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Determinations of the Non-Recrystallization Temperature for X52 Steel Produced by Compact Slab Process Combined with Direct Hot Rolling

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Deformation comprises not only dimensional accuracy but also the control of the final microstructure and mechanical properties. Deformation below the non-recrystallization temperature (T_{nr}) is important to design the proper rolling schedule to avoid grain growth in the final stages of rolling. The determination of T_{nr} for Nb-bearing carbon steel with a compact slab process mill log is carried out depending upon the Misaka concept calculation. A comparison among different formulas for predicting the T_{nr} was conducted using Misaka, Bratto, and Jonas equations. The Misaka equation depends on the chemical compositions and deformation parameters including dynamic and metadynamic recrystallization. The Bratto equation considers only the steel chemical composition. The Jonas equation depends only on the accumulated strain. The Bratto equation gives a large value of T_{nr}, while the Misaka equations show a moderate and accurate value in relation to the Jonas results, which depend on torsion tests. The effect of strain accumulation on dynamic recrystallization is investigated to predict the final grain size of ferrite.

Keywords: compact slab process, direct hot rolling, ferrite grain size, mean flow stress, Misaka concept, non-recrystallization temperature, strain accumulation

1. Introduction

The compact slab process (CSP) is usually combined with direct hot rolling to reduce production costs. In this combination, the as-cast slabs do not cool below 1000 °C before entering the hot rolling mill (Ref 1). Consequently, a large austenite grain size is usually obtained. At the same time, the CSP technique has a limited total thickness reduction during the hot rolling process that could adversely affect the mechanical properties. Therefore, Nb strengthening by precipitation using microalloying in combination with controlled rolling is the optimum solution for high strength combined with excellent toughness. Many studies have investigated the steel behavior produced by conventional processes; however, few studies have been undertaken with the CSP steel. The analysis of the mean flow stress (MFS) as a function of the inverse absolute temperature is helpful in understanding the microstructural evolution that occurs during thermomechanical processing. The MFS relationship can be used to determine the recrystallization stop temperature (i.e., the non-recrystallization temperature [T_{nr}]), the strain accumulation, the dynamic recrystallization, and the phase transformation (Ref 2).

The determination of the T_{nr} is a critical step in the design of the controlled rolling schedule, because it specifies the temperatures below which the strains are accumulated in the austenite giving a pancake structure (i.e., higher dislocation densities).

Recrystallization due to deformation at a temperature higher than the T_{nr} refines the grain size to a certain limit. Maximum deformation in the non-recrystallization region exerts a pronounced influence on the final microstructure. However, further refinement of the grains depends on processing below the T_{nr} (Ref 3). Actually, during each deformation pass, a certain amount of input energy is retained in the deformed grains as stored energy. This stored energy is subsequently consumed for different purposes at different stages (Ref 4). When the deformation process is executed at high temperature (i.e., $>T_{nr}$), where precipitates are absent, the stored energy is used as a driving force for recrystallization during the interpass periods (Ref 4).

Alternatively, below T_{nr} strain-induced precipitation inhibits any further recrystallization, and the stored energy is, therefore, retained in the deformed structure from pass to pass. This stored energy appears as high dislocation densities, deformation bands, or increased grain boundary area. These defects can appear individually or in combination (Ref 5).

2. Steel Processing

A 160 ton electric arc furnace heat of X52 steel was used to produce compact slabs with 52 mm thickness. The slabs were cast and directly reheated in a tunnel furnace for 20 min to a temperature between 1070 and 1100 °C. Rolling was scheduled to obtain coils 10 mm in thickness and 150 mm in width. Rolling was carried on a six-stand roll mill. Table 1 shows the chemical composition of the steel under investigation. Table 2

Table 1 Chemical composition of steel investigated (wt.%)

