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Constitutive relationship and hot deformation behavior of Armco-type pure iron for a wide range of temperature

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The hot deformation behavior and constitutive relationship of Armco-type pure iron were investigated using isothermal compression tests with a wide range of temperature and strain rate ranging from 923 to 1523 K, and 0.1 to 10 s^{-1}, respectively. When deformed with a single phase, the flow stress of Armco-type pure iron increases accompanied by the increase of strain rate and the decrease of deformation temperature. Instability phenomenon of Armco-type pure iron appears when deformed with dual phase. γ-Fe undergoes completed discontinuous dynamic recrystallization (dDRX) at all hot deformation conditions. α-Fe undergoes uncompleted dDRX process at high temperature and low strain rate, however, dynamic recovery (DRV) process is the main restoration process for α-Fe at low temperature and high strain rate. The modified Arrhenius-type constitutive equation considering strain compensation is used to describe the flow stress of γ-Fe and α-Fe. From correlation coefficient (*R*), root mean square error (RMSE) and average absolute relative error (AARE), the predictability of the constitutive equation for the two phases of Armco-type pure iron was evaluated.

1. Introduction

Constitutive relationship of materials plays an important role in describing the relationship between thermodynamic parameters during the process of hot deformation. The flow stress is mainly affected by the deformation temperature, strain rate, strain, inner microstructure and chemical composition of materials [1,2]. In previous studies, various models have been established to predict the constitutive relationship of metals and alloys [3–6]. Zener and Hollomon [3] concluded that the logarithm of flow stress is a linear function of the logarithm of Zener–Hollomon parameter. Johnson and Cook [4] proposed Johnson–Cook model considering the effects of strain hardening, strain rate hardening and thermal softening. Basing dislocation mechanics, Zerilli–Armstrong model with two different forms was proposed by Zerilli and Armstrong [5] to separately describe the constitutive relationship of fcc structure and bcc structure. The sine-hyperbolic law belonging to a phenomenological approach was first proposed by Sellars and Tegart [6] in which the flow stress is expressed by sine hyperbolic in an Arrhenius type of equation. However, among these constitutive models, the sine-hyperbolic law in an Arrhenius-type equation has been successfully and widely applied for predicting the high-temperature flow behavior of materials [7–11]. A strain-dependent parameter into the sine-hyperbolic constitutive equation was introduced by Slooff et al. [12], to predict the flow stress in Mg–Al4–Zn1 alloy. Meanwhile, a revised sine-hyperbolic constitutive equation was adopted with incorporation of strain compensations to predict the flow behavior of 42CrMo and XC45 steels at elevated temperature [13,14].

Fe-based alloys are some of the most important alloys in the industrial world; therefore, it is very meaningful to understand the constitutive relationships of Fe-based alloys during the process of hot deformation. Recently, constitutive relationships of some representative carbon steels and other alloy steels were widely studied [2,13–16]. However, reports and research results about the constitutive relationship of commercial pure iron cannot be detailed, although it is widely used in the industrial world. As a kind of representative commercial pure iron, Armco-type pure iron has been found useful for magnetic cores where there is a need for permeability at high flux-density [17,18]. The main purpose of this paper is to study the hot deformation behavior of Armco-type pure iron at a wide range of temperature, and use a modified sine-hyperbolic constitutive equation to describe the corresponding flow behavior of Armco-type pure iron in different phases with considering the combined effect of strain, strain rate and temperature. Meanwhile, the predictability of the constitutive equation for different phases of Armco-type pure iron was evaluated.

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Table 1
The chemical composition of Armco-type pure iron (at.%).

C	Si	Mn	P	S
0.0019	0.0294	0.1298	0.0056	0.0038

2. Materials and experimental details

The chemical composition of the Armco-type pure iron used in this paper is shown in Table 1. The compression samples with 8 mm in diameter and 12 mm in length were prepared by electro-spark wire-electrode cutting, and the surfaces of the samples were finely polished by sandpaper. The hot compression experiment was conducted using a Gleeble-1500 thermal–mechanical simulator with thermocouples embedded into the samples in order to monitor the temperature, strain and strain rate accurately. The samples were padded with quartz plates to reduce the friction during compression. The tests were carried out in the temperature range of 923–1523 K, at an interval of 50 K, while the imposed constant strain rates were 0.1 s^{-1}, 1 s^{-1}, 10 s^{-1}, and the decrease in height was 60% at the end of the compression tests. During the experiment, the samples were heated to the corresponding compression temperature and kept for 3 min to ensure the temperature uniformly distributed in the samples. The samples were then quenched in water after the compression tests. The strain–stress curves were recorded automatically in the isothermal compression. The deformed samples were sectioned through longitudinal axis by electro-spark wire-electrode cutting, then polished and chemically etched in a solution of 5% nitric acid and 95% alcohol to reveal the grain boundaries. At last, the optical microstructures of these deformed samples were observed by an optical microscope (Axio Observer A1m).

