Effect of Nb Content on the Hot Deformation Behavior of S460ML Steel

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Abstract

The hot deformation behavior of S460ML steel with different Nb contents was investigated by single-pass compression experiment on the Gleeble-1500 thermo-machine simulator at deformation temperatures ranging from 900 to 1200 °C and strain rates from 0.1 to 5.0 s⁻¹. The critical strain of dynamic recrystallization (DRC) under different conditions was determined by using working hardening rate-strain curves. The relationship between critical strain and peak strain of DRC was discussed. By means of regression analysis method, the hot deformation activation energy of steels and the mathematical model for predicting DRC critical strain were calculated and established, respectively. The results showed that DRC occurred during hot deformation. As the deformation temperature increased and strain rate decreased, the critical strain of DRC decreased. The critical strain (ε_c) showed linear relationship with peak strain (ε_p). As Nb content increased, the needed deformation temperature for occurring DRC increased, while the needed strain rate for it decreased. The activation energy for hot deformation of S460ML steel increased with increasing Nb content.

Keywords Dynamic recrystallization · Critical strain · Nb content · Deformation temperature · Strain rate · Hot deformation

1 Introduction

Microalloying elements, such as Nb, Ti and V, play an important role in the development of new generation of ultra-low carbon high strength steel, which mainly influence the properties of steel in two ways [1–5]. One way is to inhibit the recrystallization of deformation austenite and prevent grain growth during hot deformation procedure. The other way is to exhibit the precipitation strengthening effect through strain induced precipitation of carbonitrides of Nb, V and Ti.

It is known that during hot deformation, two kinds of softening behavior of dynamic recovery and recrystallization can occur in the metal material and the softening behavior of dynamic recrystallization is more obvious than that of dynamic recovery [6–9]. When the dynamic recrystallization occurs, the coarse deformed grains are

gradually replaced by fine recrystallized grains. In addition, the dislocation and microcracks generated by work hardening can be completely eliminated due to dynamic recrystallization, which can greatly improve the thermal plasticity of metal material. Therefore, studying the dynamic recrystallization behavior of Nb, Ti, V and other microalloying elements in the process of hot deformation is of great practical significance for improving the production technology and the comprehensive performance of microalloyed steel products [10–12].

The critical strain of dynamic recrystallization is usually used to determine whether the dynamic recrystallization occurs during hot deformation of the material [13–15]. If the true stress–strain curve shows a peak value of σ_p , it can be considered that the dynamic recrystallization occurs. However, it is unscientific to consider the strain ε_p corresponding to the peak stress σ_p as the critical strain ε_c . In fact, the dynamic recrystallization has already occurred when the strain does not reach the peak strain ε_p . As the critical strain of dynamic recrystallization during hot deformation is closely related to the content of Nb, it is significant to first determine the critical strain and then study the hot deformation behavior of Nb-containing microalloy steel [4, 10, 16–18]. However, the effect of Nb content on

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the hot deformation behavior of microalloyed steels has not been studied extensively.

Thus, the objective in this work is to study the effect of Nb content on the hot deformation behavior of steel.

2 Experimental

The material used in this study was S460ML steel and its chemical composition is given in Table 1. The test specimens were machined from S460ML steel with a size of $\phi 8 \text{ mm} \times 12 \text{ mm}$.

All the single-pass compression tests for the study of dynamic recrystallization were carried out on the Gleeble-1500 thermo-machine simulator. The specimens were heated to 1200 °C at a speed of 10 °C s⁻¹, held for 300 s and then cooled at a speed of 10 °C s⁻¹ to the required deformation temperature. After 10 s holding, the specimens were compressed at constant deformation temperature and strain rate. The deformation temperatures and strain rates were 1200, 1150, 1100, 1050, 1000, 900 °C and 0.1, 0.5, 1.0, 3.5, 5.0 s⁻¹, respectively. The deformation amount was 50% for all tests.

