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Research Article

Microstructure Evolution of Multi-Heat Forging and Numerical Simulation for 316LN Steel

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Abstract: Microstructure evolution has been studied by multi-heat forging experiments and numerical simulation in order to determine the reasonable forging technology of 316 LN steel. The microstructure evolution models were obtained by hot compressive tests and heat treatment tests of 316 LN steels. The one-heat and three-heat upsetting experiments were carried on. Meanwhile, the corresponding numerical simulations were performed. The results show that, the grain uniformity of three-heat upsetting is much better that of one-heat upsetting. The average grain size of three-heat upsetting is smaller than that of one-heat upsetting. So, the forging technology of multi-heat and little deformation should be adopted for 316 LN steel forging. By comparing experimental average grain sizes with simulated average grain sizes for three-heat upsetting, it is found that the simulated values are in agreement with experimental values, which shows that the numerical simulation can be employed to predict the forging microstructure evolution of 316 LN steel.

Keywords: 316 LN, microstructure evolution, multi-heat forging, numerical simulation, re-crystallization

INTRODUCTION

In recent years, the microstructure evolution of the metals and alloys in hot forming process is a hot problem. Many studies have been carried out to predict the microstructure evolution during forging process (Cho *et al*., 2005; Ma *et al*., 2007; Lin and Chen, 2009; He *et al*., 2010). Ding *et al*. (2010) and Gu *et al*. (2011) investigated the microstructure evolution during rolling process. Faraji *et al*. (2012) and Tang *et al*. (2012) studied the microstructure evolution during extruding process.

316 LN steel is widely used as a major material for nuclear main pipe. Its plasticity is low and deformation resistance is large. In past, extensive studies have been focused on creep behavior (Kim *et al*., 2008; Vodárek, 2011; Ganesan *et al*., 2013), crack (Schwartz *et al*., 2010; Kang *et al*., 2011; Zhang *et al*., 2013), weld characteristic (Kim *et al*., 2009), cutting performance (Ozcelik *et al*., 2011) and plasticity at high temperature (Hei *et al*., 2012). However, the microstructure evolution of multi-heat forging for 316 LN steel has not been reported. Thus, the investigations of microstructure evolution of multi-heat forging are necessary to determine the forging technology of 316 LN steel.

In this study, the hot compressive tests and heat treatment tests of 316 LN stainless steels were performed. The re-crystallization models and grain growth model were derived. The reliability and accuracy of these models were verified by comparing experimental values with simulated results. The influence of one-heat forging and three-heat forging on microstructure of 316 LN steel was studied by upsetting experiments and numerical simulation. Based on these, the reasonable forging technology of 316 LN steel was determined.

MICROSTRUCTURE EVOLUTION MODELS

To simulate the microstructure evolution, the modeling of microstructure evolution process must be completed, namely, the quantitative relationships between material microstructure and deformation technology parameters are established (microstructure evolution models). Then, the models are integrated into the finite element software. The prediction of microstructure evolution is obtained by finite element calculation (Li *et al*., 2004).

The single-pass and double-pass compression experiments were conducted on Gleeble-1500 D thermal simulator. The heat treatment experiments were performed in heat treatment furnace. The 316 LN steels with the dimensions of Φ 8×12 mm were machined. The chemical composition (wt%) of 316 LN steel used in present study is C≤0.02%, Mn≤2.0%, Si≤0.7%, P≤0.025%, S≤0.005%, Cr = 16-18%, Mo = 2-3%, Cu≤0.1% and N = 0.1-0.16%. For heat treatment, the

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temperature range was 900-1200°C and the holding time range was 15-60 min and the initial grain size was about 22.5 and 75.5 μm. For single-pass compression, the temperature range was 900-1200°C. The strain rate ranged from 0.005 to 0.5 s^{-1}. The initial grain size was about 75 and 170 μm. For double-pass compression, the temperature range was 900-1150°C. The strain rate ranged from 0.005 to 0.1 s^{-1}. The initial grain size was about 75 and 170 μm. In the first pass, the strain was 0.1-0.5. In the second pass, the strain was 0.05. The interpass time was set according to deformation temperature. Based on Sellars model and Avrami equation, the models of re-crystallization and grain growth model were developed by regression of experimental data (Chen, 2010).

