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A unified constitutive model for a low alloy steel during warm deformation considering phase differences

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ABSTRACT

The warm flow behaviors of a low alloy steel were investigated by isothermal compression tests over a broad range of temperatures (873–1173 K) and strain rates (0.001–1 s^{-1}). The compression strain-stress curves showed that the flow stress at 1023 K was lower than that at 1073 K under four studied strain rates, with an abnormal stress-temperature region emerging. It was found that this abnormal phenomenon appeared in the austenite-ferrite dual-phase temperature region, while ferrite occurred at low temperatures (873, 923 and 973 K) and austenite occurred at high temperatures (1123 and 1173 K), respectively. The constitutive relationship of each phase was constructed by a dislocation model coupling Arrhenius equations, which was verified by microstructure observations. Based on single phase's constitutive relationship, the abnormal stress-strain curves were manifested through a modified mixture law, in which a higher strain rate sensitivity of ferrite at intercritical temperatures was taken into consideration. In the end, a unified constitutive model which could adequately describe the warm flow behavior of the studied low alloy steel over the entire ranges of temperatures was developed.

1. Introduction

Warm forging processes of low-alloyed steels are widely applied in the production of automotive parts, including gears, crankshafts, and other complex-shaped ones. Compared with hot forging, warm forging has advantages of low energy consumption, tighter tolerance and less subsequent machining (Choi et al., 2012). Among the available studies concerning warm deformation, most attentions have been paid to the process and mechanism of grain refinement during warm deformation (Eghbali and Abdollah-zadeh, 2006). However, limited studies have been devoted to model the flow behaviors of low-alloy steels at warm temperatures considering phase differences. A reliable constitutive model that describes the flow behavior of material is greatly needed, so as to determine proper thermal-mechanical inputs during warm forming (Lin et al., 2014).

In recent years, various constitutive models have been developed to describe flow behaviors of metals and alloys. According to construction processes and principles, the constitutive models are mainly divided into two categories: phenomenological constitutive models and physics-based constitutive models (Lin and Chen, 2011). Generally, most researches construct constitutive models of single-phase materials or just simplifying multiphase materials as an entirety during analysis. However, for dual-phase materials, the phase difference should be taken into consideration, since the influence of phase composition on the flow behavior is significant. It has been widely recognized that individual phases in dual-phase material deform by their own mechanisms similar to those in corresponding single-phase alloys (Balancin et al., 2000). Thus, the mixture law has been considered as a promising way to model the flow behaviors of dual-phase materials (Spigarelli et al., 2010). For example, Momeni et al. invetigated the high temperature behavior of 2205 duplex stainless steel by considering the flow behavior of each constituent phase (Momeni et al., 2013). Besides, the flow behaviors of brass alloys and titanium alloys are studied with a view of phase variation at high temperatures (Bai et al., 2013; Momeni et al., 2015), in which, the mixture law is always adopted in order to consider the contribution of each phase to deformation.

In this study, a low alloy steel, which is widely used in industries, was selected to investigate the warm deformation behavior. The deformation temperature ranging from 873 K to 1173 K is considered as the main processing window for warm forging. Constituent phases during warm deformation include ferrite and pearlite at lower temperatures, ferrite and austenite at intercritical temperatures and austenite at higher temperatures. It's noteworthy that the stress-strain curves at intercritical temperatures don't conform

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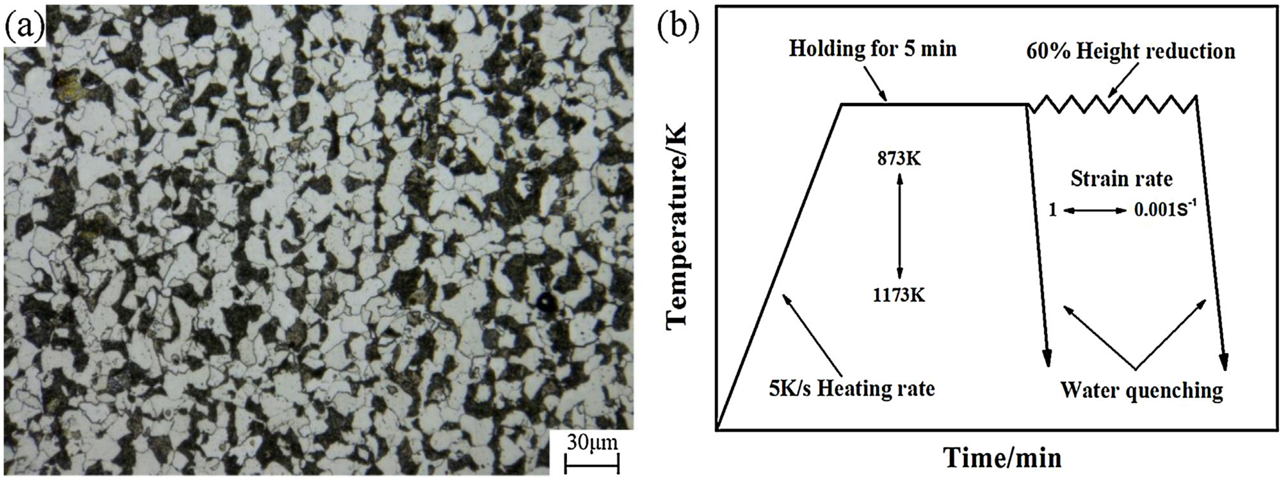

Fig. 1. (a) Original optical microstructure of studied low-alloy steel. (b) Schematic diagram of heating and deformation schedule applied in this study.