After the hot compression was completed, the specimens were immediately quenched in water, in order to keep the microstructure after hot deformation. Then, the specimen was cut along the compression direction from the center of the diameter. After polished and corroded, the original austenite grain morphology was observed. Considering the inhomogeneity of hot deformation [19, 20], the location for observing original austenite grain morphology was in the center of cutting surface.

3 Results and Discussion

3.1 Effect of Nb Content on the Experimental Conditions of Dynamic Recrystallization

The true stress–strain curves of the Nb-free S460ML steel at different deformation temperatures and different strain rates are shown in Fig. 1. It can be seen from Fig. 1 that the work hardening was very obvious at the beginning of

deformation, and the true stress increased sharply with the increase in true strain. Thereafter, due to the increase in dynamic softening, the true stress slowly increased or decreased with the increase in true strain. When the strain rate was 0.1 s⁻¹, the peak value did not appear in the true stress–strain curve at 900 °C, as shown in Fig. 1a. The true stress increased with increasing true strain and remained at the stage of work hardening. At other temperatures, the true stress began to decrease after reaching the peak value, which means that the dynamic recrystallization occurred. With increasing strain rate, the deformation temperature for generating dynamic recrystallization increased, as shown in Fig. 1b–e.

Similarly, the true stress–strain curves of S460ML steel with different Nb contents at different strain rates (0.1–5.0 s⁻¹) and deformation temperatures (900–1200 °C) were tested. The statistical results of experimental condition for occurring dynamic recrystallization are shown in Fig. 2. It could be found that for Nb-free and low level Nb content of steels, dynamic recrystallization could occur at 1000 °C at a strain rate of 0.1 s⁻¹, while it could occur at 1050 °C (for medium Nb steel) and 1100 °C (for high Nb steel), respectively, that is, the increase in Nb content inhibits the dynamic recrystallization. At the deformation temperatures of 1000–1200 °C, dynamic recrystallization could occur within the strain rate ranges of 0.1–5.0 s⁻¹ for the steels without Nb, low Nb steel and medium Nb steel, while high Nb steel could only undergo dynamic recrystallization at strain rates of 0.1 and 0.5 s⁻¹.

Based on the above discussion, the needed deformation temperature for dynamic recrystallization increased with the increase in the Nb content at a certain strain rate. Under the condition of constant deformation temperature, with the increase in Nb content, the strain rate required for dynamic recrystallization decreased, and the strain rate ranges, during which the dynamic recrystallization could occur, reduced. These results indicate that Nb content restrains the dynamic recrystallization, which is in good agreement with the experimental results in literature [21–24]. Nb is the strongest to restrain the austenite recrystallization. Nb solid solution in austenite affects the dynamic recrystallization [21]. In addition to solid solution, Nb can also form

Table 1 Chemical composition of S460ML steel (mass fraction, %)

Steels	C	Si	Mn	P	S	Ni	Al	Mo + V+Ti	Nb
Nb-free	0.03–0.04	0.2–0.25	1.4–1.6	0.009	0.003	0.4–0.6	< 0.03	< 0.20	0
Low Nb	0.03–0.04	0.2–0.25	1.4–1.6	0.009	0.003	0.4–0.6	< 0.03	< 0.20	0.01–0.02
Medium Nb	0.03–0.04	0.2–0.25	1.4–1.6	0.009	0.003	0.4–0.6	< 0.03	< 0.20	0.03–0.04
High Nb	0.03–0.04	0.2–0.25	1.4–1.6	0.010	0.003	0.4–0.6	< 0.03	< 0.20	0.05–0.06

Fig. 1 True stress-strain curves of Nb-free steel at different conditions: **a** 0.1 s^{-1} , **b** 0.5 s^{-1} , **c** 1.0 s^{-1} , **d** 3.5 s^{-1} , **e** 5.0 s^{-1}

Fig. 2 Experimental conditions for generating dynamic recrystallization for the steels with different Nb contents

compounds with C or N. These compounds can dissolve into the steel, precipitate either in the process of austenite deformation at high temperature or in the cooling process, restrain the recrystallization, and therefore improve the recrystallization temperature and expand the rolling space in non-recrystallization zone [22]. The second-phase particles dispersedly precipitated from the austenite have the effect to pin the grain boundary, increase the recrystallization grain growth activation energy, and lower the grain growth rate, playing the role in restraining the austenite recrystallization [23, 24].