The models of dynamic re-crystallization are expressed as follows:

$$\begin{cases} \varepsilon_p = 0.012 d_0^{0.00037} \dot{\varepsilon}^{0.23} \left(\frac{45501}{RT}\right) \\ X_d = 1 - \exp\left[-1.778\left(\frac{\varepsilon - 0.668\varepsilon_p}{\varepsilon_{0.5}}\right)^{0.989}\right] \\ d_d = 7.23 \times 10^7 \dot{\varepsilon}^{0.00869} \exp\left(\frac{-183092}{RT}\right) \end{cases} \quad (1)$$

The models of meta-dynamic re-crystallization are expressed as follows:

$$\begin{cases} X_m = 1 - \exp\left[-0.693\left(\frac{t}{t_{0.5}}\right)^{0.88}\right] \\ t_{0.5} = 8.62 \times 10^{-15} d_0^{1.76} \dot{\varepsilon}^{-0.21} \exp\left(\frac{279876}{RT}\right) \\ d_m = 5.18 \times 10^2 d_0^{0.293} \varepsilon^{-0.0386} \exp\left(\frac{-50669}{RT}\right) \end{cases} \quad (2)$$

The models of static re-crystallization are expressed as follows:

$$\begin{cases} X_s = 1 - \exp\left[-0.693\left(\frac{t}{t_{0.5}}\right)^{0.75}\right] \\ t_{0.5} = 2.18 \times 10^{-16} d_0^{0.85} \varepsilon^{-1.419} \exp\left(\frac{353253}{RT}\right) \\ d_s = 7.7 \times 10^3 d_0^{0.4356} \varepsilon^{-0.317} \exp\left(\frac{-85446}{RT}\right) \end{cases} \quad (3)$$

The model of grain growth is expressed as follows:

$$D_t^{2.55} - D_0^{2.55} = 1.95 \times 10^{13} t_h \exp\left(-\frac{307578}{RT}\right) \quad (4)$$

where,

ε_p = Peak strain
d_0 = Initial grain size
$\dot{\varepsilon}$ = Strain rate
R = Molar gas constant
T = Thermodynamic temperature
$\dot{T}$ = Temperature rate
X_d = Volume fraction of dynamic re-crystallization
ε = Strain
$\varepsilon_{0.5}$ = Strain when re-crystallization volume fraction is 50%
d_d = Dynamic re-crystallization grain size
X_m = Volume fraction of meta-dynamic re-crystallization
t = Time of re-crystallization
$t_{0.5}$ = Time when volume fraction of re-crystallization is 50%
d_m = Meta-dynamic re-crystallization grain size
X_s = Volume fraction of static re-crystallization
d_s = Static re-crystallization grain size
D_0 = Initial average grain diameter
D_t = Average grain diameter when holding time is t_h, t_h is holding time

FORGING EXPERIMENT AND NUMERICAL SIMULATION

Forging experiment: The cylindrical specimens with 50 mm in diameter and 75 mm in height of 316 LN steel were machined. The initial average grain size is about 213 μm. In order to study the influence of one-heat forging and three-heat forging on microstructure of 316 LN steel, the upsetting experiments were divided into one-heat upsetting and three-heat upsetting. The total deformation was same in both cases. The experiments were conducted in 2000 KN hydraulic press. For one-heat upsetting, the specimen was deformed to the total deformation and then water quenched. For three-heat upsetting, the deformation of each heat upsetting was one-third of the total deformation and the specimen was treated with solution between heats. Finally, the specimen was water quenched. The upsetted specimen was divided into three different deformation regions (Fig. 1). I, II and III represent difficult deformation region, small deformation region and large deformation region, respectively. The microstructures of different regions of one-heat upsetting and three-heat upsetting are shown in Fig. 2.

