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Dynamic recrystallization and microstructure evolution of a Nb-V microalloyed forging steel during hot deformation

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Abstract. In this study, a forging steel alloyed with both Nb and V was used as experimental material and the hot deformation behavior has been studied for this steel by conducting the compressive deformation test at temperature of 900-1150 °C and strain rate of 0.01-10 s^{-1} in a MMS-300 thermo-mechanical simulator. The microstructure evolution, particularly the dynamically recrystallized microstructure, of the experimental steel at elevated temperatures, strain rates and strain levels, was characterized by optical microstructural observation and the constitutive equation in association with the activation energy and Zener-Hollomon parameter. The curves of strain hardening rate versus stress were used to determine the critical strain and peak strain, and their relation was connected with Zener-Hollomon parameter. Under the conditions of processing temperature 900 °C and strain rate 0.01 s^{-1}, the dynamic recrystallization took place and the austenite grain size was refined from 164.5 μm to 28.9 μm.

Keywords: Nb-V microalloyed forging steel; dynamic recrystallization; microstructure evolution; constitutive equation; activation energy

1. Introduction

Microstructural control of metallic materials during hot working is an important key during thermomechanical processing since it allows to control the final microstructure and in turn the desired mechanical properties of the metals and alloys (Mejía 2011). Dynamic recrystallization (DRX) is the most important mechanism to control the microstructure, which can give rise to the refinement of microstructure and flow stress reduction. Therefore, understanding of the DRX behavior in the hot working of metals and alloys will be helpful to determine the optimal processing parameters (Liu 2013).

Microalloyed forging steels are widely used in manufacturing components and parts in automobile and machinery industries due to cancellation of quenching and tempering treatment. The conventional processing technology for microalloyed forging steels is hot deformation at elevated temperature, e.g. forging or rolling, and subsequently controlled cooling. So, the hot

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deformation process has an important influence on the microstructural evolution and mechanical properties of the forging steels. At present, most of forging steels are only microalloyed with element V, because V can enhance the strength effectively through precipitation strengthening. Recently, some investigations on DRX behaviors for V microalloyed forging steels are concentrated on modeling the DRX kinetics (Zhao 2014), developing the flow stress constitutive equation (Wei 2013) and determining the critical conditions for the initiation of DRX (Meysami 2011). Some researchers emphasized the important role in microstructural evolution of V microalloyed forging steels by investigating the interactions between the DRX and precipitation (Chen 2010, Badjena 2012, Wei 2014). It is known that V has small recrystallization-retarding effect in the rolling or forging process (Prasad 2005), since recrystallization is complete prior to the precipitation of VN. So, a coarsened microstructure of V microalloyed forging steels is generated and the resultant impact toughness is poor. In order to solve this problem, Nb is usually added in V microalloyed forging steels due to the grain refinement effect of Nb. In forging steels microalloyed with both Nb and V elements, V is used to enhance the strength through precipitation strengthening, while the microstructure can be refined by Nb through the interactions between recrystallization and strain induced precipitation of Nb(C, N) in the controlled forging process (Prasad 2005). Therefore, Nb-V microalloyed forging steels usually have good balance between strength and toughness. For Nb-V microalloyed forging steels, investigations were generally focused on the strain-induced precipitation kinetics (Pandit 2005), the transformation characteristics (Olasolo 2011), the microstructure and mechanical properties (Rao 2013). Till now, there has been a limited study available on the DRX behaviors for Nb-V microalloyed forging steels. As we know, the microstructure and mechanical properties of Nb-V micro-alloyed forging steels are closely related to the DRX behaviors. In order to promote the application of Nb-V microalloyed forging steels, there is a need to have a deep understanding of the DRX behaviors for Nb-V microalloyed forging steels.

In the present work, the DRX behavior and microstructural evolution of a Nb-V microalloyed forging steel were investigated by single-pass compression test on a MMS-300 thermo-mechanical simulator. The constitutive equation of DRX was firstly established, and the critical strain for DRX was further determined by the strain hardening rate vs flow stress curves. The models of critical and peak strains were finally established in association with the microscopic observation of microstructure evolution.