Table 1
Chemical compositions of low-alloy steel used in this investigation. (all in wt.%).

C	Cr	Mn	Si	Ti	Co	V	Mo	Fe
0.15	1.11	1.05	0.27	0.06	0.01	0.01	0.01	Rem.

to the conventional understanding. Stress level of 1073 K is higher than that of 1023 K under four experimental strain rates and this confirms that phase composition plays an important role in flow stress behavior. Furthermore, there are not appropriate constitutive models depicting these characteristics. Then, this paper aims to propose a unified constitutive model to describe the flow behavior of warm deformation which covers different phase composition as well as abnormal temperature-stress phenomenon. The model can present high efficiency and accuracy to guide the processing design of warm forging.

2. Material and experiments

Chemical compositions of the low alloy steel were characterized using a direct-reading spectrometer (Shimazu-PDA-5500S) and shown in Table 1. The material was commercially supplied as round bars with diameters of 60 mm. Fig. 1(a) showed the original microstructure of the material characterized by an optical microscope (VHX-1000C-KEYENCE). It can be seen that the original microstructure is ferrite and pearlite.

Cylindrical specimens with 8 mm in diameter and 12 mm in length were prepared from as-received bars via machining, and applied in isothermal compression tests conducted on a Gleeble-3500 thermal simulator. Before compression, tantalum foils and graphite foils were stuck on both ends of specimens to reduce contact friction and eliminate the effect of barreling. The specimens were heated to deformation temperatures and kept for 5 min to ensure the homogeneity of temperature and reach phase equilibrium.1 The overall height reduction of compression was set to be 60%. After compression finished, the specimens were quenched in water. The whole test procedure is schematically shown in Fig. 1(b). A dilatometer coupled to Gleeble-3500 was applied to measure the dimensional change of the heated specimen. The specimens were cut along the axial direction, ground, and polished using different sized abrasives. Afterward, specimens were etched by 3% nital to distinguish ferrite and austenite/martensite and picric acid to reveal the grain boundary of original austenite.

3. Methods

3.1. Physical models for constitutive descriptions

During warm deformation of metallic materials, the flow behaviors are simultaneously affected by dislocation multiplication and annihilation. The dislocation density can be represented as the function of differential hardening (+) and softening (−) terms (Estrin and Mecking, 1984):

$$d\rho/d\varepsilon = \left(d\rho/d\varepsilon\right)^{+} + \left(d\rho/d\varepsilon\right)^{-} \tag{1}$$

The relationship between the dislocation density ρ and strain ε is generally given by the following equation:

$$d\rho/d\varepsilon = U - \Omega\rho \tag{2}$$

where, U is the multiplication term resulting from work hardening; $\Omega\rho$ is the dislocation annihilation and arrangement due to softening mechanism of dynamic recovery and Ω is the remobilization parameter.

By substituting $\rho = \rho_0$ at $= 0$ into Eq. (2), the differential Eq. (2) can be solved as:

$$\rho = \rho_0 \exp\left(-\Omega\varepsilon\right) + \left(U/\Omega\right)\left[1 - \exp\left(-\Omega\varepsilon\right)\right] \tag{3}$$

The dislocation density has a basic relationship with flow stress σ (Serajzadeh and Taheri, 2003).

$$\sigma = \gamma G b \sqrt{\rho}$$

where, γ is a material constant; G is the shear modulus and b is the distance between atoms in the slip direction.

Then the flow stress can be given by the following expression in terms of strain:

$$\sigma = \sigma_0^2 \exp\left(-\Omega\varepsilon\right) + (\gamma G b)^2 \left(U/\Omega\right)\left[1 - \exp\left(-\Omega\varepsilon\right)\right] \tag{4}$$

When the flow cure gets into the steady state stress, $d\rho/d\varepsilon = 0$, $\rho = U/\Omega$ and $\sigma_s = \gamma G b\sqrt{\left(U/\rho\right)}$.

It is assumed that $\rho_0 = 0$ at $\varepsilon = 0$, which means $\sigma_0 = 0$. σ_s represents the steady state stress.

The equation can be simplified as:

$$\sigma = \sigma_s\left[1 - \exp\left(-\Omega\varepsilon\right)\right]^{0.5} \tag{5}$$