and growth; site saturation.

1. Introduction

In the hot rolling processes of steels, the phenomena such as work hardening, recovery and recrystallization of austenite (γ) interact. Austenite transforms into a variety of microstructures after hot rolling and the transformation behavior depends largely on the microstructural state of γ .^{1,2)} Therefore, it is important to understand clearly the relationship between the rolling conditions and the microstructural changes taking place in γ . In the previous report,^{8,9)} the present authors formulated the effects of Nb content and working conditions on work hardening and static recovery occurring in γ which was hot worked in similar conditions to the plate rolling.

A number of reports are available on the recrystallization behavior of γ following static recovery under hot rolling.^{3–7)} However, fundamental phenomena such as the transition from nucleation and growth (NG) to site saturation (SS) and the changes in nucleation rate I and growth rate G of recrystallized grains with progress of recrystallization are not well understood. Although the fraction of recrystallized γ is known to be simply represented in an equation based on the Johnson–Mehl–Avrami equation,^{13,14)} it fails to include these phenomena and is limited in the range of application and calculation accuracy.

In the present report, the effects of Nb contents and

deformation conditions on the fraction of recrystallized γ associated with the transition from NG to SS will first be clarified. Then, formulation will be made for the growth rate of recrystallizing grains G as a function of ρ by calculating the changes in dislocation density due to hot deformation and subsequent static recovery based on the procedure reported in the previous paper.^{8,9)}

2. Steels Tested and Experimental Conditions

Table 1 shows the chemical compositions of steels tested. The starting material with the base composition of 0.10%C–1.35%Mn (mass%) was melted in a vacuum furnace, poured into three 100 kg ingots, among which two of the ingots had 0.01 and 0.03% of Nb added respectively. From the 100 kg ingots, square columns of 10 mm in thickness, 18 mm in width and 150 mm in length were machined for the quenching test after hot deformation and holding. In order to enhance the cooling rate in quenching, the hot deformed part of the specimens was thinned to a thickness of 5 mm.

Table 1. Chemical compositions of steels tested. (mass%)

Steel	C	Si	Mn	Al	Nb	N
T0	0.10	0.20	1.37	0.027	0.0	0.0028
T1	0.10	0.20	1.37	0.027	0.010	0.0028
T3	0.10	0.20	1.37	0.027	0.030	0.0028

The specimens were hot deformed under a predetermined condition in a hot deformation simulator of plain strain-compression type¹⁰⁾ and rapidly cooled by water spray after holding for a given time interval at the deformation temperature. The experiments were carried out by changing the reheating temperature (*i.e.* γ grain size and amount of Nb in solution), deformation temperature, strain and holding time after deformation as shown in Fig. 1.

The specimens quenched after testing were cut into two pieces in the transverse direction. The section was prepared for optical microscopy by polishing and etching with picric acid for revealing the prior γ grain boundaries. In addition, extraction replicas were prepared from the specimens quenched immediately after deformation for transmission electron microscopy. The observation of the extraction replicas revealed that both dynamic recrystallization of γ and dynamic precipitation of Nb did not take place within the present experimental conditions.

By using the micrographs of continuous four fields with a magnification of 50 to 200 for the prior γ grain structures, the fraction of recrystallized γ and average γ grain size were measured by the point counting method and the linear intercepting method respectively. The mean intercept length of grains was converted into the ASTM grain size.¹¹⁾

3. Experimental Results

An example of recrystallization progress in the Si-Mn

steel reheated at 1200°C is shown in Fig. 2. The samples were deformed to a true strain of $\epsilon=0.4$ and held at 900°C for various periods of time. Figure 2 shows some fine grains evolved along prior γ grain boundaries, suggesting that recrystallization has started at 4 s after deformation. Recrystallization progressed with holding time and completed at about 1000 s after deformation. The average γ grain size was 57 μm after the completion of recrystallization.

Figure 3 shows the relationship between the holding time after deformation and the fraction of recrystallized γ . These data are the results of experiments carried out by changing the temperature of deformation and holding, T , ϵ , and Nb content. Recrystallization progressed more rapidly under the conditions of higher temperature of deformation and holding and also of higher deforma-

Fig. 1. Schematic illustration of experimental conditions.

Fig. 2. Change in prior austenite structure during holding time (0.01 mass% Nb, Reheating temp. = 1200°C, Deformation temp. = 900°C, $\epsilon=0.4$).

