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Kinetics of austenite grain growth in medium-carbon niobium-bearing steel

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Abstract: In order to locate a reasonable heating system, the austenite grain growth behavior of Nb microalloyed medium carbon steel has been experimentally studied at various austenitizing temperatures and for different holding times. It is indicated that austenite grain growth increases with increasing austenitizing temperatures and holding times. Particularly when the austenitizing temperature was above 1100 °C, austenite grains grew rapidly, and an abnormal austenite grain growth was observed. When the austenitizing temperature was lower than 1100 °C, austenite grain size and growth rate were small. The activation energy of grain growth in the tested steel is 397 679.5 J/mol. To ensure an absence of coarse grains in microstructures, the heating technology of the tested steel should be controlled for 1 h at 1100 °C. The relationships of austenite average grain size with soaking temperature and time of tested steel were obtained by mathematical calculation, and austenite average grain size was found to be in agreement with the measured size for different holding times.

Key words: Microalloyed steel, Grain growth, Modeling
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1 Introduction

Microalloying and thermo-mechanical processing (TMCP) are currently being used to obtain the best combination of strength and resilience (Xue *et al*., 2007). The heating temperature of casting slab is one of the primary parameters in controlled rolling processes. Austenite grain growth is mainly influenced by the austenitizing temperature due to the precipitation of nitrides and carbonitrides. Mechanical properties of the steel plates are also influenced (Liu, 2004). It is important, therefore, to investigate the grain growth and the precipitation of nitrides and carbonitrides in the heating process (Sellars and Whiteman, 1979; Matsuura and Itoh, 1991; Manohar *et al*., 1996; Gavard *et al*., 1998).

Extensive researches have been carried out on austenite grain growth behavior in low carbon niobium (Nb)-bearing steels (Jiao *et al*., 2000; Yu and Sun, 2006). Little information is available, however, on medium carbon Nb-bearing steels. To locate a reasonable heating system, the goal of this experiment was to investigate the influence of the austenitizing temperature and holding time on the austenite grain growth kinetics of Nb microalloyed medium carbon steel during the heating process. The relationships of austenite average grain size with soaking temperature and time of tested steel were concurrently obtained via mathematical calculation.

2 Experimental

A Nb-bearing steel was used. The composition of the experimental steel is presented in Table 1.

Table 1 Chemical compositions of the steel investigated

Element	C	Si	Mn	Nb	S	P	N
Composition (%, w/w)	0.26	1.56	0.94	0.044	0.007	0.0069	0.0042

Cylindrical specimens (Φ8 mm×15 mm) were prepared for the experiment. The specimens were heated to different temperatures (950, 1000, 1050, 1100, 1150, and 1200 °C) and held for different times (0, 0.5, 1, 3, and 5 h) using an electric furnace chamber. Upon extraction from the furnace, the specimens were immediately immersed in water. To show the prior austenite grain boundaries, the immersed specimens were treated with a saturated picric acid aqueous solution using a small amount of the wetting agent. Austenite grains were subsequently observed by optical microscope. The austenite grain size was measured and evaluated using the average linear intercept method by software Sisc-Ias. To obtain a grain size distribution, a minimum of 200 grains were measured for each specimen.

3 Results and discussion

3.1 Austenite grain coarsening behavior

Fig. 1 shows the austenite grain morphologies of the tested steel austenitized at different temperatures for 1 h. According to Fig. 1, it can be seen that the austenite grain coarsens with increasing temperatures. The average austenite grain size as a function of heating temperature for 0.5 and 1 h is shown in Fig. 2. As shown in Fig. 2, the austenite grain of the tested steel at different temperatures for 0.5 h is finer than that of the steel for 1 h, and the mean grain size seems to grow incrementally with increasing temperature. Fig. 3 shows the relationship between soaking temperatures and grain sizes for different holding times. When the heating temperature was above 1100 °C for 1 h, abnormal austenite grain growth was observed, showing austenite grain sizes above 100 μm. Moreover, it was observed that grain sizes above 100 μm increased when exposed to different soaking temperatures for 0.5 h at each temperature. The grain coarsening temperature of the experimental steel was approximately 1100 °C.