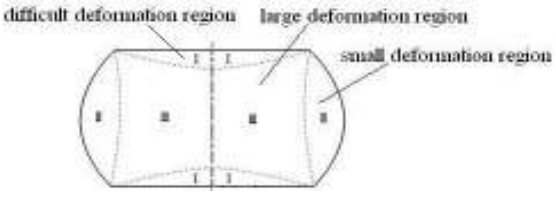
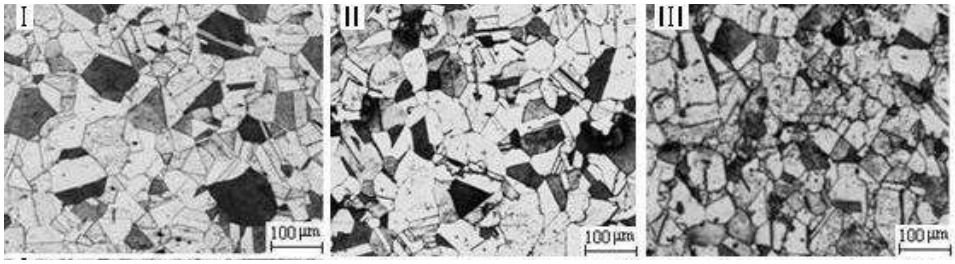
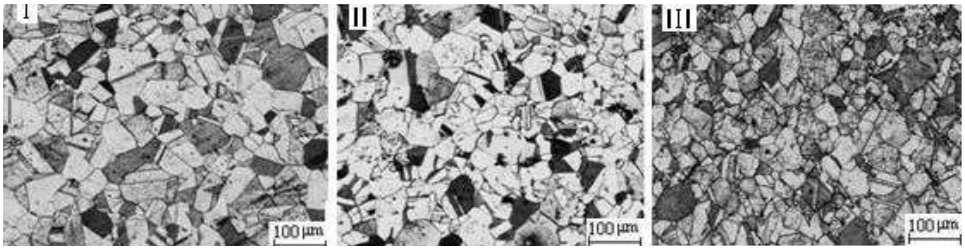


Fig. 1: Distribution diagram of deformation region

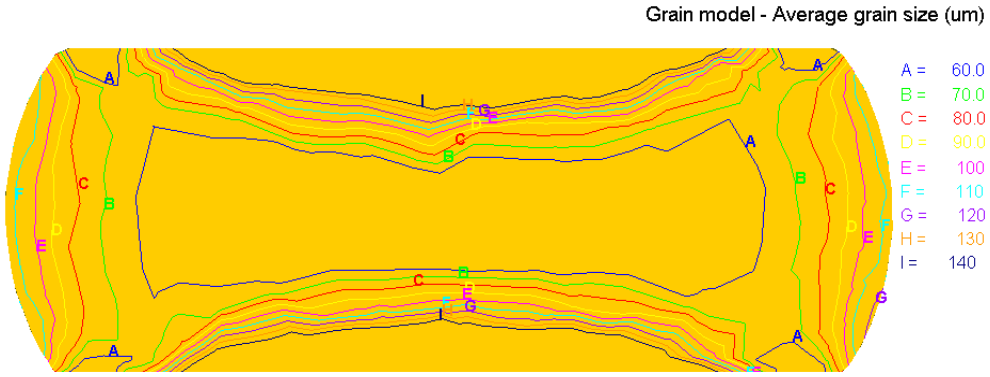


(a)

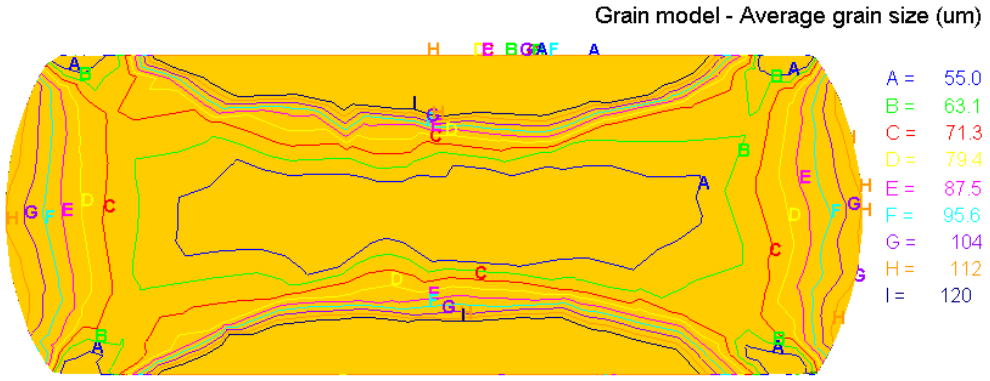


(b)

Fig. 2: The microstructures of different regions, (a) one-heat upsetting, (b) three-heat upsetting



(a)



(b)

Fig. 3: The simulated average grain sizes, (a) for one-heat upsetting, (b) for three-heat upsetting

Numerical simulation: The processes of one-heat upsetting and three-heat upsetting for 316 LN steels were calculated by coupling finite element method with microstructure evolution models, respectively. The specimen size was Φ 50×75 mm. The initial grain size was same as that of upsetting experiment. According to the actual forging condition, the velocity of upper die was 10 mm/s. The friction coefficient at the die/work piece interface was 0.3. The simulated average grain sizes of one-heat upsetting and three-heat upsetting are shown in Fig. 3.

