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Study on hot deformation behaviour and processing maps of low carbon bainitic steel

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ABSTRACT

The hot deformation behaviour of low carbon bainitic steel, 29MnSiCrAlNiMo steel, was studied at a temperature range of 800–1100 °C and a strain rate range of 1×10^{-2} to $1 \times 10^{1}\ s^{-1}$. The flow curves display two features, with steady-state region and without it. After a comprehensive consideration of the deformation temperature, strain rate and strain, a constitutive model was proposed, exhibiting a correlation coefficient of 0.982 between the experimental and predicted stress values. The result shows a decreased deformation activation energy from 460 to 267 kJ/mol with increasing strain level from 0.1 to 0.8. Processing maps at different strain levels were also constructed, which exhibit an expanded instability region with increasing strain. Microstructural observations show that the flow localisation occurred when the hot working was performed on the instability regions, and partial dynamic recrystallisation occurred along the grain boundaries and deformation bands, resulting in a mischcrystal structure. The optimum hot working processing parameters for the studied steel are at 930–980 °C and $0.001–0.014\ s^{-1}$, and a full dynamic recrystallisation structure with a fine and homogeneous grain can be obtained. Microstructure observation verifies the applicability of the processing maps for optimising the processing parameters of the 29MnSiCrAlNiMo steel.

1. Introduction

Bainitic steels have attracted extensive attention for their excellent mechanical properties, and have been widely used in industries to manufacture bearings, gears, railway rails and crossings [1–3]. Nowadays, extensive studies have been carried out on the bainite phase transformation [4,5], the chemical composition design [6,7], the microstructural and the mechanical properties analyses [8,10,11], etc. Bainitic steel products are generally fabricated by using hot working processes such as hot rolling and hot extrusion. The microstructure obtained after the hot-working process has an important effect on the final microstructure and mechanical properties of the steel. Therefore, a deeper understanding on the hot deformation behaviour of bainitic steel, such as flow stress, dynamic recovery, and dynamic recrystallisation processes, is useful. However, the information on the hot deformation behaviour of bainitic steel is lacking [12,13].

The effect of deformation parameters, such as temperature, strain rate and strain, on flow behaviour should be determined by investigating the flow stress of the materials to provide technical support for the hot working process of the material, such as optimising the rolling regulation. Constructing an accurate constitutive modelling that simultaneously considers these deformation parameters can effectively solve this matter. A number of constitutive models have been proposed for different materials, such as 55SiMnMo bainitic steel [12], Fe–23Mn–2Al–0.2C twinning-induced plasticity steel [13], 42CrMo steel [14], 410 martensitic stainless steel [15], and so on. These models exhibited a high accuracy compared with that obtained by experiments, which revealed the higher reliability of such models.

The analysis results can also be used to construct the processing maps, which are very beneficial for characterising the formability, optimising the hot working process, and controlling the microstructure of the materials. The processing map, which was first developed by Prasad et al. [16], is a product of the dynamic materials model (DMM). And the map is developed based on flow behaviour. The safe and unsafe hot working conditions can be delineated via the processing map. For example, Wang et al. constructed processing maps for X-750 nickel-based superalloy based on the hot compression flow curves, which showed that the instability region varied notably with increasing strain [17]. Quan et al.

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investigated the intrinsic workability of 42CrMo steel by using processing maps, and the stable and unstable processing regions were clarified [18].

It can be seen that establishing an accurate constitutive model and constructing suitable processing maps for the material are beneficial for optimising the hot working process and controlling the microstructure. Recently, our team designed a new low-carbon bainitic steel that has a prospect of application in railway rails and crossings [11]. The structural parts that are formed by rolling have better compressive mechanical properties compared with the parts formed by casting. Therefore, it is very beneficial to investigate the hot deformation behaviour of bainitic steel. In this paper, hot compression tests were performed to study the hot deformation behaviour of the steel. The constitutive modelling and processing maps were developed to provide technical support in optimising the hot working processing of bainitic steel.

2. Experimental procedure

The as-received material used in the present work was 29MnSiCrAlNiMo steel with a chemical composition of 0.29C–1.63Mn–1.25Si–1.23Cr–0.44Ni–0.55Al–0.39Mo–0.001S–0.004P (wt%). Columnar compression specimens with a diameter of 8 mm and a height of 12 mm were machined. Hot compression tests were conducted by using a Gleeble 3500 thermal simulation machine. The compressive deformation processes are described in detail in Fig. 1. The deformation temperature was from 800 to 1100 °C, and the strain rate $\dot{\varepsilon}$ of the deformation was from 10^{-2} to $10^{1}\ \mathrm{s}^{-1}$. The tantalum foils sprayed with graphite lubricant were used to minimise the friction between a specimen and anvils. After each compression, the deformed specimens were rapidly quenched with water to retain the microstructures. The deformed specimens were sectioned perpendicular to the longitudinal compression axis for metallographic examination. The sections were polished and etched in an abluent solution of saturated picric acid. The optical microstructures in the central region of the section were examined.