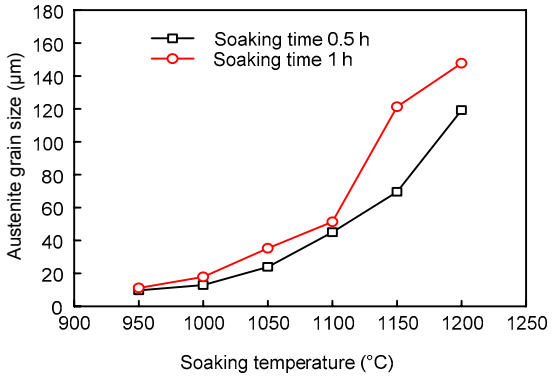

Fig. 2 Effect of soaking temperature on the austenite grain size

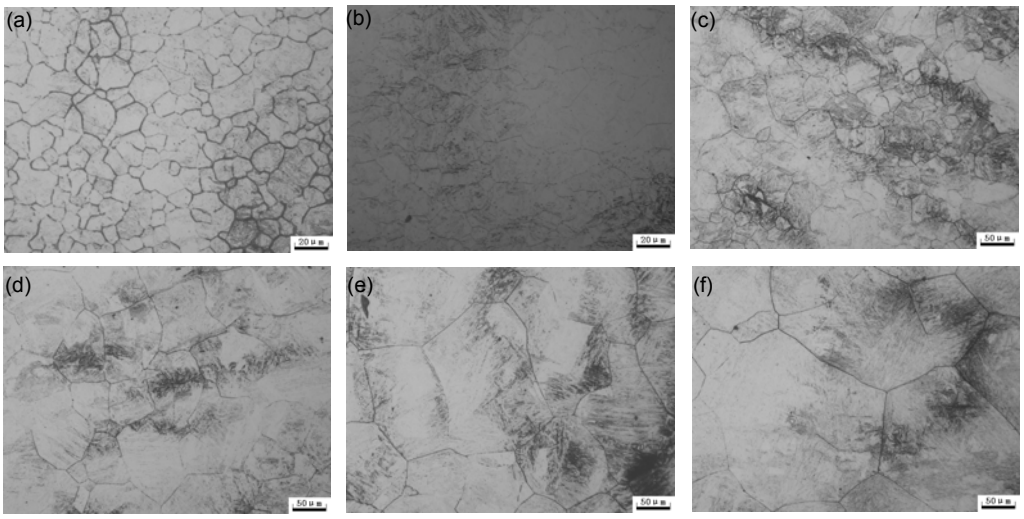

Fig. 1 Morphologies of austenite grain in experimental steel heated at different temperatures for 1 h
(a) 950 °C; (b) 1000 °C; (c) 1050 °C; (d) 1100 °C; (e) 1150 °C; (f) 1200 °C

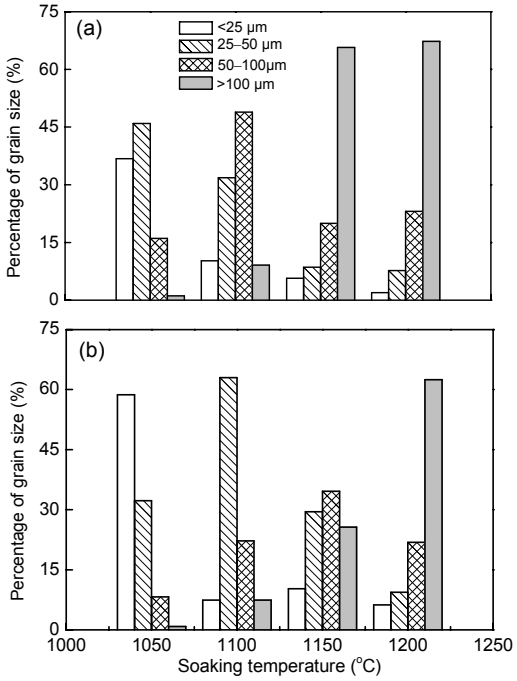

Fig. 3 Relationships between soaking temperatures and percentages of grain sizes for holding times of 1 h (a) and 0.5 h (b)

It has been well established that austenite grain size of microalloyed steels during the heating process is strongly dependant on the amount and size of pinning precipitates. Zener (1948) first developed a theory to describe the relationship between grain size and particles as

$$D=\frac{4}{3}\times\frac{d}{f_{\mathrm{v}}}, \tag{1}$$

which can be simplified as

$$D=k\times\frac{d}{f_{\mathrm{v}}}, \tag{2}$$

where D is the average grain size, k is a constant, and d and f_{v} are the size and volume fraction of second phase particles, respectively.