C	Si	Mn	S	P	Al	N, ppm	Nb
0.051	0.082	1.18	0.0017	0.006	0.042	35	0.041

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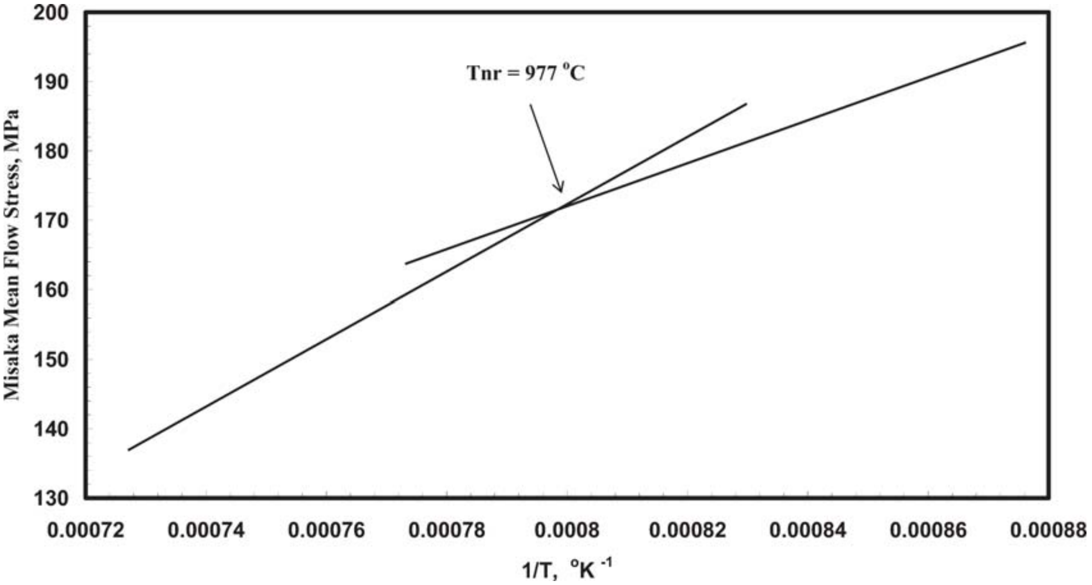

Fig. 1 Misaka MFS versus 1/T (K^{-1})

Table 2 Data abstracted from roll mill logs

Coil No. 89500			Start rolling temperature 1052 °C		Coil thickness 10 mm		
Stand No.	Roll velocity, m/s	Thickness after, mm	Exit temperature, °C	Forward strip tension, KN	Backward strip tension, KN	Rolling forces, KN	Rolling torque, KNm
1	12.35	33.64	1021	1.5	0.0	25463	1680
2	16.77	24.31	989	3.0	1.5	18686	846
3	22.71	17.47	961	4.2	3.0	20379	781
4	28.57	13.53	934	5.9	4.2	19105	553
5	45.43	11.57	909	7.0	5.9	10461	193
6	50.28	10.19	887	0.0	7.0	10753	212

represents some data abstracted from the roll mill logs. After rolling, the steel was coiled at 575 °C.

3. Mean Flow Stress and Grain Size Calculations

Misaka and Yoshimoto (Ref 6) developed a model relating carbon content, true strain, strain rate, and rolling temperature to the MFS:

$$\mathrm{MFS}_{\mathrm{Misaka}} = \left[\exp\left(\frac{\begin{array}{c}0.126 - 1.75\,[\mathrm{C}] + 0.594\,[\mathrm{C}]^2\\ + 2851 + 2968\,[\mathrm{C}] - 1120\,[\mathrm{C}]^2\end{array}}{t}\right)\right](\varepsilon)^{0.21}\,(\dot{\varepsilon})^{0.13} \tag{Eq 1}$$

where [C] is the carbon content, $\dot{\varepsilon}$ is the strain rate, ε is the true strain due to plane strain condition, and t is the deformation temperature.

$$\varepsilon = \frac{2}{\sqrt{3}}\ln\left(\frac{h_1}{h_2}\right) \tag{Eq 2}$$

where h_1 and h_2 are the slab thickness before and after the rolling reduction step.

An improved version of the Misaka and Yoshimoto (Ref 6) equation has been modified to consider the Mn content of the steel:

$$\mathrm{MFS} = \mathrm{MFS}_{\mathrm{Misaka}}(a + b[\mathrm{Mn}]) \tag{Eq 3}$$

where a and b are constants ($a = 0.78$; $b = 0.13$) (Ref 2) and [Mn] is the Mn content.

$$\mathrm{MFS} = \mathrm{MFS}_{\mathrm{Misaka}}(0.78 + 0.13[\mathrm{Mn}]) \tag{Eq 4}$$