2. Experimental

The material used in this study was melted by vacuum induction furnace and cast to a 150 kg ingot. The chemical composition of experimental steel is given in Table 1. After remelting and casting, the ingot was forged to a slab with a thickness of 12 mm. The cylindrical specimens for single-pass compression test were machined to a size of ϕ8 mm×15 mm from the hot rolled slab. The compression specimens were taken with their axis parallel to the rolling direction of the slab.

The single-pass compression tests were performed on a MMS-300 thermo-mechanical simulator. Fig. 1 shows the schematic illustration of the single-pass compression test. The specimens were heated to 1200 °C at a heating rate of 20° C/s and held for 180 s in order to homogenize the microstructure. The specimens were then cooled to the deformation temperature at a rate of 10 °C/s. After holding for 30 s at the deformation temperature, the specimens were compressed to the strain of 0.8 at a constant strain rate. The single-pass compression tests were

Table 1 Chemical composition of the experimental steel (in wt. pct)

C	Si	Mn	S	P	Cr	V	Nb	N	Fe
0.24	0.30	1.99	0.050	0.008	0.51	0.08	0.07	0.0050	Bal.

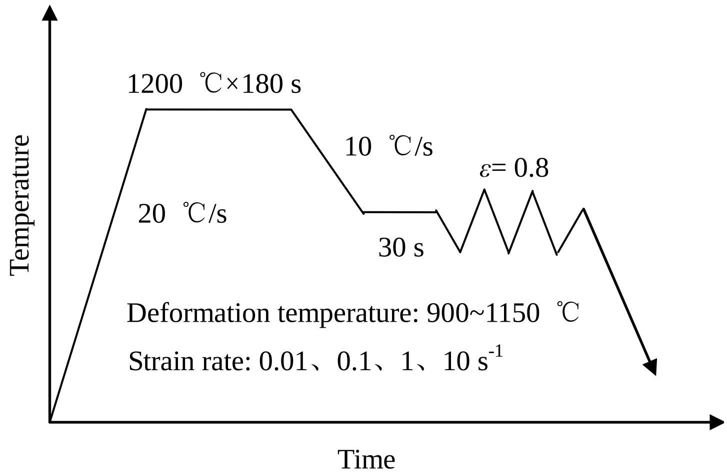

Fig. 1 Schematic illustration of the single-pass compression test

carried out at temperatures of 900, 950, 1000, 1050, 1100, and 1150°C, and at strain rates of 0.01, 0.1, 1, and 10 s^{-1}. In order to avoid oxidation, the high vacuum and high purity Ar atmosphere were employed in hot deformation process. In order to investigate the microstructure evolution, the microstructures of the experimental steel under deformation condition of 900°C and 0.01 s^{-1} with different strains were observed by optical microscopy. In these cases, the specimens were water quenched immediately after compression to reserve the austenitic microstructure. The specimens were sectioned along the longitudinal axis, and the central parts of the specimens were used for microstructure observation. The austenite grain boundaries were revealed by etching in saturated picric acid for about 2 min at 60-70°C.

3. Results and discussion

3.1 Flow stress

The flow stress curves of this Nb-V microalloyed forging steel under different deformation conditions are shown in Fig. 2. It can be seen from to Fig. 2 that, both deformation temperature and strain rate have considerable influence on the flow stress. The flow stress decreases with increasing deformation temperature at the same strain rate. On the contrary, the flow stress increases with increasing strain rate at the same deformation temperature.