The principles of second phase particle coarsening kinetics are formulized in the following equation (Lifshitz and Slyozov, 1961):

$$d^3-d_0^3=\frac{8\sigma tVDC_{\mathrm{s}}}{9RT}, \tag{3}$$

where d is the final particle radius, d_0 is the initial particle radius, σ is the interfacial energy (800×10^{-7} J/cm), V is the molar volume of second phase particles (V_{NbC}=13.75 cm^3/mol), D is the diffusivity of solute in matrix, t is the time for particle coarsening (s), C_{s} is the concentration of the saturated solution, R is the universal gas constant (8.314 J/(mol·K)), and T is the absolute temperature (K).

Diffusivity (cm^2/s) of Nb in austenite (Nordberg and Aronsson, 1968) is formulized as

$$D_{\mathrm{Nb}}=0.83\mathrm{e}^{-266\,500/RT}, \tag{4}$$

$$\log\left([\mathrm{Nb}]\cdot[\mathrm{C}]\right)=2.96-7510/T, \tag{5}$$

where [Nb] and [C] are the percentages of Nb and C in solution in austenite, respectively.

Eq. (2), a simple explanation for the evolution of austenite grain size with the soaking temperature is found (it is well known that Nb dissolved into austenite during soaking and Ostwald ripening occurs during the holding process). According to Eq. (5) (Nordberg and Aronsson, 1968) and the stoichiometric relation of Nb:C (7.74), the Nb in solid solution and precipitation as a function of soaking temperature are shown in Fig. 4. According to Fig. 4, there is more Nb in solution and less Nb precipitated with increases in soaking temperature. Meanwhile, the initial particle radius is approximately 10 nm (Manohar *et al.*, 1996). Considering an initial mean particle radius of NbC, d_0=10 nm, and t=3600 s, we can estimate particles coarsening with increasing soaking temperatures as given in Fig. 5.

In summary, due to particle coarsening and a low volume fraction of second phase particles, during the soaking process, austenite grains grow slowly when below the critical temperature, but increase rapidly when above it.

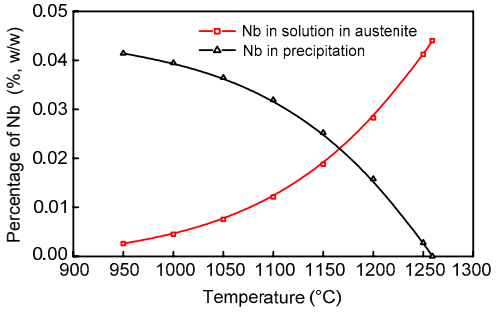

Fig. 4 Nb in solid solution and precipitation as a function of soaking temperature

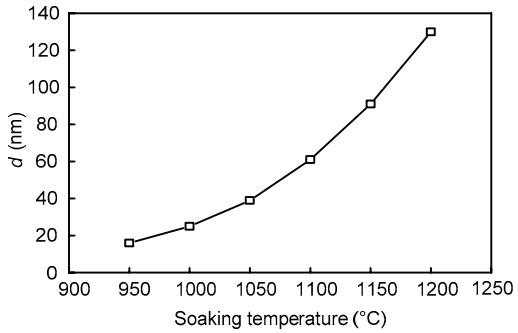

Fig. 5 Predicted particle coarsening in correlation to soaking temperature

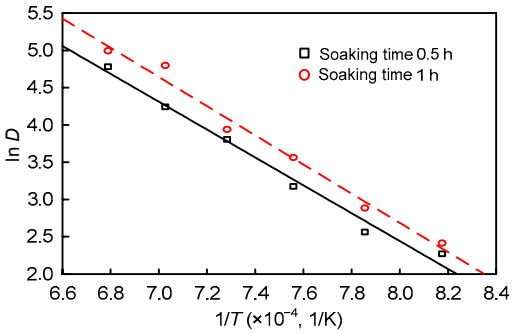

Fig. 6 Relationship between austenite grain diameter and soaking temperature

3.2 Activation energy for austenite grain growth

At present, most empirical models, which describe grain growth behavior of austenite, are based on the Sellars model (Sellars and Whiteman, 1979). This model relates the austenitic grain diameter $\overline{D}$ to the soaking time t and the absolute soaking temperature T by the following equation

