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EVOLUTION LAW OF GRAIN SIZE OF HIGH ALLOY GEAR STEEL IN HOT DEFORMATION

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Abstract

The change rules of deformation parameters such as temperature, strain and strain rate at different zones of forgings are very complex in the forging process of high alloy chromium-cobalt gear steel, and the deformation parameters have great influence on grain sizes. In this paper, recrystallization model for the steel was established with the material characteristic parameters obtained from the Gleeble isothermal compression test, influencing factors were analyzed based on the model. The results indicate that recrystallization grain size increases with increasing temperature and decreasing strain and strain rate, and the effect of temperature is more obvious than the other two. The average grain sizes are between 27.7μm~40μm at 1040℃ of forging temperature, grain size degree 6~6.5, meeting the product requirements.

Introduction

Gear is an important component transferring movement and load among the mechanical structure, usually processed by die forging. Its working environment is bad due to bearing the friction and stress load. With the rapid development of advanced equipment manufacturing, high strength and toughness requirements are put forward to meet these performances such as reliability, stability and long life. The main strengthening forms of a material include solid solution strengthening, dislocation, second phase and fine grain strengthening. Grain refinement has attracted widespread attention at home and abroad as it can simultaneously improve the yield strength and toughness of the material [1]. According to Hall-Petch formula [2] and the grain size, the relationship of yield stress and flow stress can be predicted [3]. Studies indicate that the grain size of heat treatment is positive correlate to that of die forging, while the grain size affects the performance of a forging, thus it is very necessary to investigate the evolution law of grain size during hot deformation for high alloy gearing steel.

Many researches have been carried out on the recrystallization of a material [5~14]. However, few studies are focused on the gearing forging. The grain size of a forging is usually required below 40μm. However, its control mainly relies on the experience, which easily leads to unstable control. In this work, the recrystallization model is established based on the thermal simulation test results, the effect of deformation parameters on the grain size is investigated, and the optimum forging parameters are put forward.

Research methods

Gleeble hot-compression simulation test

The main alloy composition of the investigated material is listed in Table 1. It was smelted in a 5t vacuum induced furnace then remelted in a 1t vacuum arc furnace, and then casting ingot and air-cooled to ambient temperature. The ingot was annealed at 1050℃ for 10h and then forged.
Cylindrical specimens of 12mm in length and 8mm in diameter were prepared for hot-compression tests with Gleeble-3800 thermal simulation tester. The strain of hot-compression test was $\varepsilon = 0.92$, samples were deformed at 700℃~1200℃ with 0.1, 1, 20, 50s^{-1} in sequence. The samples were heated to required temperature at the speed of 20℃/s, holding for 300s, compressed then water-cooled immediately. The quenched samples were cut along the axis. After grinded, polished and etched, the microstructures were observed with an Olympus GX51 optical microscope.

Table 1 Main chemical composition of the material

Elements	C	Si	Mn	Co	Ni	Cr	Mo	Fe
mass%	0.1~0.2	<0.1	<0.1	10~15	1~3	11~14	4~5	balance

Establishment of recrystallization model

The dynamic recrystallization of microstructures might occur during the hammer and the work piece contacting, and static recrystallization during the hammer alofting or workpiece air cooling. Based on F. Montheillet's research, YLJ model was chosen.

Dynamic recrystallization model:

$$\varepsilon_c = a_1 \cdot \varepsilon_p$$

$$\varepsilon_p = a_2 \cdot d_o^{h_2} \cdot \dot{\varepsilon}^{m_2} \cdot \exp\left(Q_2 / RT \right) + C_2$$

$$X_{drex} = 1 - \exp\left[-\beta_d \left(\frac{\varepsilon - a_3 \cdot \varepsilon_p}{\varepsilon_{0.5}} \right)^{k_d} \right]$$

$$\varepsilon_{0.5} = a_4 \cdot d_o^{h_4} \cdot \varepsilon^{n_4} \cdot \dot{\varepsilon}^{m_4} \cdot \exp\left(Q_4 / RT \right) + C_4$$

$$d_{drex} = a_5 d_o^{h_5} \varepsilon^{n_5} \dot{\varepsilon}^{m_5} \exp\left(Q_5 / RT \right) + C_5$$

