J. Shanghai Jiaotong Univ. (Sci.), 2015, 20(5): 606-611
DOI: 10.1007/s12204-015-1668-x

Microstructure Evolution of Different Forging Processes for 12%Cr Steel During Hot Deformation

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Abstract: Five forging experiments were designed and conducted to investigate the effect of process parameters on microstructure evolution during hot deformation for X12CrMoWVNbN10-1-1 steel. The experimental results indicated that average grain size became finer with the increasing number of upsetting and stretching. Especially, the size of stretching three times with upsetting twice had the most remarkable effect on refinement, and the size was only 27.36% of the original one. Moreover, the stress model was integrated into the software and finite element models were established. Simulation results demonstrated that the strain at center point of workpiece was far larger than critical strain value in each process, so that dynamic recrystallization (DRX) occurred in each workpiece, which implied DRX could occur for several times with the increasing number of upsetting and stretching, and uniform finer microstructure would be obtained. However, the results also showed that higher temperature was an unfavorable factor for grain refinement, so the times of heating should be limited for workpiece, and as many forging processes as possible should be finished in once heating.
Key words: microstructure, forging process, hot deformation, grain size, numerical simulation
CLC number: TG 316.2 **Document code:** A

0 Introduction

X12CrMoWVNbN10-1-1 (12%Cr) ferrite heat-resistant steel is developed by adding alloy element-W based on 9Cr1Mo steel (X10CrMoBNb91) in the European COST51 Program[1]. It contains a number of alloying elements with good hardenability and excellent mechanical properties including strength and toughness, creep resistance, corrosion resistance and thermal fatigue resistance. It has been widely used to manufacture high and medium pressure rotor of ultra-supercritical generating units[2]. The part is heavy forging, and the general manufacture process is that heavy steel ingot is firstly deformed by free forging processes such as upsetting and stretching, then proper heat treatment processes are selected to obtain ideal microstructure and mechanical properties. Much research work has been done to study microstructure evolution and mechanical properties during heat treatment and creep processes[3-5]. The high-temperature plasticity behavior of the steel is becoming an important research field. Wang et al.[6-7] investigated the hot deformation behavior of 12%Cr steel through compression tests, the activation energy was calculated, and constitutive equations were established. Furthermore, the effect of processing maps and Zener-Hollomon parameter on thermal deformation was studied.

In this paper, five forging experiments were designed and carried out to investigate the effect of process parameters on microstructure evolution, and average grain size was measured. The stress model of 12%Cr steel was integrated into the finite element software-DEFORM3D and numerical simulation was implemented to analyze the influence law of the macroscopic field including temperature, strain and strain rate on microstructure.

1 Forging Experiments

Five forging experiments were conducted, and they were respectively upsetting once (U1), upsetting once with stretching once (U1S1), upsetting twice with stretching twice (U2S2), upsetting three times with stretching three times (U3S3), and stretching three times with upsetting twice (S3U2).

Reduction rate was 50% for the first upsetting, and reduction rate was 30% for the other. The process of wide-die heavy-blow forging (WHF) was selected for stretching, and its reduction rate was 20%. The original

Received date: 2013-11-01
Foundation item: the National Science and Technology Major Project of China (No. 2012ZX04012-011-02) and the National Basic Research Program (973) of China (No. 2011CB012903)
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shape of workpiece was cylinder with diameter of 60 mm and height of 100 mm. It was firstly heated to 1 250°C and held for 240 min. Then forging process was conducted at a 100 t hydraulic machine, and the velocity of top die was 1.0 mm/s. The material of top die and bottom die was H13 steel, and they were both cuboid and had the same dimension with length of 200 mm, width of 80 mm and height of 60 mm. The workpiece would be reheated to 1 250°C and held for 30 min when overload occurred in the machine. Figure 1 shows the initial position of workpiece, top die and bottom die. Quenching treatment was immediately conducted for workpiece after hot deformation, and the deformed workpieces were shown in Fig. 2.