$$\overline{D}(t)^n - \overline{D}_0^n = A\mathrm{e}^{-Q_g/RT}\cdot t, \tag{6}$$

where $\overline{D}_0$ is the initial average grain diameter, $\overline{D}(t)$ is the final average grain diameter, t is the holding time, Q_g is the activation energy for grain growth, and n and A are constants that depend on material composition and processing conditions.

Due to the initial average grain size $\overline{D}_0$ being small as compared to the final average grain size $\overline{D}(t)$ after holding time t, Eq. (6) can be simplified using the following equations

$$\overline{D}(t)^n = A\mathrm{e}^{-Q_g/RT}\cdot t, \tag{7}$$

when the soaking time is constant, we obtain

$$\ln\overline{D} \propto (-Q_g/nRT). \tag{8}$$

According to Eq. (8), the relationship between $\ln\overline{D}$ and $1/T$ is linear, and $(-Q_g/nRT)$ is the rate of slope. In Fig. 6, this linear relationship between $\ln\overline{D}$ and $1/T$ is clearly seen when the experimental steel soaks for 1 h at different soaking temperatures.

According to Fig. 6, $\ln\overline{D}$ can be expressed as

$$\ln\overline{D}_{1\,\mathrm{h}} = -19\,573.3/T + 18.35, \tag{9}$$

$$\ln\overline{D}_{0.5\,\mathrm{h}} = -18\,692.7/T + 17.4, \tag{10}$$

$$\frac{Q_g}{n} = \frac{19\,573.3 + 18\,692.7}{2}\times 8.314 \approx 159\,071.8\ (\mathrm{J/mol}). \tag{11}$$

Using the above equations, Eq. (6) can be defined as

$$\overline{D}(t)^n = A\mathrm{e}^{-159\,071.8n/RT}\cdot t, \tag{12}$$

A=1.03×10^{16} μm/s, n=2.5, Q_g=397 679.5 J/mol.

The mathematical model for austenite grain growth during the soaking process can, therefore, be expressed as

$$\overline{D}(t)^{2.5} - \overline{D}_0^{2.5} = 1.03\times 10^{16}\times \mathrm{e}^{-397\,679.5/RT}\times t. \tag{13}$$

The curves of calculated austenite average grain size and measured size for different heating temperatures are shown in Fig. 7. From Fig. 7, the curves demonstrate a reasonable agreement between calculated and experimental measurements.

3.3 Isothermal growth behavior of austenite grain

Morphologies of austenite grain austenitized at 1000 °C for different holding times (0, 0.5, 1, 3, and 5 h) are shown in Fig. 8. The austenite grain coarsening behavior as a function of soaking time is shown in Fig. 9. From Fig. 9, the relationship of average grain size and soaking time follows a parabolic relation. Up to a soaking time of 1 h, the grains grow rapidly, and then decrease after 1 h.

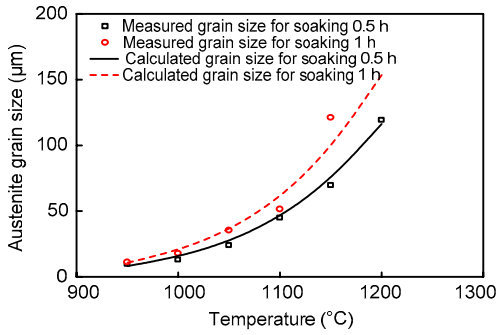

Fig. 7 Comparison of calculated austenite average grain size and measured size for different heating temperatures

Beck's equation (Beck *et al*., 1948) has generally been utilized to analyze isothermal grain growth kinetics, and is represented as

$$\overline{D} = kt^n, \tag{14}$$

where $\overline{D}$ is the average grain diameter, t is the holding time, and n and k are the time exponent and rate constant, respectively (Sangho *et al*., 2004), which are experimentally dependent on material and temperature.