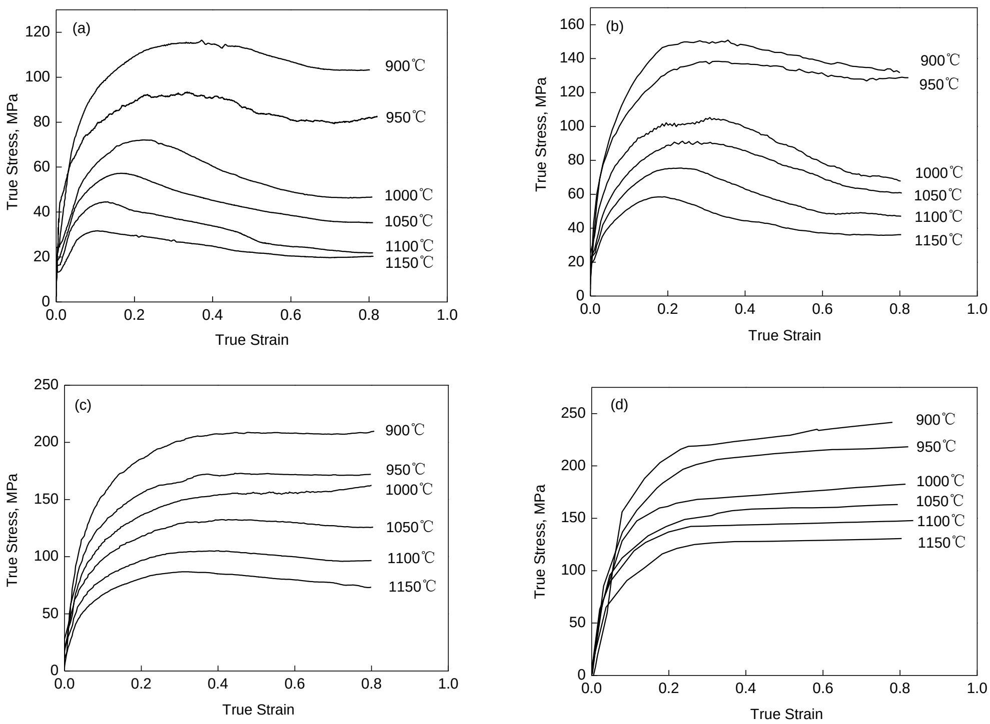

Fig. 2 Flow stress curves of the Nb-V microalloyed forging steel under different deformation conditions (a) $\dot{\varepsilon}$ =0.01 s^{-1}; (b) $\dot{\varepsilon}$ =0.1 s^{-1}; (c) $\dot{\varepsilon}$ =1 s^{-1}; (d) $\dot{\varepsilon}$ =10 s^{-1}

3.2 Constitutive equation

The effects of deformation temperature and strain rate on the peak stress (σ_p) can be represented by Zener-Hollomon parameter as shown in Eq. (1) (Sellars 1966).

$$A[\sinh(\alpha\sigma_p)]^n = \dot{\varepsilon}\exp(\frac{Q_{def}}{RT}) = Z \tag{1}$$

where A, α, and n are the constants, Q_{def} is the deformation activation energy, R is the gas constant, $\dot{\varepsilon}$ is the strain rate, T is the absolute temperature. In the present work, the parameter α is calculated by the method proposed by Medina *et al*. (Medina 1996). The value of α that gives the minimum value of the residual sum of squares (RSS) is 0.0115 MPa^{-1} (as shown in Fig. 3), which is in general consistent with the results reported by (Medina *et al*. 1996, Chen *et al*. 2010).

Taking natural logarithm for both sides of Eq. (1), we have the following equation:

$$\ln[\sinh(\alpha\sigma_p)] = \frac{1}{n}\ln\dot{\varepsilon} - \frac{1}{n}\ln A + \frac{Q_{def}}{nRT} \tag{2}$$

When T is constant, taking partial derivative for both sides of Eq. (2), we can have

$$\frac{1}{n} = \frac{\partial \mathrm{In}[\sinh(\alpha\sigma_p)]}{\partial \mathrm{In}\dot{\varepsilon}} \tag{3}$$

So, there is a linear relationship between $\ln[\sinh(\alpha\sigma_p)]$ and $\ln\dot{\varepsilon}$ when T is constant. Fig. 4a