Further development was done to introduce the effects of both fractional softening (X_{dyn}) and steady-state stress (σ_{ss})

$$\mathrm{MFS} = (0.78 + 0.137[\mathrm{Mn}]) \times (\mathrm{MFS}_{\mathrm{Misaka}}) \times 9.81(1 - X_{\mathrm{dyn}}) + K\sigma_{\mathrm{ss}}X_{\mathrm{dyn}} \tag{Eq 5}$$

where K is a coefficient for the conversion from stress to MFS equaling 1.14. Furthermore, the σ_{ss} can be formulated as (Ref 7):

$$\sigma_{\mathrm{ss}} = A\dot{\varepsilon}\exp\left(\frac{Q_{\mathrm{def}}}{RT}\right)^{\mathrm{q}} \tag{Eq 6}$$

where A and q are constants for the steady-state stress state ($A = 7.2$; $q = 0.09$), Q_{def} is the activation energy equaling 300 kJ/mol (Ref 8), T is the absolute temperature (T (K)

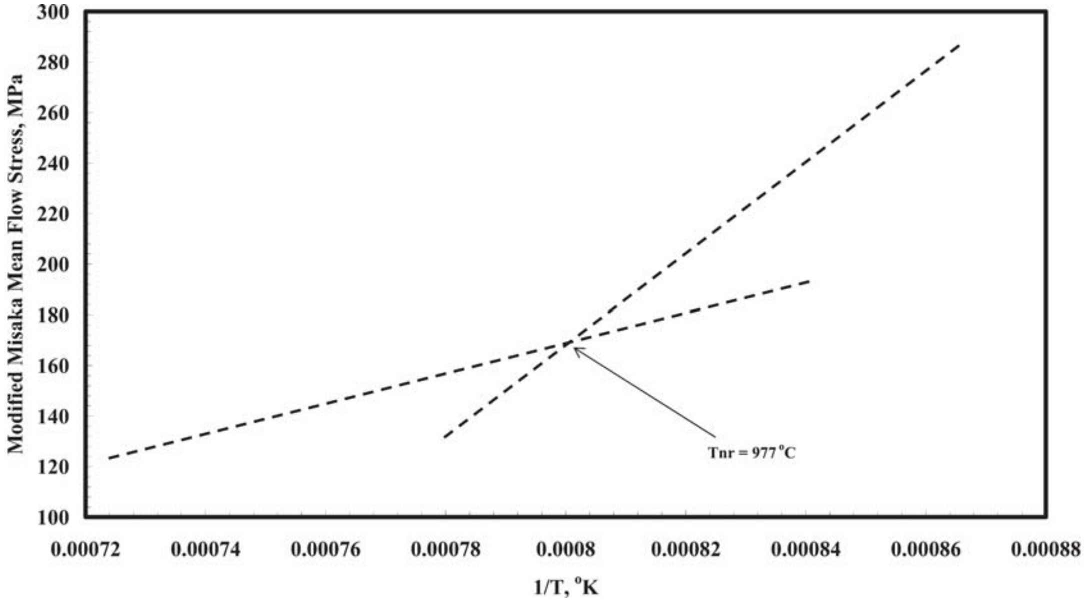

Fig. 2 Modified Misaka equation showing MFS versus 1/*T* (K^{-1})

Table 3 Deformation characteristics during the rolling process

Collected data		Calculated data							
°C	$\dot{\varepsilon}$	MFS_{Misaka}, MPa	$MFS_{modified}$, MPa	σ_{ss}, MPa	X_{dyn}	ε_n	ε_c	ε_a	$\varepsilon_a > \varepsilon_c$
1052	75.37	147.22	137.99	113.99	0.9980	0.435	0.0737	0.435	Yes
1021	107.90	153.12	147.88	163.45	0.8709	0.324	0.0875	0.436	Yes
989	172.61	173.24	177.61	261.89	0.7401	0.330	0.1069	0.478	Yes
961	216.15	178.38	193.58	328.43	0.3039	0.255	0.1240	0.564	Yes
934	344.80	180.55	234.26	524.67	0.0006	0.156	0.1500	0.742	Yes
909	366.20	183.56	251.05	557.99	0.0217	0.127	0.1688	0.898	Yes

= *t* (°C) + 273), and *R* is the gas constant (*R* = 8.317 J/mol).