Fig. 3. Relation between holding time after deformation and fraction of recrystallized austenite (Reheating temp. = 1 200°C)

Fig. 4. Relation between fraction of recrystallized austenite and recrystallized austenite grain size (Reheating temp. = 1 200°C).

tion strain in 0.01 % Nb steel. For a given deformation condition, recrystallization is suppressed more in 0.01 % Nb than in Si-Mn steel. These results are similar to the previous report.¹²⁾

Since the time interval between passes in plate rolling is about 10 s, the fraction of recrystallized γ at the position of 10 s on the horizontal axis will give the information of recrystallized or unrecrystallized state between the passes in practical mills. When deformation is applied at 900°C to a strain of $\varepsilon = 0.4$, the fraction of recrystallized γ can be 95% in Si-Mn steel and, on the other hand, 23% in 0.01 % Nb. This suggests the effectiveness of microalloying of Nb for suppressing recrystallization.

Figure 4 shows the relationship between the fraction of recrystallized γ and average γ grain diameter D_{rec} in the recrystallized regions. For every ε , D_{rec} increases with increasing fraction recrystallized. D_{rec} after completion of recrystallization can be determined mainly by the degree of ε , although it depends slightly on the de-

Fig. 5. Replot of relation between holding time after deformation and fraction of recrystallized austenite (Avrami plot, Reheating temp. = 1 200°C).

formation temperature and Nb content. As apparent in Fig. 3, the deformation temperature and Nb content influence the progress of recrystallization, but scarcely the diameter of recrystallized grains.

4. Discussion

4.1. Recrystallization Mechanism

The fraction of recrystallized γ , X , is expressed as Eq. (1) in the form of Johnson-Mehl-Avrami equation.^{13,14)} Making logarithmic transformation twice on Eq. (1) leads to Eq. (2), giving the Avrami plot of the inverse of $(1-X)$ vs. the logarithm of annealing time.

$$X = 1 - \exp(-Bt^k) \quad (1)$$

$$\log\{\ln[1/(1-X)]\} = \log(B) + k \log(t) \quad (2)$$

where B and k are constants, and t is the annealing time after deformation.

The $X-t$ relations in Fig. 3 is replotted using Eq. (2) in Fig. 5. For all of the Nb contents and temperatures of deformation and holding, each plotted line has a deflection point with the different Avrami slope from 1–2 in the range of lower X to 0.5 in that of higher X . By assuming a constant rate of nucleation and growth of recrystallizing grains, the equation derived by Cahn¹⁷⁾ for recrystallization rate of polycrystalline materials shows that the time index in the recrystallization process controlled by the NG mechanism is 4 regardless of the location of nucleation site such as grain boundaries, edges or corners. On the other hand, if recrystallization is controlled by the SS mechanism, the time index differs in accordance with the location of nucleation sites; 1 for grain boundaries, 2 for edges and 3 for corners of crystals. The time index becomes smaller for every nucleation site with the change in the mechanism from NG to SS. As the Avrami slope is time index of Eq. (1), the deflection in the plotted line can suggest the change in the recrystallization mechanism from NG to SS. However, the slopes shown in Fig. 5 is smaller than the values predicted by Cahn. As suggested by Vandermeer¹⁵⁾ for Al, this may be a result of decreases in G and I of recrystallizing grains due to recovery of unrecrystallized parts of γ . This point is discussed later.

In the next step, calculation was made for the number of grains N_γ in a unit area (1 mm^2). When the observed area is completely occupied with recrystallized grains, the number of grains per 1 mm^2 is equal to $(D_{\text{rec}}/1000)^{-2}$.²³⁾ At the fraction of recrystallized X , the area occupied by recrystallized grains is $X \text{ mm}^2$ and N_γ is expressed by Eq. (3).

$$N_\gamma = (1000/D_{\text{rec}})^2 X \quad \dots\dots\dots(3)$$

The relationship between the fraction of recrystallized γ , X , and N_γ under the same deformation conditions shown in Fig. 3 is illustrated in Fig. 6. The values of N_γ are saturated at a certain point of X and sometimes N_γ decreases with increasing X in the range of higher X . Since nucleation can be finished around the maximum X , X_{crn} , the recrystallization mechanism may change from NG to SS at around X_{crn} . Decrease in N_γ in over X_{crn} can be a result of coalescence of recrystallization grains. Since the decrement of N_γ from the maximum is small

Fig. 6. Relation between fraction of recrystallized austenite and number of recrystallized grains per unit area (Reheating temp. = 1200°C).

Fig. 7. Relation between fractions of recrystallized austenite showing maximum number of recrystallized grains (X_{crn}) and that showing change in slope of Avrami plot (X_{cra}).

enough to ignore in practical application, however, the effects of grain coalescence here are not taken into consideration.

Figure 7 compares the value of X_{cra} defined at the point of deflection in Fig. 5 and the X_{crn} indicated by the arrows in Fig. 6. The close agreement between X_{cra} and X_{crn} suggests that both can represent the fractions of recrystallized γ on change of the recrystallization mechanism from NG to SS. Since the X_{crn} includes some errors due to the broad range of the maximum value, the values of X_{cra} will be used as the fraction of recrystallized γ corresponding to the change in recrystallization mechanism in the following analysis. The fact that the number of recrystallized grains saturate for $X \geq X_{\text{cra}}$ was confirmed by the microstructural observation of specimens that were treated to vary the holding time under typical working conditions.