3.2 Effect of Nb Content on the Critical Strain of Dynamic Recrystallization

3.2.1 Calculation of the Critical Strain of Dynamic Recrystallization

Studies [25, 26] showed that when the dynamic recrystallization softening of the material occurs, the curve between the work hardening rate (θ) and true stress (σ) will exhibit inflection point, and the dynamic recrystallization critical strain (ε_c) corresponds to the maximum value in $d\theta/d\sigma$ curve and the inflection point in θ - σ curve.

Fig. 3 True stress-strain curve of Nb-free steel at strain rate of 0.1 s^{-1} and $1200 \text{ }^{\circ}\text{C}$

Taking the true stress–strain curve of Nb-free steel obtained at a strain rate of 0.1 s^{-1} and 1200°C (see Fig. 3) as an example, the following shows how to calculate the critical strain of dynamic recrystallization based on the theory of work hardening rate.

In order to determine the slope of true stress (σ)–strain (ε) curve in Fig. 3, it is needed to fit the curve firstly (the fitting curve is also shown in Fig. 3) and get the fitting equation:

$$\begin{aligned} \sigma = & 7.18292 + 2106.91601\varepsilon - 40797.39531\varepsilon^2 \\ & + 425612.41016\varepsilon^3 - 2.53798\text{E}6\varepsilon^4 + 9.08586\text{E}6\varepsilon^5 \\ & - 1.99112\text{E}7\varepsilon^6 + 2.61741\text{E}7\varepsilon^7 - 1.89558\text{E}7\varepsilon^8 \\ & + 5.81496\text{E}6\varepsilon^9. \end{aligned} \quad (1)$$

The slope of the curve at different strain could be obtained by the derivation of the fitting Eq. (1), and then the relationship between working hardening rate and true stress is drawn, as shown in Fig. 4a. After that, the equation for describing the curve in Fig. 4a is obtained by polynomial fitting:

$$\begin{aligned} \theta = & 17825.42404 - 2093.01703\sigma + 98.88479\sigma^2 \\ & - 2.28402\sigma^3 + 0.02583\sigma^4 - 1.15089\text{E} - 4\sigma^5. \end{aligned} \quad (2)$$

Differentiating Eq. (2) and then drawing the $d\theta/d\sigma$ – σ curve, as shown in Fig. 4b. When $d^2\theta/d\sigma^2 = 0$, the stress corresponding to the inflection point (maximum value) on the curve in Fig. 4b is considered as the critical stress σ_c , and the strain corresponding to the stress σ_c in Fig. 3 is considered as the critical strain ε_c .

As shown in Fig. 4b, it can be seen that the maximum stress on the curve is 58.2 MPa and the true strain corresponding to 58.2 MPa in Fig. 3 is 0.13, which indicates that the critical strain of the dynamic recrystallization for Nb-free steel at 0.1 s^{-1} and 1200°C is 0.13.

3.2.2 Metallographic Observation of Dynamic Recrystallization

In order to verify the correctness of the above calculation results, a series of single-pass compression experiments were performed when the strains were 0.08, 0.11, 0.13, 0.15, 0.20 and 0.30, respectively.

It is known that the location in the specimen after hot deformation significantly affects the observation of the original austenite grain morphology. The studies from Jiang et al. [19] indicated that the microstructure and texture inhomogeneity in Cu/Nb added ultra-low carbon steels was found through the different layers during hot rolling and in the center layer the grains was fine and homogenous relatively. The texture in the surface layer mainly comprises orientations caused by plane strain deformation condition and in the center typical shear textures related to the shear strain distribution caused by milling are observed. Sander et al. [20] found that after 90% thickness reduction strong through-thickness texture and microstructure gradients were observed. These gradients were explained in terms of heavy shear at the surface and plane strain deformation in the center followed by strong dynamic and post dynamic recrystallization processes in the surface layers (top, bottom) and strong recovery in the center layer. Therefore, considering the microstructure and texture inhomogeneity in the specimen during hot deformation and the relatively homogenous in the center layer, in this study the center of cutting surface was selected as the location for observing original austenite grain morphology for all specimens.