The fraction softening of the structure due to dynamic recrystallization (X_{dyn}) is a function of critical strain (ε_c) and can be expressed as:

$$X_{dyn} = 1 - \exp\left[-0.693\left(\frac{\varepsilon - \varepsilon_c}{\varepsilon_{0.5}}\right)\right] \quad \text{(Eq 7)}$$

where ε is the deformation strain and $\varepsilon_{0.5}$ is the 50% recrystallization strain.

$$\varepsilon_c = 0.84 \times 0.0016 \times d_0^{0.5} \times \left\{\dot{\varepsilon}\exp\left(\frac{241000}{RT}\right)\right\}^{0.17} \quad \text{(Eq 8)}$$

$$\varepsilon_{0.5} = 1.144 \times 10^{-3}\, d_0^{0.25}\, \dot{\varepsilon}^{0.05} \exp\left(\frac{6420}{T}\right) \quad \text{(Eq 9)}$$

$$\varepsilon_a = \varepsilon_n + (1 - X_{dyn})\varepsilon_{n-1} \quad \text{(Eq 10)}$$

In these equations, ε_a is the accumulated strain and ε_n is the strain at pass n.

Two possibilities can then be considered: either ε_a is less than the accumulated strain, which would result in static recrystallization. The expected grain size due to static recrystallization (d_{SRX}) can be computed as:

$$d_{SRX} = 343 \times \varepsilon^{-0.5}\, d_0^{0.4} \exp\left(\frac{-45000}{RT}\right) \quad \text{(Eq 11)}$$

for the case where $\varepsilon_a > \varepsilon_c$.

However, if ε_a equals or is larger than the accumulated strain, this would lead to metadynamic recrystallization, and the expected grain size due to metadynamic recrystallization (d_{MDRX}) can be computed as (Ref 9):

$$\mathrm{d}_{MDRX} = 2.6 \times 10^4\, Z^{-0.23} \quad \text{(Eq 12)}$$

for the case where $\varepsilon_\alpha > \varepsilon_\chi$, where *Z* is the Zener-Hollomon parameter.

4. Results and Discussion

4.1 Mean Flow Stress and Grain Size Evaluation

The MFS values have been calculated from the mill logs using both the Misaka and Yoshimoto equation, and the modified Eq 1 and 3. The MFS values of different coils are plotted against 1/*T* (Fig. 1, 2). The slope of the original Misaka and Yoshimoto equation for MFS gradually changes, identifying