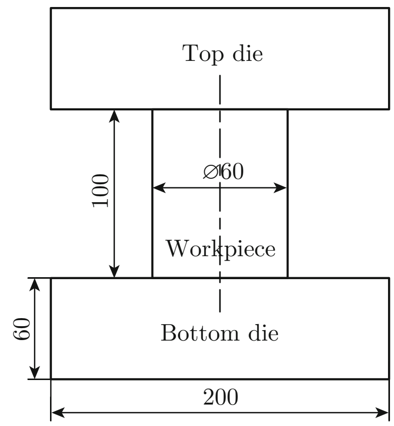


Fig. 1 Diagram of workpiece, top and bottom die (mm)

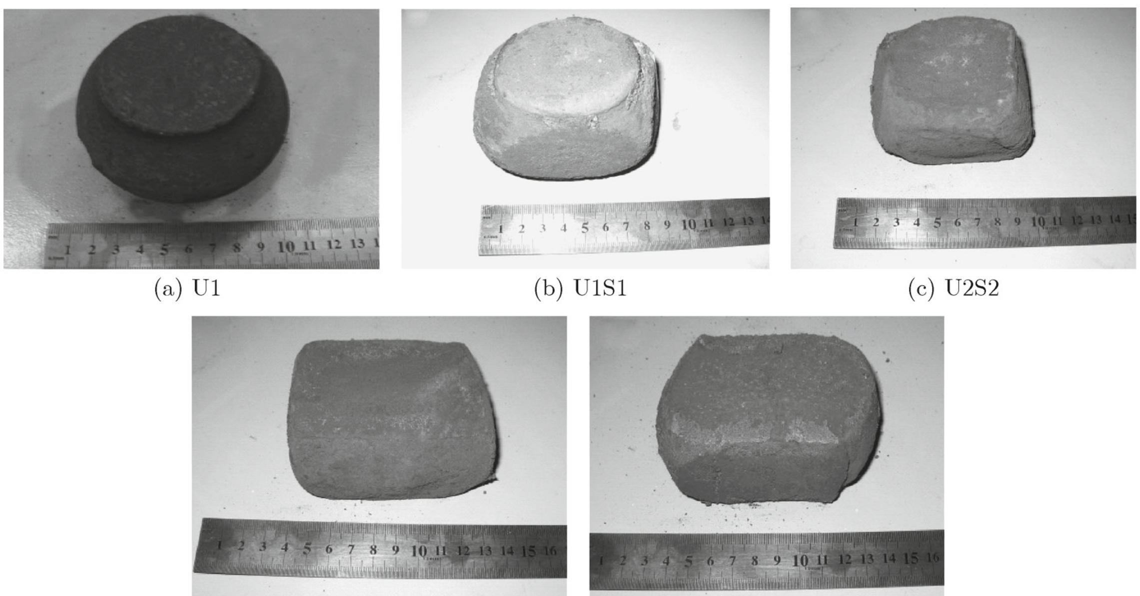

(a) U1 (b) U1S1 (c) U2S2 (d) U3S3 (e) S3U2

Fig. 2 Workpiece after deformation

The average grain size was measured by linear intercept method, and the detailed results were presented in Table 1.

Table 1 Average grain size of different forging processes

Process	Average grain size/μm
Original	138.04
U1	130.13
U1S1	128.77
U2S2	66.57
U3S3	60.13
S3U2	37.63

The deformed workpieces were sliced, and a specimen of 8 mm × 8 mm × 8 mm was sampled at the center of cross section, as shown in Fig. 3 for U1. Each sample was made into metallographic specimen, and the corresponding metallographic photos were shown in Fig. 4.