Figure 5 shows the metallographic morphologies of the austenite grain of Nb-free steel under different strains at a strain rate of 0.1 s^{-1} and 1200°C . It can be seen clearly that the austenite grain was compressed and elongated when the strain was 0.08. When the strain was within the range of 0.11–0.13, most of the austenite grains were still

Fig. 4 Curves of θ versus σ **a** and $d\theta/d\sigma$ versus σ **b** of Nb-free steel at 1200°C with 0.1 s^{-1}

Fig. 5 Metallographic morphologies of austenite grain of Nb-free steel under different strains: **a** 0.08, **b** 0.11, **c** 0.13, **d** 0.15, **e** 0.20, **f** 0.30

elongated, but there was a small amount of recrystallized grains appeared in local austenite grain boundaries. As the strain increased, the number of recrystallization grain gradually increased. When the strain was 0.30, the elongated austenite grains were nearly disappeared and full dynamic recrystallization occurred.

Comparing the austenite grain morphologies under different strains in Fig. 5, it could be concluded that the critical strain of dynamic recrystallization for Nb-free steel at the strain rate 0.1 s^{-1} and 1200°C should be in 0.11–0.15. Based on the above working hardening rate theory, the calculated value for the dynamic recrystallization was 0.13, which is close to the results obtained from the metallography method. This is proved that it is feasible to calculate the critical strain of dynamic recrystallization according to the theory of the working hardening rate.

3.2.3 Effect of Nb Content on the Critical Strain of Dynamic Recrystallization

Based on the above method, the critical strain of dynamic recrystallization for different Nb contents of steels at different deformation temperatures and at a strain rate of 0.1 s^{-1} are listed in Fig. 6 (at low deformation temperatures, there were no data points for medium and high Nb contents in the steel, which represents no dynamic recrystallization occurred). It can be seen that with increasing Nb content, the required deformation temperature for generating dynamic recrystallization increased. Dynamic recrystallization could occur at 1000°C for Nb-

Fig. 6 Variation curves of critical strain for dynamic recrystallization with deformation temperature at strain rate of 0.1 s^{-1}

free and low content of Nb steels, while it was at 1050°C for medium content of Nb steel. For high content of Nb steel, only at 1100°C or above temperatures dynamic recrystallization could occur.

From Fig. 6, it could be also found that with increasing deformation temperature to 1100 and 1200°C , all steels with different Nb contents generated dynamic recrystallization. However, the addition of different contents of Nb showed different effects on the dynamic recrystallization. The critical strain of dynamic recrystallization between Nb-free steel and low content of Nb steel had little difference. However, for medium and high contents of Nb

steel, the critical strains of dynamic recrystallization were higher than those of Nb-free and low content of Nb steels, indicating that the addition of medium and high contents of Nb inhibits the occurrence of dynamic recrystallization.

Figure 7 shows the critical strain of dynamic recrystallization for different Nb contents of steels at different strain rates at 1200 °C (at high strain rate, there were no data points for high content of Nb steel, which represents no dynamic recrystallization occurred). It can be seen that the required strain rates for dynamic recrystallization were reduced with increasing Nb content at a certain deformation temperature. For the steels without Nb and with low and medium contents of Nb, the dynamic recrystallization could occur at the whole strain rate range (0.1–5.0 s⁻¹), while for the steel with high content of Nb, the dynamic recrystallization could occur only at low strain rates (0.1 and 0.5 s⁻¹). Moreover, the critical strain of dynamic recrystallization increased from zero, low, medium to high content of Nb steel.