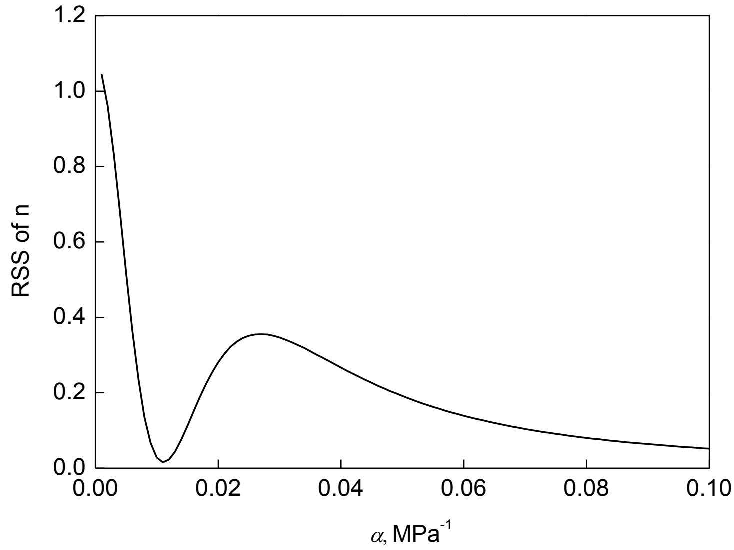

Fig. 3 RSS of n against the value of α for the Nb-V microalloyed forging steel

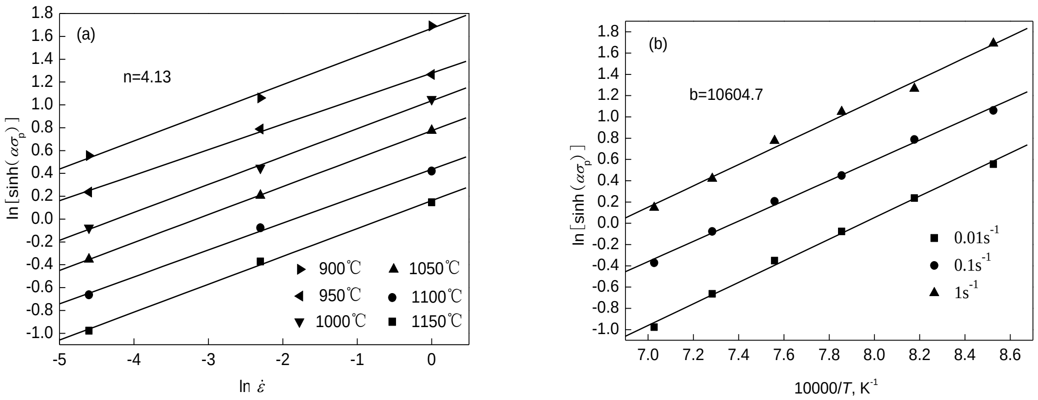

Fig. 4 Relationships between strain rate and peak stress (a), and deformation temperature and peak stress (b)

shows a plot of $\ln[\sinh(\alpha\sigma_p)]$ vs $\ln\dot{\varepsilon}$ at different deformation temperatures, and the reciprocal of the slope of the line is the value of n, which is calculated to be 4.13.

When $\dot{\varepsilon}$ is constant, we may take partial derivative for both sides of Eq. (2), which can be rewritten as:

$$Q_{def} = \mathrm{R}nb = \mathrm{R}\left.\frac{\partial \ln \dot{\varepsilon}}{\partial \ln[\sinh(\alpha\sigma_p)]}\right|_T \left.\frac{\partial \ln[\sinh(\alpha\sigma_p)]}{\partial(1/T)}\right|_{\dot{\varepsilon}} \tag{4}$$

where b is the average of the slopes of the $\ln[\sinh(\alpha\sigma_p)]$ vs $1/T$ curves. As shown in Fig. 4b, the value of b is estimated to be 10604.7 K. So the deformation activation energy Q_{def} can be calculated to be 364.13 kJ/mol using Eq. (4), which is slightly larger than that of V microalloyed forging steel (Zhao 2012), which is mainly due to the larger drag effect of Nb than that of V. Substituting the values of α, n, and Q_{def} into Eq. (1), the value of A is calculated to be 1.14×10^{13} s^{-1}. So the constitutive equation of the experimental steel can be expressed as follows.

$$\dot{\varepsilon} = 1.14\times10^{13}[\sinh(0.0115\sigma_p)]^{4.13}\exp(-\frac{364130}{RT}) \quad (5)$$