RESULTS AND DISCUSSION

One fourth of upsetted specimen was used and divided into 8 different regions, as shown in Fig. 4. 1 to 3 represents difficult deformation regions; 6, 7 and 8 represent large deformation regions. The experimental average grain sizes are shown in Fig. 5. The simulated average grain sizes are shown in Fig. 6. The comparisons between experimental average grain sizes and simulated average grain sizes of 8 different regions for three-heat upsetting are shown in Fig. 7.

Figure 5 and 6 show that, in both upsetting experiment and numerical simulation, the grain uniformity of three-heat upsetting is much better that of one-heat upsetting and the average grain size of three-heat upsetting is smaller than that of one-heat upsetting. This is because that, for one-heat upsetting, only dynamic re-crystallization occurs and the grains become fine, but the non-uniformity of billets is not eliminated, the grain uniformity is not good. For three-heat upsetting, besides dynamic re-crystallization during upsetting process, due to solution treatment between heats, the meta-dynamic re-crystallization and static re-crystallization occur. Because the meta-dynamic re-crystallization and static re-crystallization can eliminate the distortion grains and elongated grains and the grains which have high storage energy, which make grains fine and uniform and the errors which be caused by non-uniformity of the initial grains are eliminated. Thus, the microstructures become more refinement and more uniform by three re-crystallization mechanisms and the mixed grains are also avoided. Therefore, the grain uniformity of three-heat upsetting is much better that of one-heat upsetting. The average grain size of three-heat upsetting is smaller than that of one-heat upsetting.

Figure 7 indicates that the simulated values of average grain size are in agreement with experimental values of average grain size, which shows that, the models of re-crystallization and grain growth model

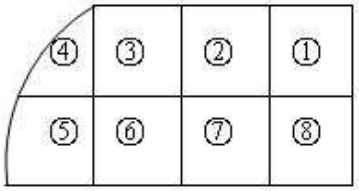


Fig. 4: Region lable

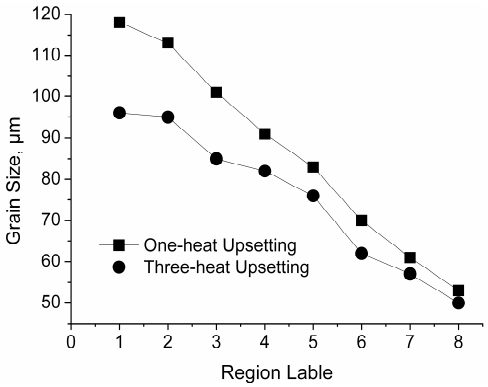


Fig. 5: The experimental average grain sizes

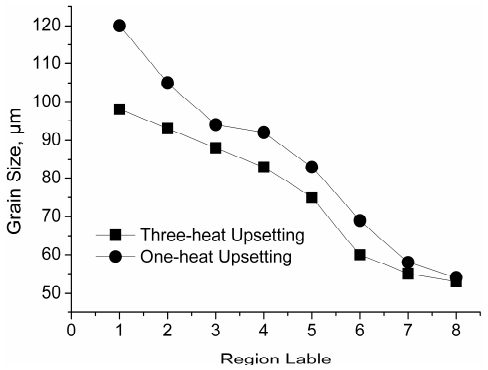


Fig. 6: The simulated average grain sizes

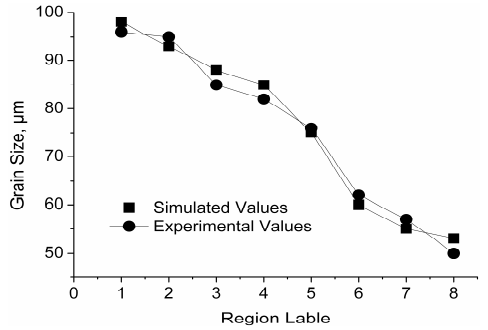


Fig. 7: The comparisons of experimental average grain sizes and simulated average grain sizes for three-heat upsetting

developed of 316 LN steels are reliable and the simulation accuracy is high. The numerical simulation technology can be employed to predict the multi-heat forging microstructure evolution of 316 LN steel.

In view of the research above, the forging technology of multi-heat and little deformation should be adopted for 316 LN steel forging.

CONCLUSION

The re-crystallization models and grain growth model of 316LN steels were derived. The reliability and accuracy of these models are verified by comparing simulated results with experimental values.

The forging technology of multi-heat and little deformation should be adopted for 316 LN steel forging in order to improve the grain uniformity and refine the grain.

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