3. Results and discussion

3.1. Analysis of flow stress behavior and microstructure for Armco-type pure iron

Fig. 1 shows the true stress–true strain curves of γ-Fe after hot compression tests at various temperatures and strain rates with strain up to 0.7. As shown in these figures, the true stress–true strain curves are characterized by a peak stress and then a stable value of flow stress at higher strain levels, which indicates the occurrence of discontinuous dynamic recrystallization (dDRX). However, as long as strain rate increases and temperature decreases, the peaks are not so obvious and the stable states of these curves disappear, especially for these curves deformed at 10 s^{-1} and low temperatures presented in Fig. 1(c). New grains resulted from dDRX produce softening and decrease the work hardening rate until eventually there is a clear stress peak in the true stress–true strain curves. When strain hardening reaches a dynamic equilibrium with strain softening caused by new grains and grain boundary migration, there will be clearly steady states followed the stress peaks of these curves [19–21]. The critical strain for the operation of dDRX increases accompanied by the decrease of temperature and increase of strain rate [19,21], therefore, the peaks and the steady states of these curves at high strain rates and low temperatures presented in Fig. 1(c) become unobvious due to the limited strain of 0.7. Fig. 2 shows the microstructure of γ-Fe with various strain rates at different deformation temperatures. As shown in these figures, the grains of γ-Fe are isometric crystal, which indicates complete dDRX. Meanwhile, it is evident that the dimension of these grains decreases accompanied by the increase of strain rate and the decrease of temperature.

Fig. 3 shows the true stress–true strain curves of α-Fe after hot compression tests at various temperatures and strain rates with

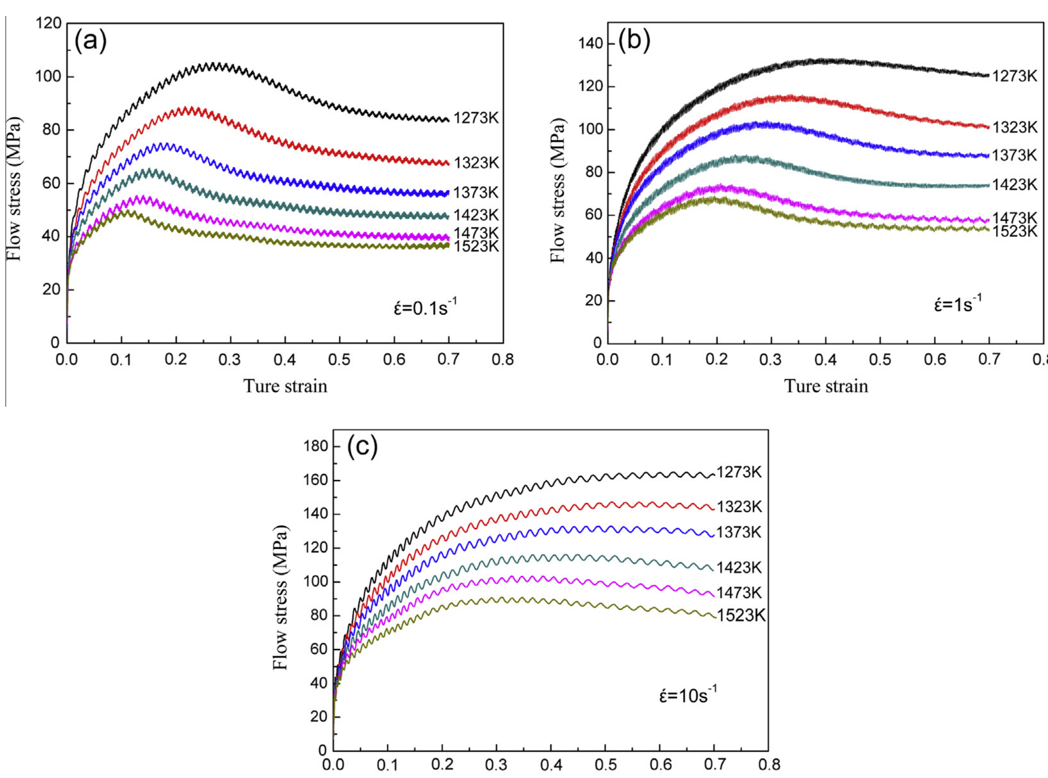

Fig. 1. True stress–true strain curves of γ-Fe for Armco-type pure iron during hot compression deformation: (a) $\dot{\varepsilon} = 0.1\ s^{-1}$; (b) $\dot{\varepsilon} = 1\ s^{-1}$; (c) $\dot{\varepsilon} = 10\ s^{-1}$.