3. Results and discussion

3.1. Hot deformation behaviour

The flow curves of the studied steel deformed at a temperature range of 800–1100 °C and a strain rate range of 1×10^{-2}–$10^{1}\ \mathrm{s}^{-1}$ are presented in Fig. 2. The flow curves can be classified into the following two types: with steady-state region and without it. As can be observed in Fig. 2a and b, the flow curves obtained at the lower strain rates and higher temperature (900–1100 °C, $10^{-2}\ \mathrm{s}^{-1}$; 950–1100 °C, $10^{-1}\ \mathrm{s}^{-1}$;) exhibit a steady-state plateau at higher strains. The flow curves with a broad peak suggest that the dynamic recrystallisation (DRX) is the dominant deformation mechanism, and the flow curves without any peak reveal a dynamic recovery (DRV) mechanism for the deformation process [13,19]. The further increase in the flow stress at higher strains is probably due to strain hardening, which is similar to that observed on other materials [12,13]. At strain rates higher than $10^{-1}\ \mathrm{s}^{-1}$ and/or the temperature lower than 950 °C (850–900 °C), no steady-state plateau occurs on the flow curves and the flow stress increases continuously, revealing a continuous strain hardening behaviour. It can be seen that there are serrations in the flow curves at high strain rates, which could be resulted from the DRX, unstable deformation or cracking, et al. [21]. According to the processing maps and the microstructure observation reported in the following section, it is confirmed that the serrations in the flow curves at high strain rates are attributed to the unstable deformation.

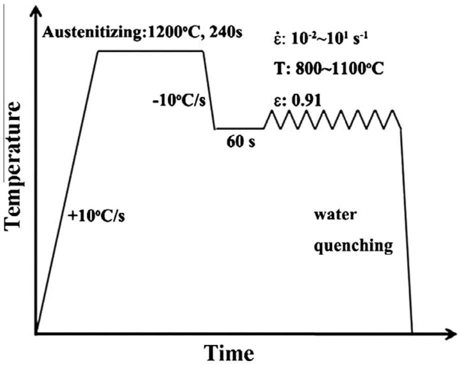

Fig. 1. Schematic illustrations of the compressive deformation processes.

The Zenger–Holloman parameter Z which provides the combined effects of strain rate and temperature on flow behaviour, can be introduced to elucidate the deformation behaviour. Z-parameter can be expressed as Eq. (1) [20]:

$$Z = \dot{\varepsilon} \exp\left(\frac{Q}{RT}\right) \tag{1}$$

where Q is the activation energy (kJ/mol) for deformation, R is the universal gas constant (8.314 J/mol K^{-1}), and T is the absolute temperature (K). Thus, it can be concluded that the DRX and DRV process frequently occurred under the condition of a lower Z, and the when the Z-parameter is high, strain hardening dominates the deformation process.

It is well known that the deformation process consists of dislocation generation and dislocation annihilation, resulting in strain hardening and strain softening, respectively. The two inverse behaviours take place simultaneously, and directly affect the resultant dislocation density which can be reflected by the flow curves. An annealing treatment was carried out on the specimens before the deformation process, making a low dislocation density before the compression test and rapidly accumulated dislocations at the initial strain, which manifests as a rapidly increasing flow stress, as shown in Fig. 2. With increasing strain, more dislocations were generated, so that the dislocation annihilation process inevitably took place, which reduced the strain hardening. However, the dislocation evolution depended on the deformation condition. Under the low Z conditions, the dislocation movement is easy which facilitates DRX and DRV and reduces the dislocation density. And then, the strain hardening is balanced by the strain softening. Then, a steady-state plateau occurs in flow curves. While for the high Z conditions, the low dislocation movement rate and the short time reduce the probability of dislocation annihilation, weakening the softening effect; the rate of dislocation multiplication is higher at higher strain rates, strengthening the hardening effect. And then the flow stress increases with increasing strain. The stress–strain data, as a function of strain rate and temperature, were used to construct the constitutive modelling and processing maps, as described below.

3.2. Constitutive modelling analysis

The flow stress of the materials deformed under different temperatures, strain rates and strains can be predicted by constitutive modelling. The relationship between strain rate and flow stress can be expressed as Eqs. (2)–(4) [20]:

$$\dot{\varepsilon} = A_1 \sigma_1^{n} \exp\left(-\frac{Q}{RT}\right) \tag{2}$$

$$\dot{\varepsilon} = A_2 \exp(\beta\sigma) \exp\left(-\frac{Q}{RT}\right) \tag{3}$$