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Dynamic Recrystallization and Grain Growth Behavior of 20SiMn Low Carbon Alloy Steel[*]

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Abstract: A series of thermodynamics experiments were used to optimize the hot forging process of 20SiMn low-carbon alloy steel. A dynamic recrystallization and grain growth model was developed for the 20SiMn steel for common production conditions of heavy forgings by doing a nonlinear curve fit of the experiment data. Optimized forging parameters were developed based on the control of the dynamic recrystallization and the MnS secondary phase. The data shows that the initial grain size and the MnS secondary phase all affect the behavior of the 20SiMn dynamic recrystallization and grain growth.

Key words: 20SiMn; flow stress; dynamic recrystallization; grain growth; secondary phase

Introduction

Hot working of metallic materials results in work hardening. However, the materials also have several softening mechanisms, including dynamic recovery, dynamic recrystallization, meta-dynamic recrystallization, static recovery, and static recrystallization. Experiments have shown that the microstructure resulting from dynamic recrystallization gives better mechanical performance than the structures of other softening mechanisms because of the refined austenite grain size[1,2].

The hydro-generator shaft is a key part of heavy hydro-generator units, which demands superior mechanical performance. The most common material used in China for hydro-generator shafts is 20SiMn, which is a low carbon Si-Mn alloy steel. Previous work has indicated that refined grain sizes improve markedly the yield strength and failure limit. In forging, dynamic recrystallization is the most important means to refine the grain size. Thus, a dynamic recrystallization model is needed for 20SiMn to improve the manufacturing of 20SiMn hydro-generator shafts. This paper presents a dynamic recrystallization model for 20SiMn, with a grain growth model that is used to optimize the hot forming process based on the dynamic recrystallization and grain growth characteristics to improve the properties of the formed products.

1 Model Description

1.1 Dynamic recrystallization

The mechanical flow behavior of metals is normally based on the Zener-Hollomon parameter, which is a temperature-compensated strain rate function:

$$Z = \dot{\varepsilon} \exp(Q / (RT)) \tag{1}$$

where $\dot{\varepsilon}$ represents the strain rate, Q the activation energy for dynamic recrystallization, R the ideal gas constant $(8.31\ \mathrm{J \cdot mol^{-1} \cdot K^{-1}})$, and T the deforming temperature. Research showed that when dynamic recrystallization occurs in metallic materials, the peak stress in the flow stress curve is related to Z as[3,4]

$$Z = A\sigma_{\mathrm{p}}^{n} \tag{2}$$

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where A and n are material dependent constants.

When dynamic recrystallization occurs, the critical strain, ε_c, peak strain, ε_p, and the steady state strain, ε_s can be related to Z as

$$\varepsilon_p = A d_0^{\Gamma} Z^{m} \tag{3}$$

$$\varepsilon_s = B d_0^{\Gamma'} Z^{m'} \tag{4}$$

$$\varepsilon_c = a\varepsilon_p \tag{5}$$

where A, B, Γ, Γ', m, and m' are material dependent constants and a is always set to 0.8 for C-Mn steels[5].

An Avrami type expression is used to describe the kinematics of dynamic recrystallization in metallic materials[6]:

$$X = 1 - \exp\left[-k\left(\frac{\varepsilon - \varepsilon_c}{\varepsilon_p}\right)^n\right] \tag{6}$$

where X represents the volume fraction of the dynamic recrystallizations and k and n are material dependent constants.

The grain size of the dynamic recrystallization, d_{DRX}, is related to Z as

$$d_{\text{DRX}} = AZ^n \tag{7}$$

1.2 Grain growth

Various studies have shown that the optimized grain growth is given by[7,8]