According to Fig. 9, the relationship between average grain size $\overline{D}$ and holding time t at 1000 and 1100 °C can be expressed as follows:

$$\overline{D}_{1000\,°C} = 0.9t^{0.36}, \tag{15}$$

$$\overline{D}_{1100\,°C} = 2.25t^{0.38}. \tag{16}$$

Fig. 10 demonstrates that the calculated austenite average grain size is in agreement with the measured size for different holding times.

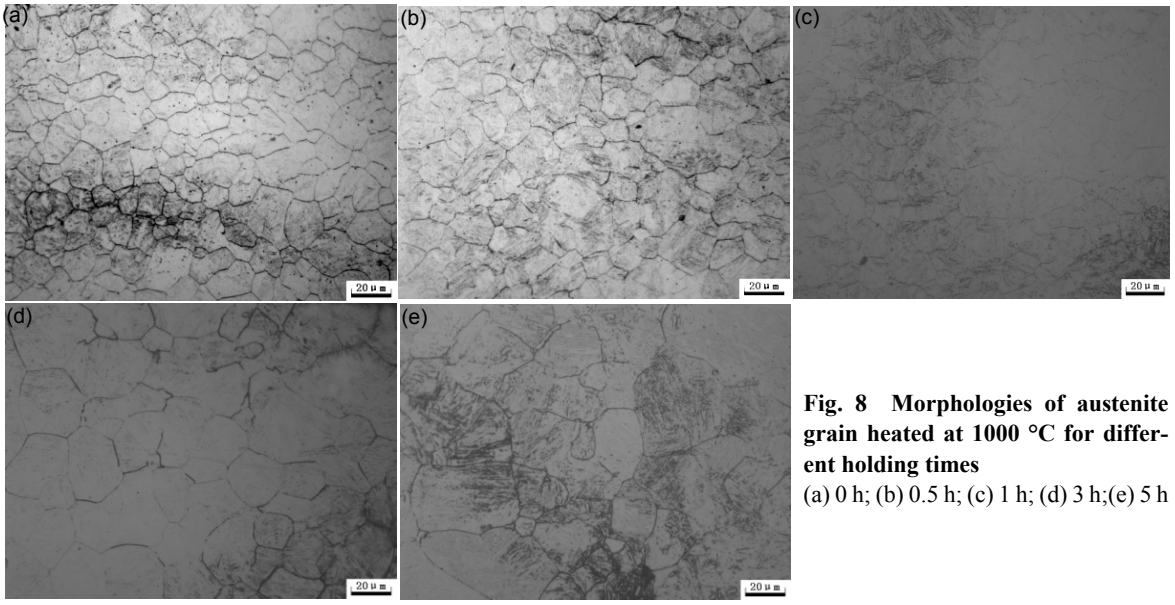

Fig. 8 Morphologies of austenite grain heated at 1000 °C for different holding times
(a) 0 h; (b) 0.5 h; (c) 1 h; (d) 3 h;(e) 5 h

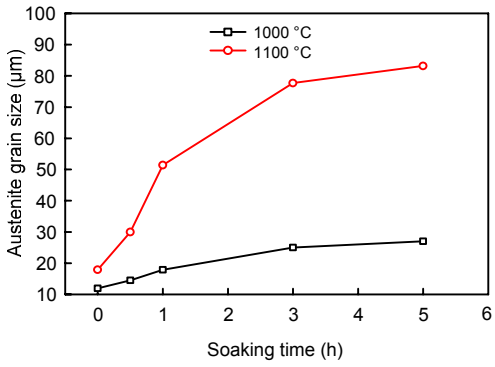

Fig. 9 Effect of soaking time on average grain diameter

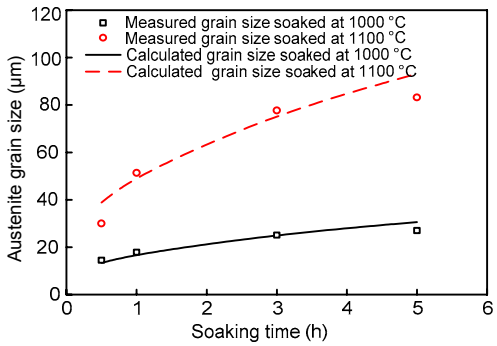

Fig. 10 Comparison of calculated austenite average grain size and measured size for different soaking times