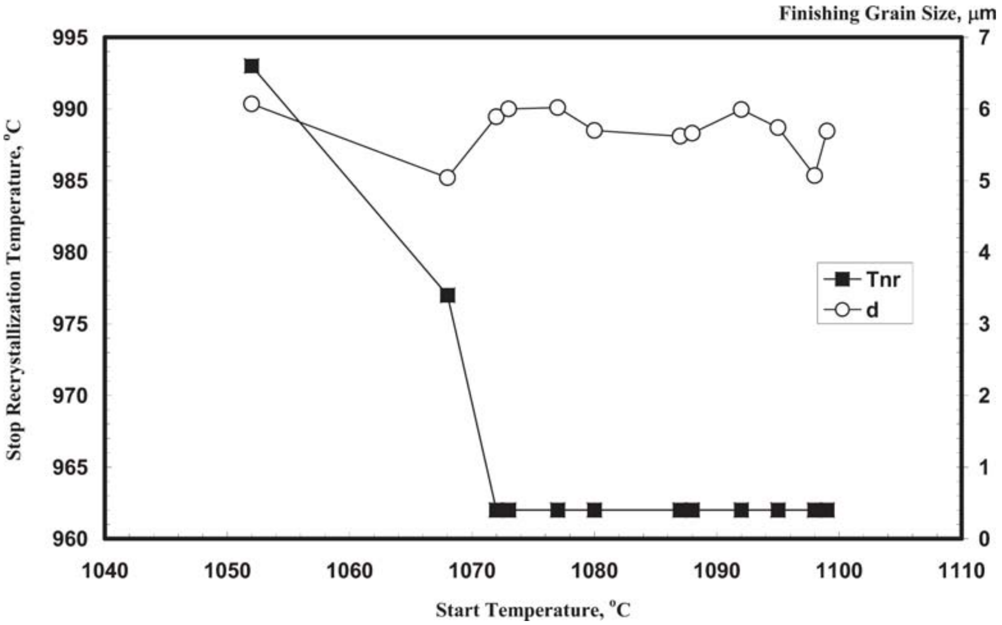

Fig. 3 Effect of start temperature on the T_{nr} and the final grain size

T_{nr}. As shown in Fig. 1 and 2, the two straight lines intersect at T_{nr}. The T_{nr} intersection for all coils is located at $1/T = 0.0008$ when using the original Misaka and Yoshimoto equation and 0.0008 for the modified Misaka and Yoshimoto equation (i.e., the expected temperature T_{nr} is 977 °C).

For different coils, the T_{nr} usually appears at the third stand; therefore, it seems clear that T_{nr} is not dependent on the starting deformation temperature, as is shown in Fig. 3. It is observed that the average T_{nr} for all rolling trials is about 970 °C. Consequently, the final value of T_{nr} using the original equation of Misaka and Yoshimoto or the modified equation provides the same result. In 1994, Yue et al. (Ref 5) developed a relationship between T_{nr} and accumulated strain using a torsion test:

$$T_{nr} = 1050 - 314\,\varepsilon_a \quad \text{if} \quad \varepsilon_a \geq 0.26 \qquad \text{(Eq 13)}$$

The T_{nr} from the equation of Yue et al. (Ref 5) for Nb steel is 913 °C, and this is the lowest value. Referring to the results of Misaka and Yoshimoto, and the concept of CSP with Nb addition, it is clear that the value of T_{nr} due to the equation of Jonas and colleagues is very low and does not reflect the Nb effect.

Barbosa et al. (Ref 10) developed the following correlation to predict T_{nr} using chemical composition as the starting point:

$$T_{nr} = 887 + 464\,\text{C} + (6445\,\text{Nb} - 644\sqrt{\text{Nb}}) + (732\,\text{V} - 230\sqrt{\text{V}}) + 890\,\text{Ti} + 363\,\text{Al} - 357\,\text{Si} \qquad \text{(Eq 14)}$$

The T_{nr} value calculated using this equation is about 1030 °C. It is very high for the CSP, and this can be attributed to the fact that the approach does not consider the effect of metadynamic recrystallization due to high accumulated strain.

To predict the final grain size of ferrite, the MFS and the steady-state stress were calculated to follow the dynamic, static, and metadynamic recrystallization. Table 3 shows the data from the mill log and the calculated results for the MFS used to calculate grain size. The predicted final grain size of ferrite is ~5.6 μm.

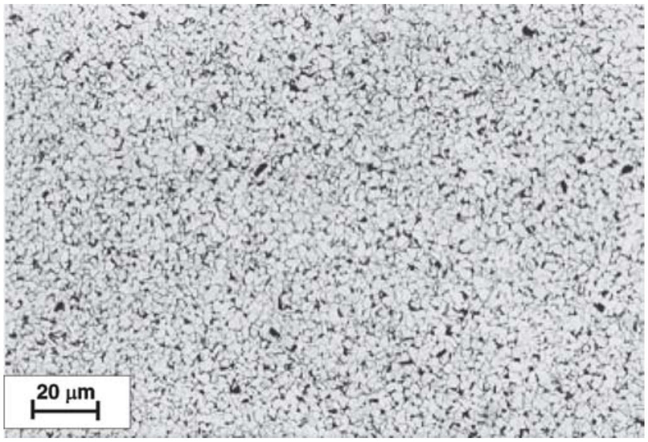

Fig. 4 Final microstructure of steel after early cooling

Figure 4 shows the final microstructure of the steel. The final grain size is about 6 μm. It is clear that the results for grain size deduced that are from the calculations coincide with those seen in the micrograph.

5. Conclusions

- The equations of Misaka and Yoshimoto can predict T_{nr} depending on chemical composition, deformation parameters, and dynamic recrystallization.
- The T_{nr} does not depend on the start temperature.
- The Barbosa equation predicts the T_{nr} of CSP steel, but it gives a higher value in relation to the Misaka method.
- The equation of Jonas and colleagues predicts T_{nr} for CSP steel, but it provides a lower value.
- The calculation of ferrite grain size using the modified

Misaka and Yoshimoto equation shows good agreement with the obtained microstructure.

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