These results indicated that the dynamic recrystallization became difficult with increasing Nb content, which was confirmed by other studies [21, 27]. Lei et al. [27] found that as a result of Nb addition, the critical strain for starting a DRX in 5% Ni steel was increased by 4–10% when deformed at a strain rate of 0.01 s⁻¹ and temperatures varied from 950 to 1000 °C, and the critical temperature for starting a DRX was also raised by 50 °C when deformed at a strain rate of 0.1 s⁻¹. The results from Qiao et al. [21] showed that the effects of Nb on hot deformation and phase transformation behaviors strongly lie on the behavior of Nb solid solution and precipitation during reheating and rolling processes, which has a strong relation to the contents of Nb and C in steels. With increasing the Nb content in steels, the amount of solid solution Nb in austenite increases during reheating. Dissolved Nb and

precipitation NbC can delay dynamic recrystallization and improve the dynamic recrystallization temperature.

3.3 Effect of Nb Content on Hot Deformation Activation Energy of Austenite

There are many empirical formulas for calculating the hot deformation activation energy of austenite [12, 13, 28, 29]. Here, the widely accepted hyperbolic sine function is used to represent the relationship among stress, deformation temperature and strain rate in the process of hot deformation [28]:

$$\dot{\epsilon} = A \{ \sinh(\alpha \sigma_p) \}^n \exp \left(-\frac{Q}{RT} \right), \quad (3)$$

where $\dot{\epsilon}$ is the strain rate, s⁻¹; σ_p is the peak stress, MPa; A is constant; n is the stress exponent; Q is the hot deformation activation energy of austenite, J/mol; R is the ideal gas constant, 8.314 J mol⁻¹ K⁻¹; T is the deformation temperature, K; α is the stress factor, MPa⁻¹. For carbon and low alloy steels, α is usually using 0.012 MPa⁻¹ [29].

The parameters in Eq. (3) can be calculated by the regression analysis method according to the deformation temperature, the strain rate and the peak stress in the true stress–strain curve.

First, the logarithm of the two sides of Eq. (3) can be shown as follows:

$$\ln \dot{\epsilon} = \ln A + n \ln [\sinh(\alpha \sigma_p)] - Q/RT. \quad (4)$$

When the strain rate $\dot{\epsilon}$ is constant, both sides of Eq. (4) differentiate with the reciprocal of temperature to get the following equation:

$$Q = Rn \left[\frac{\partial \ln [\sinh(\alpha \sigma_p)]}{\partial (\frac{1}{T})} \right]_s = Rnb. \quad (5)$$

When the deformation temperature T is constant, both sides of Eq. (4) differentiate with the peak stress σ_p to obtain the following equation:

$$n = \left. \frac{\partial \ln \dot{\epsilon}}{\ln [\sinh(\alpha \sigma_p)]} \right|_T. \quad (6)$$

Based on the above analysis, as long as the stress exponent n and the parameter b are obtained, the hot deformation activation energy of the austenite can be calculated according to Eq. (5).

Taking the Nb-free steel as an example. First of all, measuring its true stress–strain curves at different deformation temperatures and strain rates to obtain the peak stress data (σ_p), and then plotting the data of peak stress (σ_p), deformation temperature and strain rate, as shown in Fig. 8a, b. After that, the data points in Fig. 8a, b are linearly fitted, respectively.

Fig. 7 Variation curves of critical strain for dynamic recrystallization with strain rate at 1200 °C

Fig. 8 Relationship between peak stress and strain rate **a**, deformation temperature **b** for Nb-free steel

From the fitting equations (also shown in Fig. 8), it could be obtained that the slope of the curve was 4.36 in Fig. 8a and 0.7974 in Fig. 8b. So, the stress exponent n and parameter b were equal to 4.36 and 7974, respectively. By substituting the stress exponent n (4.36) and the parameter b (7974) into Eq. (5), it could be calculated that the hot deformation activation energy of austenite for Nb-free steel was $289.1 \text{ kJ mol}^{-1}$.