$$d = \sqrt[m]{d_{\text{DRX}}^m + At\exp(-Q_G/(RT))} \tag{8}$$

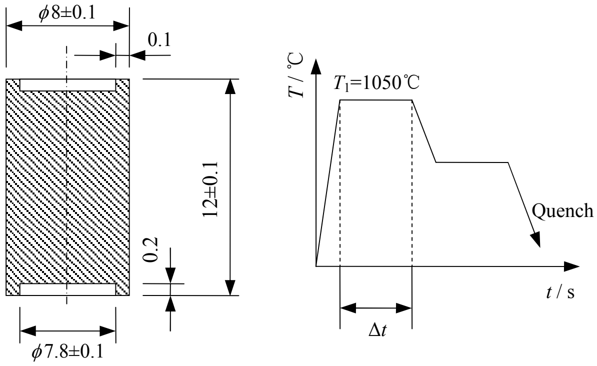
where d represents the grain size, t the holding time, and Q_G the activation energy for grain growth, while A and m are both material dependent constants.

2 Materials and Experimental Procedure

The chemical composition of the tested materials and its industry standard are listed in Table 1[9], with the sample specification and the compression test experimental procedures on GLEEBLE shown in Fig. 1. The samples were held for various holding times of 120 s, 240 s, and 480 s at 1050℃ before deforming to get different initial grain sizes of 14 μm, 25 μm, and 40 μm. The deforming temperatures are set as 800℃, 850℃, 900℃, 950℃, 1000℃, and 1050℃. The strain rates are set as 0.5 s^{-1}, 0.05 s^{-1}, and 0.005 s^{-1}. In the recrystallized grain growth experiments, the samples were compressed to above $1.5\varepsilon_s$ to achieve a completely recrystallized grain structure. The strains and strain rates are based on Eqs. (3)-(6). After the compression tests, the samples were immediately quenched to preserve the austenite grain structure with the measurements based on the average grain size at the axial center of each tested sample.

Table 1 Chemical composition of 20SiMn

	Chemical composition (%)				
	C	Si	Mn	S	P
Industry standard	0.16-0.22	0.60-0.80	1.00-1.30	≤0.025	≤0.025
Tested material	0.180	0.710	1.110	0.018	0.007



(a) Sample specification (mm) (b) Thermodynamic procedure

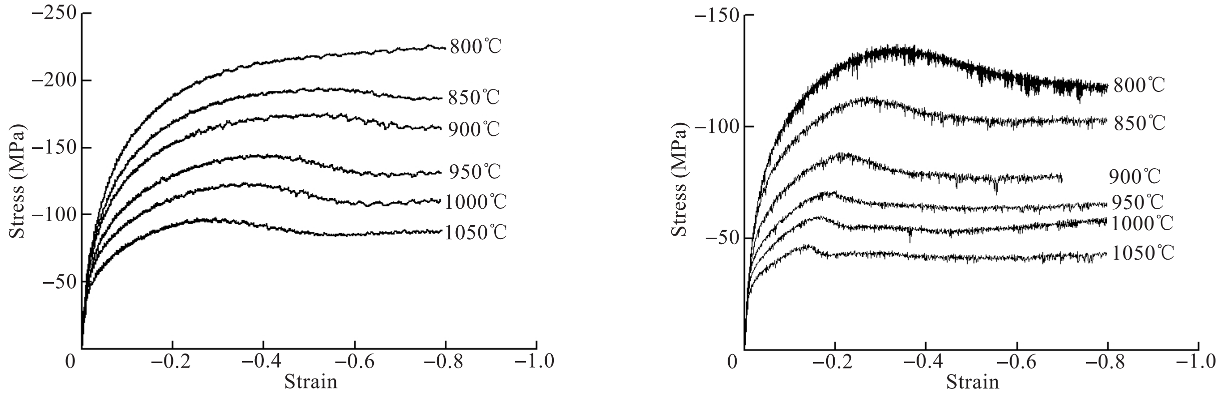
Fig. 1 Sample specification and thermodynamic test procedure