4 Conclusions

1. Austenite grains coarsen with increases in soaking temperature and soaking time. When the experimental steel is soaking for 1 h and heated at different temperatures ranging from 950 to 1200 °C, the mathematical model for austenite grain growth and the activation energy for grain growth can be expressed as

$$\overline{D}(t)^{2.5}-\overline{D}_0^{2.5}=1.03\times10^{16}\times\mathrm{e}^{-397\,679.5/RT}\times t,$$
$$Q_{\mathrm{g}}=397\,679.5\ \mathrm{J/mol}.$$

2. The relationship between average grain size $\overline{D}$ and holding time t at 1000 and 1100 °C can be expressed as $\overline{D}_{1000\,^\circ\mathrm{C}}=0.9t^{0.36}$ and $\overline{D}_{1100\,^\circ\mathrm{C}}=2.25t^{0.38}$, respectively.

3. To ensure that no obvious coarse grains materialize in microstructures, the heating technology of the experimental steel should be controlled for 1 h at approximately 1100 °C.

References

Beck, P.A., Kremer, J.C., Demer, L.J., 1948. Grain growth in high purity aluminum and in aluminum-magnesium alloy. *Transaction of American Institute of Mining, Metallurgical, and Petroleum Engineers*, **175**:372.

Gavard, L., Montheillet, F., Coze, L.J., 1998. Recrystallization and grain growth in high purity austenitic stainless steels. *Scripta Materialia*, **39**(8):1095-1099. [doi:10.1016/S1359-6462(98)00276-0]

Jiao, S., Penning, J., Leysen, F., Houbaert, Y., Aernoudt, E., 2000. The modeling of the grain growth in a continuous reheating process of a low carbon Si-Mn bearing TRIP steel. *ISIJ International*, **40**(10):1035-1040. [doi:10.2355/isijinternational.40.1035]

Matsuura, K., Itoh, Y., 1991. Analysis of the effect of grain size distribution on grain growth by computer simulation. *ISIJ International*, **31**(4):366-371. [doi:10.4028/www.scientific.net/MSF.94-96.331]

Lifshitz, I.M., Slyozov, V.V., 1961. The kinetics of precipitation from supersaturated solid solution. *Journal of Physics and Chemistry of Solids*, **9**:35-50. [doi:10.1016/0022-3697(61)90054-3]

Liu, W., 2004. Effect of heating temperature on solid solution precipitation of second phase particles and grain growth. *Wide and Heavy Plate*, **10**(2):24-27 (in Chinese).

Manohar, P.A., Dunne, D.P., Chandra, T., Killmore, C.R., 1996. Grain growth predictions in microalloyed steels. *ISIJ International*, **36**(2):194-200. [doi:10.2355/isijinternational.36.194]

Nordberg, H., Aronsson, B., 1968. Solubility of niobium carbide in austenite. *Journal of the Iron and Steel Institute*, **12**:1263-1266.

Uhm, S., Moon, J., Lee, C., Yoon, J., Lee, B., 2004. Prediction model for the austenite grain size in the coarse grained heat affected zone of Fe-C-Mn steels: considering the effect of initial grain size on isothermal growth behavior. *ISIJ International*, **44**(7):1230-1237. [doi:10.2355/isijinternational.44.1230]

Sellars, C.M., Whiteman, J.A., 1979. Recrystallization and grain growth in hot rolling. *Metal Science*, **13**(3-4):187-194.

Xue, R.D., Zhao, Z.Y., Xie, J.X., Li, X.E., 2007. Effect of heating temperature on morphology and composition of undissolved particles in high strength steel containing Ti-Nb. *Journal of Iron and Steel Research*, **19**(4):80-84 (in Chinese).

Yu, Q.B., Sun, Y., 2006. Abnormal growth of austenite grain of low-carbon steel. *Materials Science and Engineering A*, **420**(1):34-38. [doi:10.1016/j.msea.2006.01.027]

Zener, C., 1948. Grain, phases and interface: an interpretation of microstructure. *Transaction of American Institute of Mining, Metallurgical, and Petroleum Engineers*, 1**75**: 15-51.