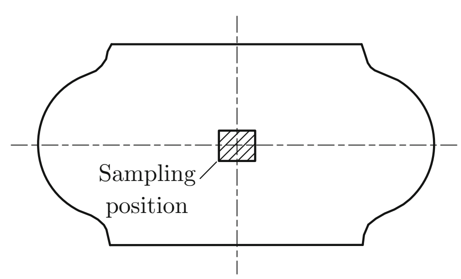
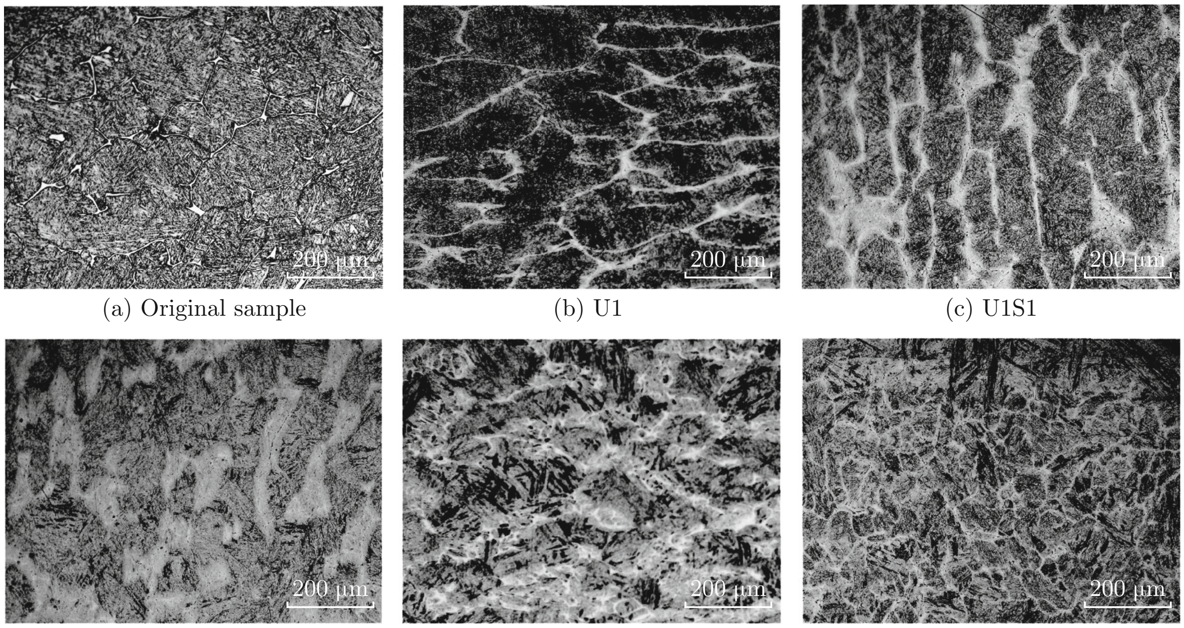


Fig. 3 Sampling position for metallographic specimen for U1



(a) Original sample (b) U1 (c) U1S1

(d) U2S2 (e) U3S3 (f) S3U2

Fig. 4 Metallographic photos

2 Finite Element Modeling

Finite element models were established for the five forging experiments, and numerical simulation was implemented to analyze the influence law of the macroscopic field on microstructure.

2.1 Material Properties

The isothermal compression tests were carried out on a Gleeble-1500D thermo-mechanical simulator to study the high-temperature plasticity behavior of 12%Cr steel. The tests were conducted at the temperature of 950, 1 050, 1 100, 1 150, 1 200, 1 250 °C and the strain rate of 0.1, 0.01, 0.001, 0.000 5 s^{-1}, respectively. The high-temperature flow stress curves were obtained, and some of them were shown in Fig. 5.