3.3 Critical and peak strains

The critical strain (ε_c) for DRX is an important parameter, by which the DRX can be described (Zeng 2011). The ε_c can be determined either by flow stress curves analysis or by microstructure observations. Compared to microstructure observations, flow stress curves analysis is a simpler and quicker method, as the former needs a large quantity of samples to be examined and it is different to precisely determine the new grains (Badjena 2014). So, in the present work, flow stress curves analysis method was used to define the ε_c. The method proposed by (McQueen *et al*. 2002) was adopted to determine the ε_c in the present work, i.e. the ε_c can be identified as the inflexion

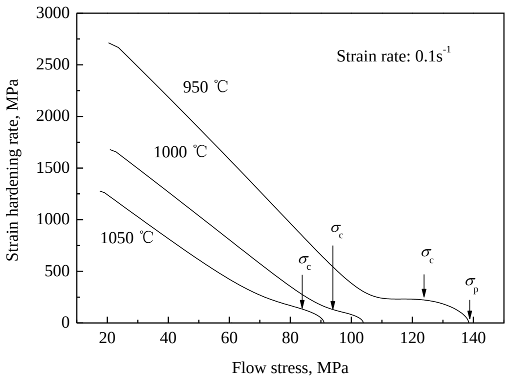

Fig. 5 Typical θ-σ curves of the Nb-V microalloyed forging steel deformed at different temperatures

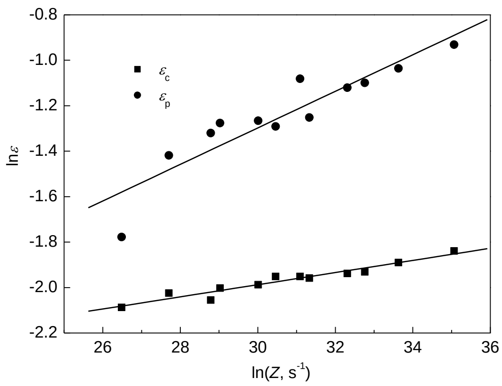

Fig. 6 Relationship between ε_c and Z parameter or ε_p and Z parameter for the Nb-V microalloyed forging steel

point of the strain hardening rate θ-σ curves (where θ=dσ/dε, σ is the flow stress).

Computing θ requires numerical differentiation of the initial flow stress curves. Such a differentiation usually results in substantial noise in the θ-values amplified by the input noise of the testing machine load cell during deformation (Poliak 2003). To solve this problem, the initial flow stress curves were fitted by ninth order polynomial to eliminate the noise produced in differentiation process. The slope change in the θ-σ curves can be used to identify the σ_c, as shown in Fig. 5, and the ε_c can be defined from the flow stress curves.

The correlation of critical or peak strain with Z parameter is usually expressed as follows (Badjena 2012):

$$\varepsilon = Bz^m \tag{6}$$

where *B* and *m* are constants, *Z* is Zener-Hollomon parameter. According to Fig. 5, the ε_c and ε_p can be determined under different deformation conditions (corresponding to different Z parameter). The *Z* parameter vs ε_c and ε_p curves are plotted in Fig. 6, it can be seen that there are linear relationships between ε_c and Z, and ε_p and Z parameter. Through regression analysis, the constant *B* and *m* can be determined, and the relationships of ε_c and ε_p with *Z* parameter can be expressed as follows.