3 Results and Discussion

3.1 Flow stress curves

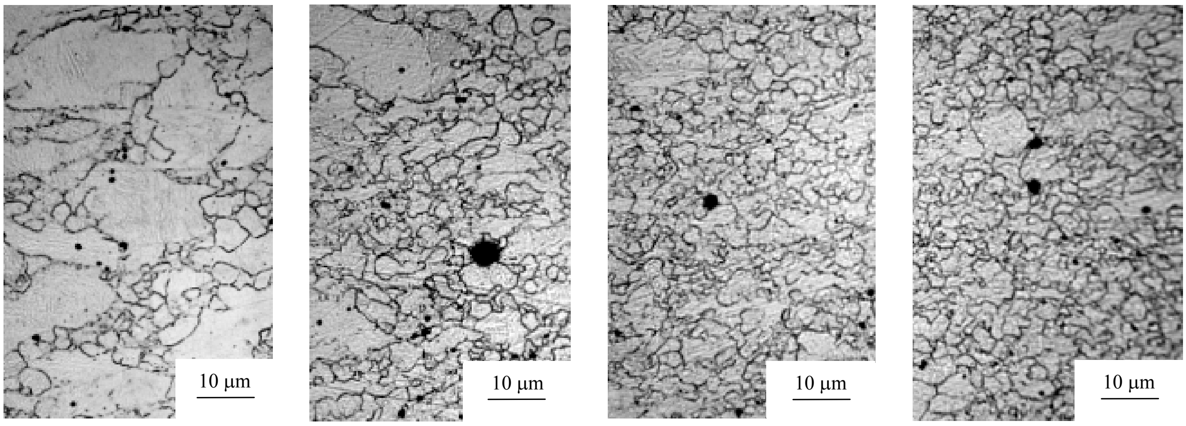
The stress-strain curves at different temperatures and strain rates are shown in Fig. 2, which shows that dynamic recrystallization occurred in most of the tested samples since the stress-strain curves have a peak followed by a slightly lower steady state stress. The metallographic research in Fig. 3 shows that refined grains exist along the original austenite grain boundaries.

The results also show that at higher strain rates, dynamic recrystallization occurs in the tested material only at higher temperatures, which means that increased temperatures and decreased strain rates will improve the softening in 20SiMn.



(a) High strain rate of 0.5 s^{-1} (d_0=25 μm) (b) Low strain rate of 0.005 s^{-1} (d_0=25 μm)

Fig. 2 Stress-strain curves of 20SiMn



(a) Recrystallization starts (b) Recrystallization process (c) Recrystallization process (d) Recrystallization completed

Fig. 3 Metallographic samples of 20SiMn during dynamic recrystallization at 900℃, 0.05 s^{-1}, and 25 μm

3.2 Recrystallization model

Nonlinear curve fits of the experimental data educed the following equations for dynamic recrystallization in 20SiMn.

$$Z = \dot{\varepsilon}\exp(317\,542.63/(RT)) = 0.119\sigma_{\mathrm{p}}^{6.61},$$

$$X = 1-\exp\{-1.930[(\varepsilon-\varepsilon_{\mathrm{c}})/\varepsilon_{\mathrm{p}}]^{1.392}\},$$

$$\varepsilon_{\mathrm{p}} = 0.005d_0^{0.120}Z^{0.127},$$

$$\varepsilon_{\mathrm{s}} = 0.005d_0^{0.266}Z^{0.128},$$

$$\varepsilon_{\mathrm{c}} = 0.8\varepsilon_{\mathrm{p}},$$

$$d_{\mathrm{DRX}} = 1266.89Z^{-0.1778}.$$

3.3 Grain growth

Figure 4 shows the growth process of recrystallized grains at different temperatures. The grains grow rapidly after being recrystallized, with the growth more apparent as the temperature increases. At each temperature, the grains have a maximum size, which contradicts Eq. (8). The regression of the experimental data using Eq. (8) resulted in correlation coefficients R_{c}, as low as 0.604, which indicates that Eq. (8) is not appropriate for the recrystallized grain growth process of 20SiMn at these forging temperatures.