By using the same method, the hot deformation activation energies of different contents of Nb steels were obtained, e.g. $292.6 \text{ kJ mol}^{-1}$ (low Nb), $298.4 \text{ kJ mol}^{-1}$ (medium Nb) and $347.9 \text{ kJ mol}^{-1}$ (high Nb), respectively. It can be seen that with increasing Nb content, the hot deformation activation energy increased. However, the hot deformation activation energies of steels with low and medium contents of Nb had little difference with that of Nb-free steel, while it was obviously higher for high content of Nb steel than that of without Nb. These results indicate that the increase in Nb content enhances the hot deformation activation of steels, which is in good agreement with the experimental results of Qiao et al. [21], Xiao et al. [30] and Sellars et al. [31]. The effect of Nb on recrystallization is correlative to the variety of the Nb content dissolved in austenite and dynamic precipitation during the hot deformation under different conditions [21]. Dynamic soft process (dynamic recovery and/or recrystallization) of steel during hot deformation is controlled by the thermal activation, which is relative to the atomic diffusion ability. The hot deformation activation energy is roughly equal to the atom diffusion activation energy [31]. Adding Nb into steels can notably delay the dynamic recrystallization during the continuous deformation, and the deformation activation energy is raised notably because of the effect of atom drag [30].

3.4 Mathematical Model for Predicting the Critical Strain of Dynamic Recrystallization

In the process of hot deformation, whether dynamic recrystallization occurs or not is the comprehensive effect of many factors, such as deformation temperature, deformation amount, strain rate, hot deformation activation energy, and so on [12–15, 28, 29]. For the prediction of the critical strain of dynamic recrystallization, the most widely used model is the Sellars model [29, 31]:

$$\varepsilon_c = aZ^b, \quad (7)$$

$$Z = \dot{\varepsilon} \exp \frac{Q}{RT}, \quad (8)$$

where a and b are constants; $\dot{\varepsilon}$ is the strain rate, s^{-1} ; R is the ideal gas constant, $8.314 \text{ J mol}^{-1} \text{ K}^{-1}$; Q is the hot deformation activation energy of austenite, J/mol ; T is the deformation temperature, K ; Z is the Zener–Hollomon parameter, which is widely used to characterize the comprehensive effect between deformation temperature and strain rate in the process of hot deformation.

In order to establish the mathematical model for predicting the critical strain of dynamic recrystallization, the critical strain ε_c and the value of Z at different deformation temperatures and strain rates for Nb-free steel are calculated according to the theory of the hardening rate and Eq. (8), respectively. The relationship between $\ln \varepsilon_c$ and $\ln Z$ is shown in Fig. 9. It can be seen from Fig. 9 that $\ln \varepsilon_c$ shows approximate linear relationship with $\ln Z$. By linear fitting, the fitting equation is shown as follows:

$$\ln \varepsilon_c = -5.34416 + 0.16461 \ln Z. \quad (9)$$

By comparing Eq. (7) with (9), it could be obtained that the constants a and b are 4.78×10^{-3} and 0.16461,

Fig. 9 Relationship between $\ln \varepsilon_c$ and $\ln Z$ for Nb-free steel

respectively. Substituting a and b to Eq. (7), to get the following equation:

$$\varepsilon_c = aZ^b = 4.78 \times 10^{-3} Z^{0.165}. \quad (10)$$

By substituting Eq. (8) and the value of the hot deformation activation energy Q into Eq. (10), the mathematical model for predicting the critical strain of dynamic recrystallization for Nb-free steel can be expressed as:

$$\varepsilon_c = 4.78 \times 10^{-3} \left(\dot{\varepsilon} \exp \frac{34767}{T} \right)^{0.165}. \quad (11)$$

Thus, under the given deformation temperature and the strain rate, the critical strain of dynamic recrystallization can be calculated according to Eq. (11) which is usually called as Z parameter model.

From the above discussion, when the dynamic recrystallization occurs, the true stress–strain curve shows a peak, and the peak stress (σ_p) and strain (ε_p) can be easily read out from the stress–strain curve. However, the critical strain (ε_c) cannot be directly read out from the stress–strain curve and needs to be obtained from a series of mathematical calculations.