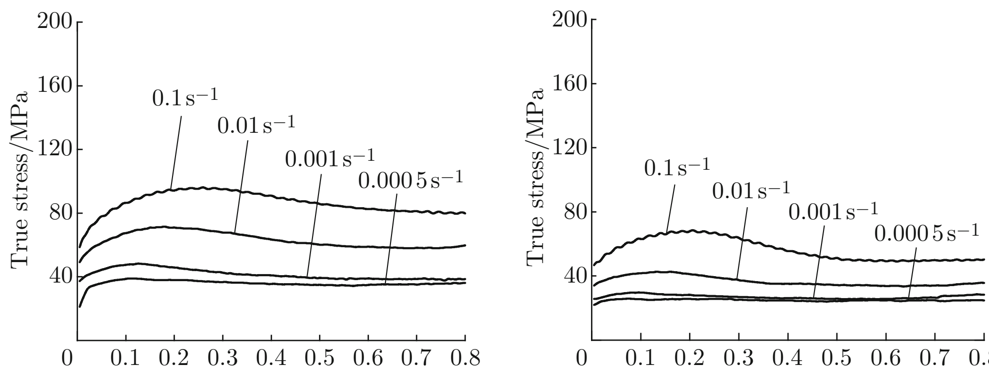
The stress model of 12%Cr steel was established and verified through the classical Laasraoui two-stage stress model based on the measured data[8-9], and the detailed derivation process can be referred to Ref. [10]. The stress model is given as

$$\left.\begin{aligned} &\sigma_{\mathrm{WH}} = [\sigma_{\mathrm{S}}^2 + (\sigma_0^2 - \sigma_{\mathrm{S}}^2)\exp(-\Omega\varepsilon)]^{0.5}, \quad \varepsilon < \varepsilon_{\mathrm{c}} \\ &\sigma = \sigma_{\mathrm{WH}} - (\sigma_{\mathrm{S}} - \sigma_{\mathrm{SS}})\times \\ &\qquad \left\{1 - \exp\left[-k_{\mathrm{d}}\left(\frac{\varepsilon - \varepsilon_{\mathrm{c}}}{\varepsilon_{\mathrm{p}}}\right)^{n_{\mathrm{d}}}\right]\right\}, \quad \varepsilon \geqslant \varepsilon_{\mathrm{c}} \end{aligned}\right\}, \tag{1}$$

where

$$Z = \dot{\varepsilon}\exp\left(\frac{452\,090.0}{RT}\right), \tag{2}$$

$$\varepsilon_{\mathrm{c}} = 0.83\varepsilon_{\mathrm{p}}, \tag{3}$$



(a) Temperature of 1 050 °C (b) Temperature of 1 150 °C

Fig. 5 Stress-strain curves of 12%Cr steel

$$\varepsilon_\mathrm{p} = 0.000\,94 Z^{0.14}, \tag{4}$$

$$\sigma_0 = 0.52 Z^{0.12}, \tag{5}$$

$$\sigma_\mathrm{S} = 43.77 \mathrm{arsinh}(2.49 \times 10^{-4} Z^{0.25}), \tag{6}$$

$$\sigma_\mathrm{SS} = 43.77 \mathrm{arsinh}(2.90 \times 10^{-4} Z^{0.24}), \tag{7}$$

$$\Omega = 155.11 Z^{-0.074}, \tag{8}$$

$$k_\mathrm{d} = 1.05, \tag{9}$$

$$n_\mathrm{d} = 1.24, \tag{10}$$

k_d and n_d are determined by the material property and deformation condition, R is gas constant, T is thermodynamical deformation temperature, Z is Zener-Hollomon parameter, σ is instant stress, σ_0 is initial stress, σ_WH is epitaxial stress of work hardening stage, σ_S is saturated stress, σ_SS is steady stress, Ω is softening amount of dynamic recovery, $\dot{\varepsilon}$ is strain rate, ε_c is critical strain, and ε_p is peak strain.

The stress model was integrated into the software-DEFORM3D to construct the material database by user subroutine.

2.2 Initial and Boundary Conditions

The initial conditions included 1 250.0°C initial temperature of workpiece and 20.0°C initial temperature of top die and bottom die.

The boundary conditions included: the heat transfer coefficient (HTC) between workpiece and environment was 20.0 W/(m^2·K), and the HTC between workpiece and die was 1.50 kW/(m^2·K). The friction factor between workpiece and die was 0.5.

Tetrahedral element was selected and the top die and bottom die were both meshed to guarantee simulation accuracy. The finite element model was established, as shown in Fig. 6.