$$\varepsilon_c = 6.148\times10^{-2} Z^{2.671\times10^{-2}} \tag{7}$$

$$\varepsilon_p = 2.449\times10^{-2} Z^{8.040\times10^{-2}} \tag{8}$$

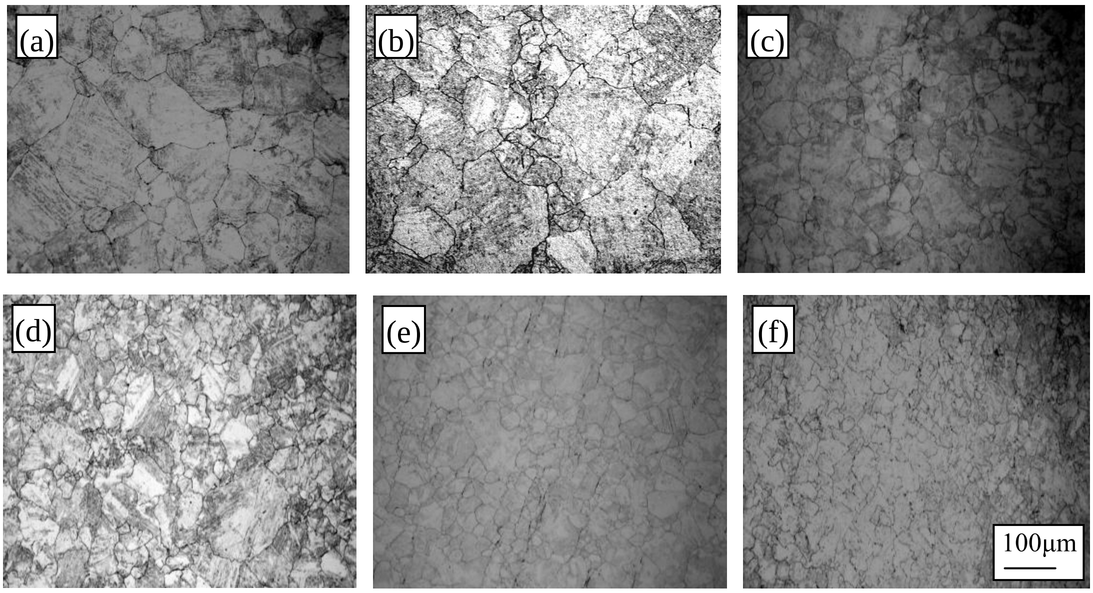

Fig. 7 Microstructure evolution of DRX for the Nb-V microalloyed forging steel under condition of 900 °C and 0.01 s^{-1} (a) ε=0; (b) ε=ε_c; (c) ε=ε_p; (d) ε=0.3; (e) ε=0.5; (f) ε=0.7

3.4 DRX microstructures

The optical micrographs of the Nb-V microalloyed forging steel at different strains under the condition of 900 °C and 0.01s^{-1} are shown in Fig. 7. As shown in Fig. 7a, the undeformed austenite grains are equiaxed, and the average austenite grain size is 164.5 μm. When $\varepsilon=\varepsilon_c$, as can be seen in Fig. 7b, the austenite grains are bent and elongated, and there are small equiaxed austenite grains located at local grain boundary, which indicates the onset of DRX in deformation process. When $\varepsilon=\varepsilon_p$ or 0.3, the small equiaxed austenite grains gradually increase, as shown in Fig. 7c and 7d, respectively, which indicates that the occurrence of DRX is continuous. When ε=0.5, the austenite grain is further refined, as shown in Fig. 7e. It can be seen from Fig. 7f, when ε=0.7, the flow stress achieves the steady state, the austenite grain size does not change any more, and the final average austenite grain size is 28.9 μm. This suggests that the austenite grain can be significantly refined by DRX, and DRX is an important method to control the microstructure.

4. Conclusions

In this study, the dynamic recrystallization behavior and microstructure evolution of a Nb-V microalloyed forging steel have been investigated by experimental observation and theoretical analysis. The following conclusions can be drawn.

(1) Strain rate has significant influence on the shapes of the flow stress curves. At strain rates of 0.01 and 0.1 s^{-1}, the flow stress curves are of DRX shape; at the strain rate of 10 s^{-1}, the flow stress curves are of DRV shape.

(2) The constitutive equation of the experimental steel can be described as

$$\dot{\varepsilon} = 1.14\times10^{13}[\sinh(0.0115\sigma_p)]^{4.13}\exp(-\frac{364130}{RT}).$$

(3) The critical and peak strains of the experimental steel can be expressed by Zener-Hollomon parameter as follows.

$$\varepsilon_c = 6.148\times10^{-2} Z^{2.671\times10^{-2}}$$

$$\varepsilon_p = 2.449\times10^{-2} Z^{8.040\times10^{-2}}$$

(4) The average austenite grain size of the experimental steel was refined from 164.5 μm to 28.9 μm by DRX under the condition of 900°C and 0.01 s^{-1}. DRX is an effective way to control the microstructure.

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