In order to obtain the relationship between critical strain (ε_c) and peak strain (ε_p), the value of them obtained under different deformation temperatures and strain rates are drawn in Fig. 10. It can be seen that there is a good linear relationship between the critical strain (ε_c) and peak strain (ε_p), which is in good agreement with the experimental results of Zhu et al. [32] and Sellars et al. [33]. By linear fitting, the relationship between the critical strain (ε_c) and the peak strain (ε_p) can be shown as follows:

$$\varepsilon_c \approx 0.73\varepsilon_p. \quad (12)$$

By the same method, the mathematical models for predicting the critical strain of dynamic recrystallization for steels with different Nb contents can be also obtained, as

Fig. 10 Relationship between critical strain ε_c and peak strain ε_p for Nb-free steel

Table 2 Mathematical model for predicting critical strain of dynamic recrystallization for steels with different Nb contents

Steels	Z parameter model	Peak strain model
Nb-free	$\varepsilon_c = 4.78 \times 10^{-3} \left(\dot{\varepsilon} \exp \frac{34767}{T} \right)^{0.165}$	$\varepsilon_c \approx 0.73\varepsilon_p$
Low Nb	$\varepsilon_c = 2.98 \times 10^{-3} \left(\dot{\varepsilon} \exp \frac{35194}{T} \right)^{0.178}$	$\varepsilon_c \approx 0.74\varepsilon_p$
Medium Nb	$\varepsilon_c = 1.74 \times 10^{-3} \left(\dot{\varepsilon} \exp \frac{35893}{T} \right)^{0.198}$	$\varepsilon_c \approx 0.73\varepsilon_p$
High Nb	$\varepsilon_c = 8.53 \times 10^{-3} \left(\dot{\varepsilon} \exp \frac{41847}{T} \right)^{0.115}$	$\varepsilon_c \approx 0.8\varepsilon_p$

listed in Table 2. The results showed that the ratio of the critical strain to the peak strain for steels with different Nb contents was about 0.7–0.8.

4 Conclusions

The hot deformation behavior of S460ML steel with different Nb contents at different deformation temperatures and strain rates was investigated. The following conclusions could be drawn:

1. The dynamic recrystallization occurred during hot deformation. As the deformation temperature increased and strain rate decreased, the critical strain of dynamic recrystallization decreased.
2. As Nb content increased, the needed deformation temperature for generating dynamic recrystallization increased, while the needed strain rate for it decreased.
3. The critical strain (ε_c) showed linear relationship with peak strain (ε_p): $\varepsilon_c/\varepsilon_p = 0.7\text{--}0.8$.
4. The hot deformation activation energy of S460ML steel increased with increasing Nb content.