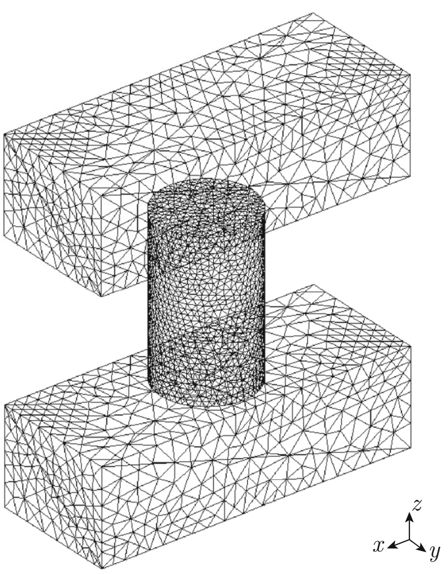


Fig. 6 Finite element model

3 Results and Discussion

3.1 Analysis of Experimental Results

It could be seen from Table 1 that average grain size became finer with the increasing number of upsetting and stretching. Compared with the original size, the size of processes U1 and U1S1 basically had not been refined, while the size of processes U2S2 and U3S3 had been refined and it was about 45% of the original one. Moreover, process S3U2 had the most remarkable effect on grain refinement, and the size was only 27.36% of the original one. The experimental results indicated that multiple upsetting and stretching processes were the important measurement for grain refinement when reduction rate was large enough in each process.

3.2 Analysis of Simulation Results

According to the experiments and sampling location, the center point of each workpiece was selected to display some simulation results which included temperature, equivalent strain, and equivalent strain rate. All the results were presented in Fig. 7—Fig. 11.

The minimum temperature, maximum equivalent strain and equivalent strain rate of center point in each forging process can be obtained from Fig. 7—Fig. 11. The detailed data were summarized in Table 2.

Table 2 Simulation results at center point

Experiment	Times of heating	Min temperature/°C	Max strain	Max strain rate/s^{-1}
U1	1	1 174.7	1.885	0.051
U1S1	2	1 043.3	2.402	0.051
U2S2	4	1 069.3	2.383	0.051
U3S3	7	1 145.6	1.885	0.065
S3U2	5	1 123.8	1.780	0.071

It is well known that grain size is related with critical strain, deformation temperature and strain rate when original grain size remains constant, and higher strain rate and lower temperature can facilitate the dynamic recrystallization (DRX) process and gain uniform finer microstructure when strain is larger than critical strain[11-12].

The lowest temperature is 1 043.3°C in Table 2. The corresponding critical strain is about 0.15—0.22 when strain rate is 0.01—0.1 s^{-1} and temperature is 1 050°C according to Fig. 1(a). A comprehensive analysis of strain curves in Fig. 7(b)—Fig. 11(b) shows that the strain at center point is far larger than critical strain value for each upsetting or stretching in any of experiment, which means DRX can occur in each process, and grain size can be refined step by step through multiple DRX with the increasing number of upsetting and stretching. Meanwhile, it can be found from Fig. 7(c)—Fig. 11(c) that higher strain rate can be gained for each upsetting or stretching so that DRX

