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Modified constitutive analysis and activation energy evolution of a low-density steel considering the effects of deformation parameters

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ABSTRACT

In the present study, typical hyperbolic sine equation was found inappropriate to model the flow behavior of a Fe-18Mn-8Al-0.8C low-density steel in warm to hot deformation regime. This is related to the fact that the materials constants do not actually remain constant during deformation. Considering the effects of deformation parameters, a modified model was derived and used to accurately predict the flow behavior of the steel. The 3D activation energy map showed that the activation energy would decrease at high temperature due to the thermally activated nature of dislocation motion. However, the calculated activation energies are higher than those for conventional austenitic steels since the present highly alloyed steel is considered to be strongly strengthened by solid solution. The solute drag effect of alloying elements is found to be the main reason for obtaining higher activation energy values at relatively low strain rates. The subsequent calculations showed that the activation energy would decrease by about 50 kJ.mol^{-1} by increasing the strain due to the occurrence of dynamic recrystallization at above 1073 K. In contrast, the accumulation of deformation energy in the absence of dynamic recrystallization (below 1073 K) would lead to activation energy increase by increasing the amount of deformation.

1. Introduction

The demand for high-strength steels has led to development of several advanced high strength steels with a high strength-to-weight ratio (Matlock et al., 2012). However, the strength was usually achieved by sacrificing the formability of the material (Capdevila et al., 2006). Since then, lots of efforts have been made to establish an acceptable balance between strength and ductility using different heat treating cycles (Bracke et al., 2009; Sugimoto et al., 2002) or by employing controlled thermomechanical processing methods (Beladi et al., 2004; Mohamadizadeh et al., 2014, 2015b; Timokhina et al., 2003). The complexity and cost of such processing methods have forced the industries to look for an alternative path for enhancing the properties of automotive steel.

More recently, a new approach to specific strength has been developed through reducing the density of steels by adding light weight elements such as aluminum (Suh and Kim, 2013). Accordingly the low-density steel has attracted so much attention as a promising candidate for automotive applications due to its remarkable properties. The most important characteristics of low-density steel are remarkable strength-to-weight ratio, stable austenitic structure at room temperature and the possibility of twin formation and/or transformation induced martensite, which may lead to a great combination of high ductility and high strength

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(Bhattacharya et al., 2009; Mohamadizadeh et al., 2015a; Rana et al., 2014).

In addition to the inherent properties of the low-density steels, their room temperature mechanical properties can be improved through carefully controlled thermomechanical processing, which is usually used to form the steels into final shape (Raabe et al., 2014). However, developing a proper processing route requires a detailed knowledge on the flow behavior of the steel at different working conditions. Many researchers have put lots of efforts to develop constitutive equations to express the flow behavior of steels at different hot working regimes (Lin and Chen, 2011; Mirzaei et al., 2014; Zhang et al., 2014c). Amongst the various physical, empirical and phenomenological models (Abbasi-Bani et al., 2014; Johnson and Cook, 1983; Lin et al., 2015; Zerilli and Armstrong, 1987) hyperbolic sine equation proposed by Sellars and McTegart (1966) is the most employed model due to its simplicity and wide range of applicability. From a physical point of view, the hyperbolic sine equation is the best choice for flow modeling since it can directly take the effect of deformation parameters into account. Moreover, the activation energy of the material extracted from this equation is capable of describing the difficulty of deformation (Seshacharyulu et al., 2002). Basically, the activation energy values, as the most important hot deformation characteristic of the materials, have been generally considered to be constant within a working range (Liu et al., 2014; Mandal et al., 2009; Zhang et al., 2013). Recently, many researchers (Haghdadi et al., 2012; Samantaray et al., 2009; Zhang et al., 2014b) have criticized the previous studies indicating that the activation energy of deformation cannot remain constant during deformation since the ease of deformation is under the influence of temperature and the applied stresses (Caillard and Martin, 2005). However, the reports on the effects of deformation parameters on flow behavior modeling and the evolution of activation energy are so rare.

The aim of the current study is to reveal the shortcomings of the original hyperbolic sine constitutive equation in flow behavior prediction of a low-density steel and to take the effects of temperature, strain rate and strain into calculations. Establishing a correlation between microstructural evolution and the activation energy of deformation is also targeted.

2. Experimental procedure

The low-density steel used in this work was received as a cast Fe-17Mn-8Al-0.8C (wt.%) billet. This was homogenized at 1473 K for 120 min and hot rolled at the same temperature to the final thickness of 20 mm. The cylindrical compression specimens with the aspect ratio of 1.5 (i.e., 10.5 mm in height and 7 mm in diameter) were machined holding their axes parallel to the hot rolling direction according to the ASTM E9 standard. Isothermal compression tests were performed according to ATSM E209 standards using a GOTECH AI-7000 universal testing machine coupled with resistance furnace. The specimens were heated up at 20 K.s^{-1} to deformation temperature ranging from 873 and 1373 K with 100 K intervals and then held for 10 min to obtain a thermal steady state before deformation. Mica plates (0.2 mm thick) were placed on the top and bottom of each specimen to reduce the friction between die and surface of the material and also to assure better thermal isolation during the test. The deformation temperature was measured and controlled by a digital thermometer attached to the mid-height surface of the specimens. Uniaxial compressive deformation was conducted under different strain rates from 10^{-3} to 1 s^{-1} up to the logarithmic strain of 0.6 followed by water quenching. It is worth noting that the reproducibility and reliability of the experimental data were verified by repeating the hot compression tests for 3 times under the same conditions.

The compressed specimens were then sectioned parallel to deformation axis for further microstructural observation. The samples were mounted and then electro-polished in 20:1 acetic acid and perchloric acid at 40 V. Tint etching was established using conventional 4% nital solution followed by rapid immersion in Villela's reagent (100 ml ethanol, 5 ml HCl and 1 gr dry picric acid). Images were analyzed using Vision Clemex software to measure phase fractions and the grain size.

3. Results and discussion

3.1. Flow behavior

The true stress-true (logarithmic) strain curves of the experimental low-density steel are shown in Fig. 1. It is worth noting that the flow curves were corrected for the effect of friction and adiabatic heating under all deformation conditions based on the equations proposed by Wanjara et al. (2005) and Goetz and Semiatin (2001), respectively.

Typically, the flow stress decreases by decreasing the strain rate and raising the temperature. As is seen, the flow curves are characterized by an increase in flow stress up to a peak value followed by a flow softening behavior; this typically shows that the dynamic recrystallization (DRX) is operating. As is observed in Fig. 1a and b, the stress peaks are broader at temperatures lower than 1073 K and there is no clear steady state regime up to the logarithmic strain of 0.6. At higher temperatures, i.e. at 1073 and 1173 K, the peak stress shifts to lower strain values by decreasing the strain rate (Fig. 1c and d). A steady state flow behavior is reached at 1173 K/0.01 s^{-1} indicating that flow softening and work hardening rates are balanced. The flow curves at 1273 and 1373 K exhibit a clear peak stress at early stages of deformation followed by a rapid flow softening toward a steady state. In these conditions, this high temperature provides additional thermal activation energy for DRX nucleation (Castan et al., 2013; Dehghan-Manshadi et al., 2008a; Zhang et al., 2014a).

3.2. Constitutive equations

Zener–Hollomon parameter (Z) is usually used to present the relationship between deformation variables, i.e. strain rate and temperature, and deformation of materials at elevated temperatures (Medina and Hernandez, 1996):