References

- [1] J. Dong, C. Li, C.X. Liu, Y. Huang, L.M. Yu, H.J. Li, Y.C. Liu, *J. Mater. Res.* **32**, 3777 (2017)
- [2] J. Dong, X.S. Zhou, Y.C. Liu, C. Li, C.X. Liu, H.J. Li, *Mater. Sci. Eng. A* **690**, 283 (2017)
- [3] Z.Q. Wang, H. Zhang, C.H. Guo, W.B. Liu, Z.G. Yang, X.J. Sun, Z.Y. Zhang, F.C. Jiang, *J. Mater. Sci.* **51**, 4996 (2016)
- [4] R.J. Song, N. Fonstein, H.J. Jun, N. Pottore, D. Bhattacharya, S. Jansto, *Metallogr. Microstruct. Anal.* **3**, 174 (2014)
- [5] A. Pandit, A. Murugaiya, A.S. Podder, A. Haldar, D. Bhat-tacharjee, S. Chandra, R.K. Rayb, *Scr. Mater.* **53**, 1309 (2005)
- [6] H.J. Mcqueen, *Encycl. Mater. Sci. Technol.* **1**, 2375 (2001)
- [7] T. Furuhashi, B. Poorganji, H. Abe, T. Maki, *J. Miner. Metals. Mater. Soc.* **59**, 64 (2007)
- [8] R.C. Souza, E.S. Silva, A.M.J. Jr, J.M. Cabrera, O. Balancin, *Mater. Sci. Eng. A* **582**, 96 (2013)
- [9] E.J. Giordani, A.M. Jorge, O. Balancin, *Scr. Mater.* **55**, 743 (2006)
- [10] T. Chandra, I. Weiss, J.J. Jonas, *Metal Sci. J.* **16**, 97 (1982)
- [11] W.F. Shen, L.W. Zhang, C. Zhang, Y.F. Xu, X.H. Shi, *J. Mater. Eng. Perform.* **25**, 2065 (2016)
- [12] D. Qian, Y. Peng, *J. Mater. Eng. Perform.* **24**, 1906 (2015)
- [13] M.R. Barnett, G.L. Kelly, P.D. Hodgson, *Scr. Mater.* **43**, 365 (2000)
- [14] S. Solhjoo, *Mater. Des.* **54**, 390 (2014)
- [15] J.R. Cao, Z.D. Liu, S.C. Cheng, G. Yang, *Acta Metall. Sin.* **43**, 35 (2007). (in Chinese)
- [16] W.L. Gao, G.R. Bai, Z.M. Zhou, G. Luan, C. Long, *Acta Metall. Sin. (Engl. Lett.)* **6**, 53 (1993)
- [17] X.G. Zhou, Z.Y. Liu, D. Wu, Z. Li, C.M. Li, *Acta Metall. Sin. (Engl. Lett.)* **19**, 385 (2006)
- [18] W.C. Xu, X. Ma, F. Sun, *Acta Metall. Sin. (Engl. Lett.)* **2**, 174 (1989)
- [19] Y.H. Jiang, Y.K. Park, O.Y. Lee, *Korean J. Mater. Res.* **17**, 634 (2007)
- [20] B. Sander, D. Raabe, *Mater. Sci. Eng. A* **479**, 236 (2008)
- [21] G.Y. Qiao, F.R. Xiao, X.B. Zhang, Y.B. Cao, B. Liao, *Trans. Nonferrous Metals Soc. China* **19**, 1395 (2009)
- [22] D.T. Jiao, Q.W. Cai, H.B. Wu, *J. Iron. Steel Res. Int.* **17**, 39 (2010)
- [23] G.F. Zhou, M.B. Wen, P.H. Li, X.L. He, *Acta Metall. Sin. (Engl. Lett.)* **2**, 623 (2000)
- [24] K.B. Kang, O. Kwon, W.B. Le, *Scr. Mater.* **36**, 1303 (1997)
- [25] G.V. Prasad, M. Goerdelem, G. Gottstein, *Mater. Sci. Eng. A* **400**, 231 (2005)
- [26] A.D. Rollett, U.F. Kocks, *Solid State Phenom.* **35**, 1 (1993)
- [27] X.R. Lei, Q.F. Ding, Y.Y. Chen, X.L. Rui, S.R. Li, Q.F. Wang, *J. Iron Steel Res. Int.* **20**, 38 (2013)
- [28] C. Sanghyun, K.B. Kang, J.J. Jonas, *ISIJ Int.* **41**, 766 (2001)
- [29] A. Laasroui, J.J. Jonas, *ISIJ Int.* **32**, 95 (1991)
- [30] F.R. Xiao, B. Liao, Y.Y. Shan, G.Y. Qiao, Y. Zhong, C.L. Zhang, K. Yang, *Mater. Sci. Eng. A* **431**, 41 (2006)
- [31] C.M. Sellars, W.J. McTegart, *Acta Metall.* **14**, 1136 (1966)
- [32] S.L. Zhu, H.Z. Cao, J.S. Ye, W.H. Hu, G.Q. Zheng, *J. Iron Steel Res. Int.* **22**, 264 (2015)
- [33] C.M. Sellars, *Mater. Sci. Technol.* **6**, 1072 (1990)