Basically, X_{cra} follows Eq. (2) and B in the equation is a function of γ grain size before deformation D_1 , temperature of deformation and holding T , ε , and Nb content. Thus, the quantity of X_{cra} was assumed to be expressed by Eq. (4) as a function of D_1 , ε , and content of added Nb (Nb^T) because recrystallization is controlled by a thermally activated process and the conventional simplified formula can give a good summary of the effects of D_1 and ε in a form of exponential function. The constant for each factor was obtained with multiple regression analysis of all the data of X_{cra} . The result is shown in Eq. (4).

$$X_{\text{cra}} = 22.3 \varepsilon^{0.463} D_1^{-0.0347} \exp(-32.6 Nb^T - 3190/T) \quad \dots\dots\dots(4)$$

where D_1 is in the unit of μm , Nb^T in mass%, and T in K.

This equation suggests that deformation to a higher strain enhances recrystallization by the NG mechanism to a higher fraction of recrystallization. This phenomenon is consistent with the observation results that the number of ferrite nuclei increase by applying the deformation of higher strains in the nonrecrystallization temperature region of austenite.^{16,24)} Equation (4) includes a small influence of D_1 and has a tendency of decrease in X_{cra} with coarsening of initial grains. This

Fig. 8. Effects of Nb and deformation conditions on fraction of recrystallized austenite where mechanism of recrystallization changes from nucleation and growth to site-saturation, plot of Eq. (4).

may be a result of the occupation of grain boundaries by recrystallized grains at the earlier stage because coarse grains have a smaller area of grain boundaries for a unit volume.

The relation between Nb^T and X_{cra} calculated from Eq. (4) is shown in Fig. 8. Transition from NG to SS occurs at a smaller fraction of recrystallized γ for a higher Nb content in Fig. 8.

4.2. Growth Rate of Recrystallizing Austenite Grain

It is concluded from the previous discussions that recrystallization can proceed by the NG mechanism for $X \leq X_{\text{cra}}$ and, on the other hand, by the SS mechanism for $X > X_{\text{cra}}$. Equation (5) holds for the progress of recrystallization by the SS mechanism in which recrystallized grains nucleate and grow from grain boundaries.¹⁷⁾

$$X = 1 - \exp(-2S_{\gamma}Gt) \quad \dots\dots\dots(5)$$

where S_{γ} is the area of austenite grain boundaries per unit volume as expressed by Eq. (6) obtained from D_1 and ε on the assumption that the grain shape is spherical.⁶⁾

$$S_{\gamma} = (24/\pi D_1) \{0.491e^{\varepsilon} + 0.155e^{-\varepsilon} + 0.143e^{-3\varepsilon}\} \quad \dots\dots(6)$$

As a result of calculation of G from Eq. (5) by using the X - t relations for each Nb content and deformation condition, G decreases monotonously with increasing t . This may be caused by decrease in the strain energy of unrecrystallized regions due to recovery. Equation (7) gives the growth rate as a function of lattice strain energy F_v in unrecrystallized regions based on the classical theory.¹⁸⁾

$$G = (D_{\text{GB}}/kT)(F_v/N_0\lambda) \quad \dots\dots\dots(7)$$

where D_{GB} is the self diffusion constant at grain boundaries ($D_{\text{GB}} = D_{\text{GB0}} \exp(-Q_{\text{GB}}/RT)$), k the Boltzmann's constant, N_0 the Avogadro's number, and λ the thickness of grain boundaries. Further F_v is expressed by Eq. (9) in terms of the self energy of dislocation (E_{disl}) per unit length¹⁹⁾ as given in Eq. (8). In the Eq. (8), E_{disl} represents the value of an edge dislocation and the radius of dislocation core is taken as 1/4 of Burgers' vector b .²⁰⁾

$$E_{\text{disl}} = [\mu b^2/4\pi(1-\nu)] \ln[(4r/b) + 1] \quad \dots\dots\dots(8)$$

where μ the shear modulus, b the length of Burgers' vector (2.6×10^{-7} mm), ν the Poisson's ratio (0.333), and r the average spacing of dislocations ($\rho_r^{0.5}/2$ in the present study). The shear modulus is taken to be 8×10^4 MPa with reference to the data of austenitic stainless steel at room temperature and its temperature dependence is not taken into account in the present study.

$$F_v = E_{\text{disl}}\rho_r \quad \dots\dots\dots(9)$$

where ρ_r is the dislocation density in unrecrystallized regions of γ . The value of ρ_r was calculated with the functions of Nb content, deformation condition and holding time after deformation formulated in previous papers.^{8,9)} As the observed flow stresses of the second pass in the double compression test in which the time interval between the first and the second passes changed

from 0.1 s to 9000 s have been adopted in the formulation,⁹⁾ both ρ_r and F_v can be calculated properly since the start to the end of recrystallization process.