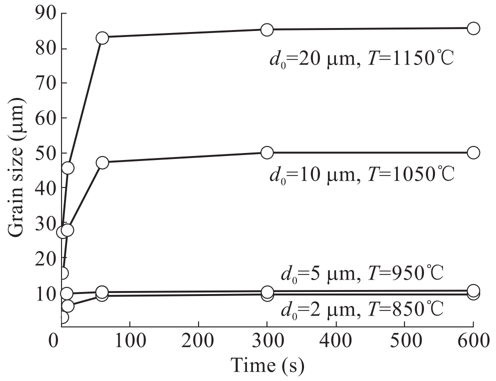


Fig. 4 Growth of 20SiMn recrystallized grains

Further experiments showed that if the time range was limited to within 60 s, R_{c} increased to 0.792, and to within 10 s, R_{c} was 0.941, which shows that Eq. (8)

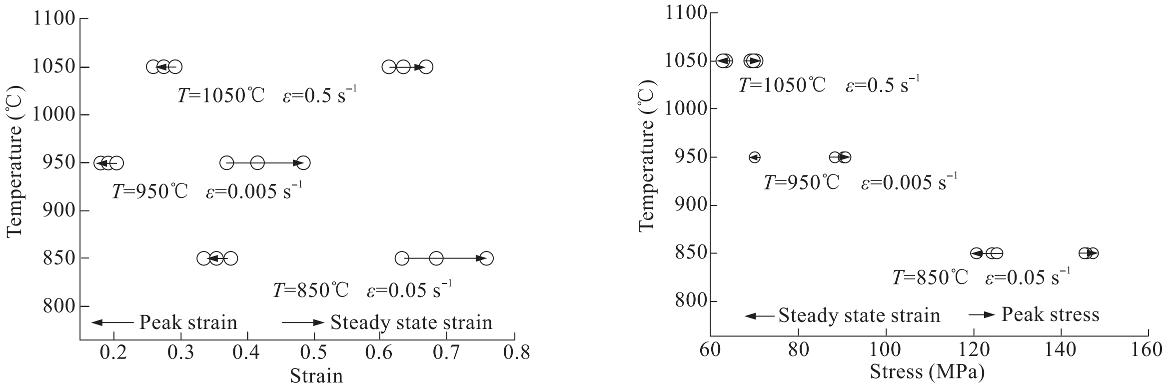
is more appropriate for describing grain growth at shorter times just after the recrystallization is completed. The reason for this is that the grain growth model in Eq. (8) is based on several assumptions such as ideal pure metals and unchanged grain shapes, which cannot be satisfied in actual industrial metal forming because of the secondary phase. However, just as the recrystallization grain growth begins, these factors are the dominant driving forces, so Eq. (8) fits the experimental data at those times. At later times, the obstructions of the grain growth by the secondary phase increase, so the assumptions are not appropriate and the recrystallized grain growth slows and Eq. (8) becomes less appropriate.

Therefore, the 20SiMn recrystallized grain growth model for t less than 10 s is

$$d = \sqrt[2.263]{d_{\mathrm{DRX}}^{2.263} + 2.52\times10^{10}\, t \exp(-223\,769/RT)}\ .$$

3.4 Effect of initial grain size on recrystallization

Initial grain size distribution reflects the density of the grain boundaries and dislocations, which to some extent affect the stress behavior of the metallic material. Figure 5a shows the peak strain and steady state strain distributions at different temperatures and strain rates for 20SiMn, in which the data points are in order of 14 μm, 25 μm, and 40 μm in the initial grain size from left to right. Thus, as the initial grain size increases, the peak strain, ε_{p}, and the steady state strain, ε_{s}, increase simultaneously. The increase of ε_{s} is more obvious than that of ε_{p}, which leads to the result that the finer initial grain structure will accelerate the dynamic recrystallization.



(a) Strain distribution

(b) Stress distribution

Fig. 5 Peak strain and peak stress distributions for 20SiMn dynamic recrystallization

Figure 5b shows the distribution of the peak stress and steady state stress at different temperatures and strain rates at initial grain sizes of 14 μm, 25 μm, and 40 μm. The data shows that the initial grain size has little effect on σ_{p} and σ_{s}; thus, they are only temperature and strain rate dependent which confirms the validity of Eq. (2).