Static recrystallization model

$$\dot{\varepsilon}_{ss} = A \cdot exp\left(b_1 - b_2 \cdot d_o - \frac{Q_{ss}}{T} \right)$$

$$X_{srex} = 1 - \exp\left[-\beta_s \left(\frac{t}{t_{0.5}} \right)^{k_s} \right]$$

$$t_{0.5} = a_6 \cdot \dot{\varepsilon}^{m_6} \cdot \exp\left(Q_6 / RT \right)$$

Grain growth model

$$d_g = \left[d_o^m + a_7 \cdot t \cdot \exp\left(-\frac{Q_7}{RT} \right) \right]^{1/m}$$

Average grain size model

$$D = X_{rex} \cdot d_{rex} + \left(1 - X_{rex}\right) \cdot d_o$$

Where

ε_c—critical strain; ε_p—peak strain; ε—strain; $\dot{\varepsilon}$—strain rate; d_0—initial grain size, μm; R—gas constant, 8.314J/(mol · K); T—temperature, K, X_{drex}—dynamic recrystallization ratio; X_{srex}—static recrystallization ratio; $\varepsilon_{0.5}$—strain at recrystallization 50%; d_{drex}—grain size of dynamic recrystallization, μm; $\dot{\varepsilon}_{ss}$—critical strain rate of static recrystallization, s^{-1}; t—static recrystallization time, s; $t_{0.5}$—time at static recrystallization 50%, s; d_g—grain size, μm; X_{srex}—recrystallization ratio; d_{rex}—recrystallization grain size, μm; D—average grain size, μm.

Calculation of model parameters

The dynamic recrystallization parameters were obtained by single pass hot simulation test. The stress and strain parameters obtained were fitted to get σ = σ (ε) function, drawing θ—σ curve with the results of σ on ε derivation to obtain ε_c and the maximum recovery stress σ_{sat}, back to stress-strain curve to get ε_c and ε_p, d_0, d_{drex} and X_{drex} were obtained by metallographic statistics.

The static recrystallization parameters were obtained by double pass hot compression test. The recrystallization ratio was calculated by the following formula:

$$X_{mrex} = \left(\sigma_m - \sigma_2\right) / \left(\sigma_m - \sigma_1\right)$$

Where σ_m is the unload stress at the first time, σ_1 and σ_2 are yield stresses for two loads.

Grain growth model was obtained by the grain sizes at different holding times.

Results and discussion

Figure1 gives part stress-strain curves. They are fitted and derivated to obtain stress-strain fitting curve and hardening rate curve as figure 2.

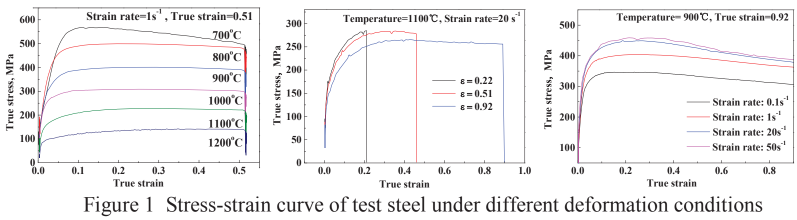

Figure 1 Stress-strain curve of test steel under different deformation conditions

Table 2 is the obtained parameters of recrystallization model. The effect of deformation parameters on dynamic recrystallization grain size is shown in Figure 3.