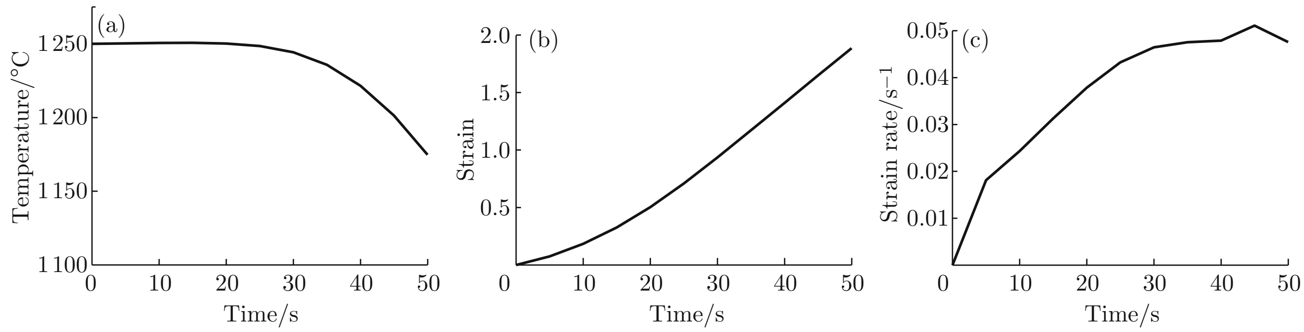


Fig. 7 Simulation results of U1 at center point

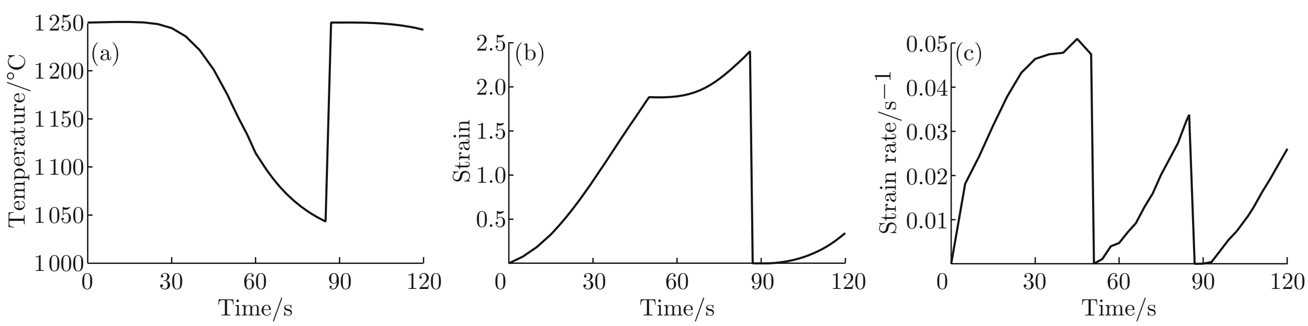


Fig. 8 Simulation results of U1S1 at center point

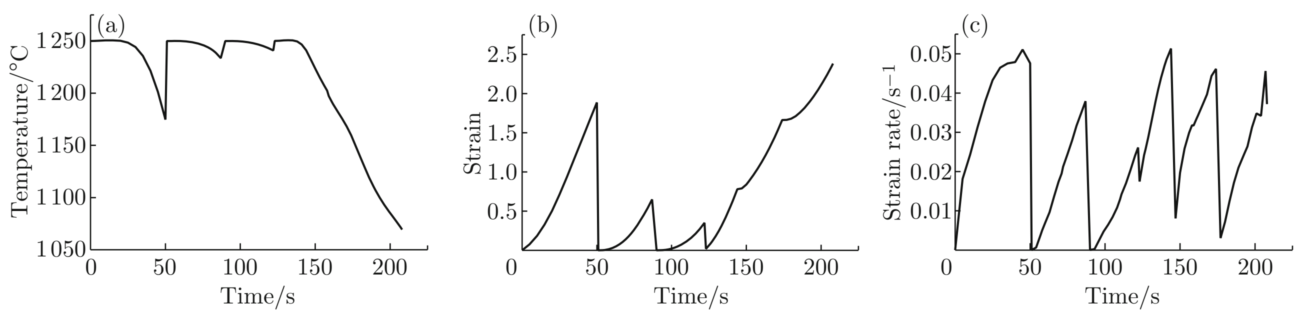


Fig. 9 Simulation results of U2S2 at center point

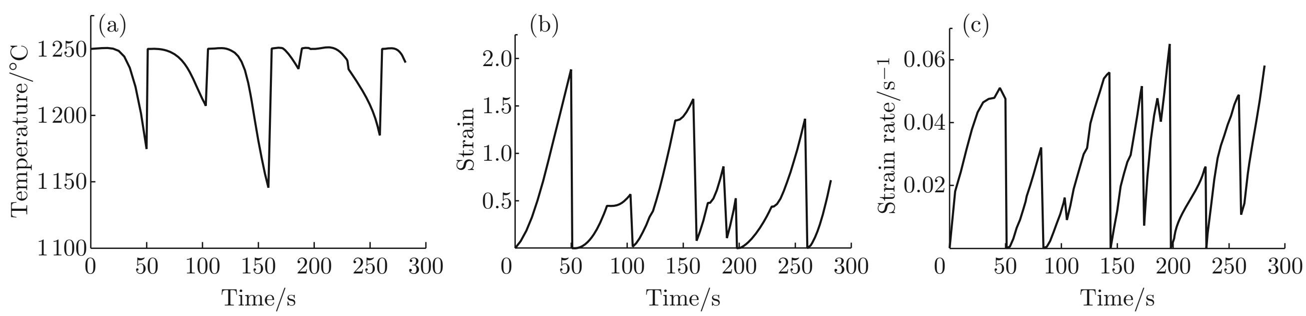


Fig. 10 Simulation results of U3S3 at center point

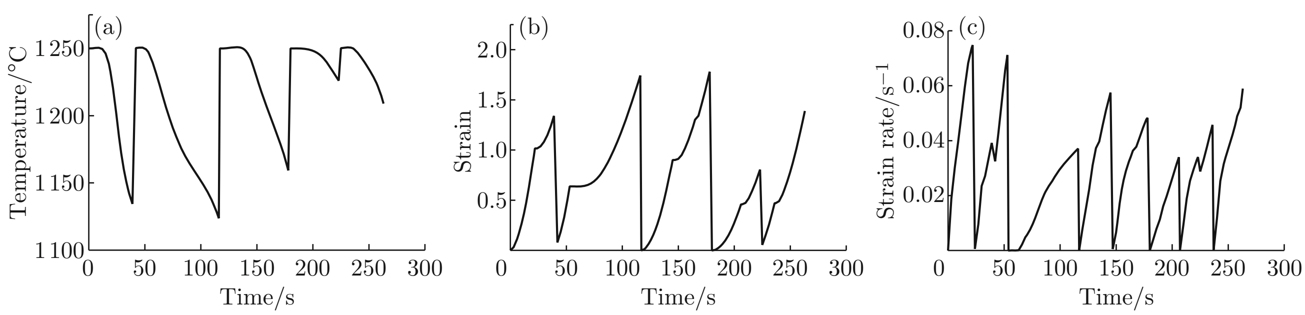


Fig. 11 Simulation results of S3U2 at center point

can be facilitated. Furthermore, it can be known from Fig. 7(a)—Fig. 11(a) that temperature curve differs from each other because of different times of heating. Multiple heating is an unfavorable factor for refinement because more times of heating can imply higher temperature field in workpiece. For example, workpiece was heated for seven times in U3S3 while five times in S3U2, which meant the temperature in S3U2 was higher than the temperature in U3S3, so process S3U2 obtained finer grain size.

Based on the above analysis and experimental results, the three processes of U2S2, U3S3 and S3U2 had better effect on grain refinement. Multiple upsetting and stretching processes meant that DRX could occur several times when strain was larger than critical strain. However, the times of heating for workpiece should be limited, and as many forging processes as possible should be finished in once heating which can facilitate DRX process and obtain uniform finer microstructure.

4 Conclusion

Five forging experiments were designed and conducted to study the effect of process parameters on microstructure. The experimental results indicated that the size of processes U1 and U1S1 basically had not been refined, while the size of processes U2S2 and U3S3 was about 45% of the original one, and the size of process S3U2 was only 27.36% of the original one. Multiple upsetting and stretching processes were the important measurement for grain refinement.

Finite element models were established for experiments. Simulation results demonstrated that the strain at center point of workpiece was far larger than critical strain value for each process, so that DRX could occur in workpiece, which meant DRX could occur for several times with the increasing number of upsetting and stretching, and uniform finer grain could be obtained.

The results of simulation and experiments showed that higher temperature field was an unfavorable factor to refine the microstructure, so the times of heating for workpiece should be limited, and as many forging processes as possible should be finished in once heating.

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