3.5 Effect of temperature on grain growth

20SiMn grain growth rates at constant temperatures were measured after holding the samples to 2 h at various temperatures to make the grains grow to their maximum size without any deformation, after which the samples were quenched and the average grain sizes were measured. Figure 6 shows that the maximum grain sizes, also called steady state grain size, began to rapidly increase between 950℃ and 1000℃ after experiencing little change from 850℃ to 950℃. This limits the temperature of the final forging and the final rolling to under 1000℃ to keep the recrystallized austenite grains from growing.

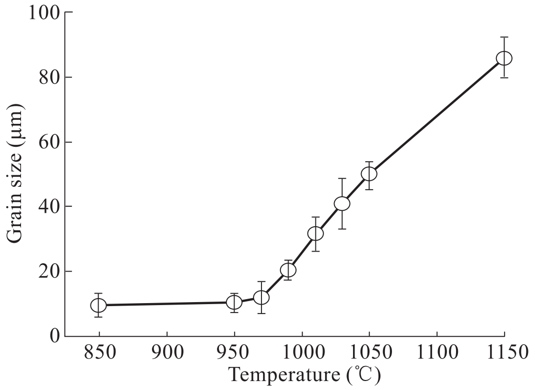
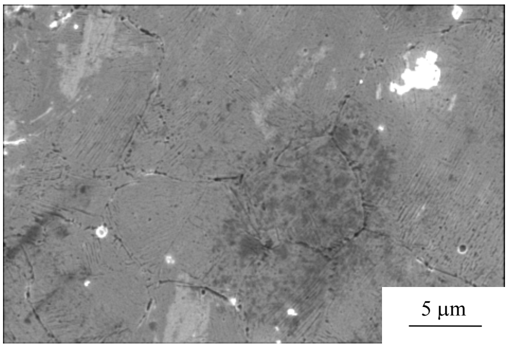
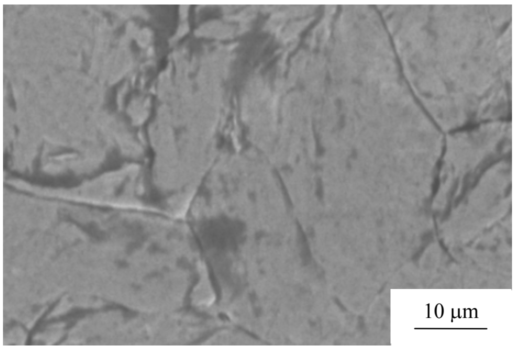


Fig. 6 Steady state grain size for 20SiMn

SEM photographs of corroded fully grown 20SiMn samples showed that secondary phase appears in the samples heat treated at temperatures less than 950℃, with very few at heat treatment temperatures above 1000℃ (Fig. 7). Energy spectra of the secondary phase showed the existence of substantial manganese and sulfur. Thus, the existence and disappearance of the compound MnS causes the sudden increase of the austenite grain size. As shown in Fig. 7, at lower temperatures (<950℃), MnS prevents the grain boundaries from moving and converging, so the grain structure is very fine. As the temperature rises, the MnS, whose solid solution point is about 950℃, starts to disappear, so a mixed grain structure exists. At temperatures over 1100℃, the MnS has almost totally dissolved, so the obstacles to grain movement are all removed. Coarse grains then occupy the whole area.



(a) 850℃, 10 kV



(b) 1150℃, 10 kV

Fig. 7 SEM photographs of the secondary phase distribution in 20SiMn

4 Conclusions

(1) As a typical low carbon alloy steel, 20SiMn exhibits good self-softening capability with hot forging or rolling. Dynamic recrystallization occurs in the metal at temperatures over 850℃ and strain rate lower than 0.5 s^{-1}.

(2) The initial grain size strongly affects the dynamic recrystallization of 20SiMn. Finer initial austenite grains accelerate the dynamic recrystallization.

(3) The recrystallized grains in 20SiMn grow rapidly after being deformed for more than 10 s. The traditional grain growth model is, therefore, only appropriate for times less that 10 s.

(4) When holding the samples at high temperatures, steady state grain size of 20SiMn steel increases rapidly above 950℃ due to rapid growth of the austenite grains. The MnS is the main factor causing the sudden increase in the grain size.

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