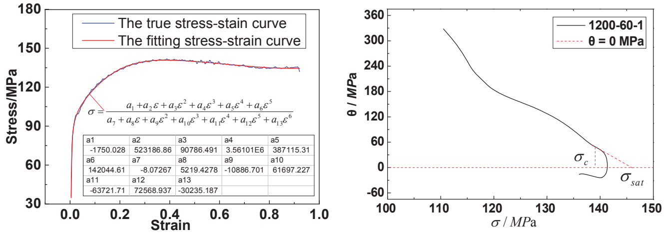

Figure2 Stress- strain fitting curve and hardening rate curve

Table 2 Parameters of recrystallization model

Parameters	Values	Parameters	Values	Parameters	Values	Parameters	Values	Parameters	Values
a_1	0.729	Qss	0	h_2	-0.0479	m_2	0.0454	n_4	1.7042
a_2	0.1299	Q_2	12898.7	h_4	0.1414	m_4	0.1208	n_5	-0.5373
a_3	0.379	Q_4	25839.04	h_5	0	m_5	-0.1888	A	0
a_4	0.3125	Q_5	-69965.58	C_2	-0.378	m_6	-0.3614	β_S	0.693
a_5	1649.9	Q_6	93402.79	C_4	0.18	m	1.1116	k_S	0.723
a_6	0.0003073	Q_7	66644.1	C_5	3.393	β_d	1.303		
a_7	7.444	b_1	0	b_2	0	k_d	-6.144		

From figure 3(a), the effect of temperature on grain size of dynamic recrystallization is obvious. The recrystallization grain sizes approximately linearly increase with increasing temperature. This is because some substances nailing on grain boundaries dissolve, their resistances to inhabit the austenite grain growth decrease. Part grains will break the restrictions from the precipitated phase particles and begin to grow, generating mixed grain phenomenon. When temperature continues to rise, Ostwald ripening of precipitation phase will occur, and the grains continue to grow [14,15].

The grain size increases by 30% when temperature increases 100℃. Comparing these curves at different strain and strain rate, the smaller the strain and strain rate are, the larger the effect of temperature on grain size is. When the strain is 0.2 and strain rate 0.15, the effect is the largest, grain size varies from 9μm to 18μm.

Figure 3(b) gives the relationship of strain and grain size of dynamic recrystallization. It is seen that the grain become smaller with the increase of the strain. When the strain is more than 0.5, its effect on grain size weakens significantly. The higher temperature and smaller strain rate are, the greater effect.

Figure 3(c) is the effect of strain rate on grain size of dynamic recrystallization. With the increase of strain rate, the grain size decreases slowly. When the strain rate is below $0.3s^{-1}$, there is larger effect of strain rate on grain size, while at strain rate is over $0.3s^{-1}$, the change is minor.

Comparing the three figures, it is found that the effects of temperature and strain are more significant than strain rate.

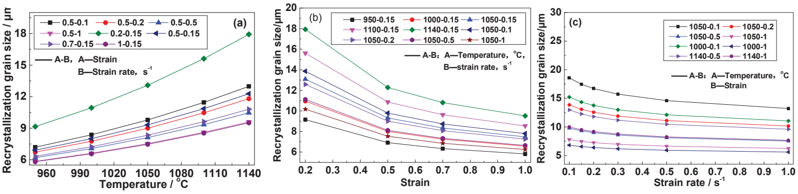

Figure3 Effect of deformation parameters on dynamic recrystallization grain size

Generally, the peak values of strain rate in the process of die forging are at $0.2s^{-1}$ ~$1.2s^{-1}$. The effect of strain rate on recrystallization grain size is smaller in this range from figure 3(c). For different batches of forgings, the strain change in the same region is also minor. Thus, the initial forging temperature is the main restrictive factor for the grain size of a gearing forging. In actual forging, when the temperature is at 1040^{o} C, the grain size is 27.7μm~40μm as in figure 4, grain size degree 6~6.5, meeting the product requirements.

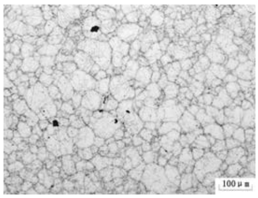

Figure4 The microstructure of actual forging at 1040^{o} C

Conclusions

(1) The recrystallization grain size of gear steel increases with increasing temperature and decreasing strain and strain rate, and the effect of temperature is more obvious than the other two.
(2) The average grain sizes are between 27.7μm~40μm at 1040℃ of forging temperature, grain size degree 6~6.5, meeting the product requirements.

Acknowledgements

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