By selecting the data for $X \geq X_{\text{cra}}$ in which recrystallization proceeds by the SS mechanism, the values of F_v calculated with the above procedure were correlated with the values of G calculated from Eq. (5) based on microstructural observation. An example at the reheating temperature of 1200°C and $\varepsilon = 0.4$ is shown in Fig. 9. Both are correlated in a linear relationship as predicted from Eq. (7) with a slope of about 1. This means that G decreases with progress of recovery (or decrease in dislocation density) taking place in unrecrystallized regions. It must be noted that this linear relationship is confirmed for the data observed in a later stage of recrystallization process. However, as the values of F_v in Fig. 9 change widely, this linear relationship may be kept in a range of larger F_v . Figure 9 suggests that G is strongly influenced by Nb content and temperature of deformation and holding as well as lattice strain energy F_v .

Next, the formulation of G was intended as a function of these influencing factors. By summarizing the constants in Eq. (7) as A and applying the functional forms taking into account γ grain diameter D_1 and Nb as used in the previous paper,^{8,9)} G is formulated as Eq. (10).

$$G = A(F_v/T)D_1^B \exp(C \cdot Nb^{\text{sol}} + D \cdot Nb^{\text{pre}} - E/T) \quad \dots\dots(10)$$

where $A = D_{\text{GB0}}/kN_0\lambda$, Nb^{sol} and Nb^{pre} are the amounts of solute Nb and precipitated Nb in mass% respectively, A , B , C , D and E are constants. The amount of Nb^{pre} increases according to the time after deformation and Nb^{pre} is also affected by T and ε .^{12,25)} The Nb^{pre} used was calculated by using the Akamatsu's program²¹⁾ in which Nb^{pre} is formulated as a function of T , ε and time after deformation. By using the calculated values of F_v as mentioned above and determining the values of A , B , C , D and E to minimize the difference of measured G s and the values calculated from Eq. (10), the result

Fig. 9. Relation between estimated strain energy of the unrecrystallized part of deformed austenite and observed growth rate of recrystallizing grain (Reheating temp. = 1200°C, $\varepsilon = 0.4$).

Fig. 10. Relation between growth rate of recrystallizing grain calculated by Eq. (5) and growth rate calculated by Eq. (10).

Fig. 11. Effects of Nb in solution and deformation conditions on calculated growth rate of recrystallizing grain (Reheating temp. = 1200°C), plot of Eq. (10).

is that $A = 7.46 \times 10^{16} \text{ (m}^3 \text{ kMN}^{-1} \text{ s}^{-1}\text{)}$, $B = -0.035 \text{ (mass\%}^{-1}\text{)}$, $C = -108.0 \text{ (mass\%}^{-1}\text{)}$, $D = -142.0 \text{ (mass\%}^{-1}\text{)}$, and $E = 41\,000.0 \text{ (K)}$. The effect of D_1 is very small. Moreover, G is more strongly suppressed by precipitated Nb (Nb^{pre}) than solute Nb (Nb^{sol}).

Figure 10 compares the values of G obtained by substituting the measured fraction of recrystallized γ for X in Eq. (5) with those calculated from Eq. (10). Both hold close agreement and the validity of Eq. (10) is confirmed. The effects of solute Nb content, temperature of deformation and holding and F_v on G calculated by Eq. (10) are shown in Fig. 11. It is shown that G decreases remarkably with increase in solute Nb content, lowering of deformation and holding temperature and decrease in F_v .

5. Conclusion

The fraction of recrystallized γ and recrystallized γ

grain size after hot deformation were examined in Si-Mn steel and Nb added steels. Based on the present work, the effect of recovery in unrecrystallized regions on the growth rate of recrystallizing γ grains were analyzed. The results are summarized as follows.

(1) The recrystallization fraction X_{cra} , representing the change of the recrystallization mechanism from nucleation and growth (NG) to site saturation (SS), is formulated as a function of deformation conditions (T, ϵ) and Nb contents. Deformation to high strains and holding at high temperatures retain nucleation up to higher fractions of recrystallization. A higher amount of solute Nb before deformation results in the transition of the recrystallization mechanism from NG to SS at lower fraction of recrystallization.

(2) The growth rate of recrystallizing γ grain is formulated as a function of Nb content and lattice strain energy (F_v) in unrecrystallized parts of γ . Since F_v decreases with the progress of recovery in γ after deformation, the growth rate of recrystallizing γ grain decreases rapidly immediately after deformation. Microalloying of Nb remarkably lowers the growth rate.

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