Available online at www.sciencedirect.com
ScienceDirect
Acta Materialia 59 (2011) 6441–6448
Acta MATERIALIA
www.elsevier.com/locate/actamat

Constitutive relationships for hot deformation of austenite

Hamed Mirzadeh [a,b,*], Jose Maria Cabrera [a,c], Abbas Najafizadeh [b]

[a] *Departamento de Ciencia de los Materiales e Ingeniería Metalúrgica, ETSEIB, Universitat Politècnica de Catalunya, Av. Diagonal 647, 08028 Barcelona, Spain*
[b] *Department of Materials Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran*
[c] *Fundació CTM Centre Tecnologic, Av. Bases de Manresa 1, 08242 Manresa, Spain*

Received 17 May 2011; received in revised form 16 June 2011; accepted 2 July 2011
Available online 29 July 2011

Abstract

Constitutive equations were used to derive the flow stress of a 17–4 PH stainless steel during hot compression testing. Two general methods were used: (i) a conventional method of finding apparent materials constants; and (ii) a physically based approach which accounts for the dependence of the Young's modulus and the self-diffusion coefficient of austenite on temperature. Both methods were critically discussed and some modifications and easy-to-apply methods were also introduced. The second approach was also performed for peak and critical stresses to find out the effect of dynamic recrystallization on the ideal theoretical values. The discussion of results proved that when the deformation mechanism is controlled by the glide and climb of dislocations, a constant creep exponent (n) of 5 can be used in the classical hyperbolic sine equation, and the self-diffusion activation energy can be used to describe the appropriate stress.

Keywords: Hot working; Thermomechanical processing; Compression test; Dynamic recrystallization

1. Introduction

Hot deformation processing of steels, which is usually conducted in the stability range corresponding to the austenite phase, plays an important role in industry for the production of steels with a number of desirable mechanical properties while keeping production costs as low as possible. In order to achieve this goal, the parameters of the forming process must be carefully controlled. An understanding of the microstructural behavior of the steel under consideration is therefore required, together with the constitutive relation describing material flow.

The modeling of hot flow stress using constitutive equations is quite important in metal-forming processes from the mechanical and metallurgical standpoints, because any feasible mathematical simulation needs an accurate flow description. As a result, considerable research has been carried out to model the flow stress of metals and alloys, and steels in particular [1–15]. The simplest and most widely applied method in the literature is the modeling of flow stress using an expression which relates the Zener–Hollomon parameter (Z) [16] to the flow stress (σ):

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

In Eq. (1), the Zener–Hollomon parameter is the temperature-compensated strain rate and Q is the activation energy of deformation. It was shown by Sellars and Tegart [8,9] and others [17–21], using the hyperbolic sine function suggested by Garofalo [22], that hot working can be considered as a thermally activated process and can be described by strain-rate equations similar to those employed in creep studies. Based on these works, the Z parameter can be related to the flow stress in different ways [23]:

$$Z = \dot{\varepsilon} \exp\left(\frac{Q}{RT}\right) = f(\sigma) = A'\sigma^{n'} \tag{2}$$

* Corresponding author at: Department of Materials Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran. Fax: +98 311 3912752.
E-mail address: h-m@gmx.com (H. Mirzadeh).

1359-6454/$36.00
doi:10.1016/j.actamat.2011.07.008

$$Z = \dot{\varepsilon} \exp\left(\frac{Q}{RT}\right) = f(\sigma) = A'' \exp(\beta\sigma) \quad (3)$$

$$Z = \dot{\varepsilon} \exp\left(\frac{Q}{RT}\right) = f(\sigma) = A[\sinh(\alpha\sigma)]^n \quad (4)$$

where A', A'', A, n', n, β and $\alpha(\approx\beta/n')$ are known as apparent material constants. The stress multiplier α is an adjustable constant which brings $\alpha\sigma$ into the correct range that gives linear and parallel lines in $\ln\dot{\varepsilon}$ vs. $\ln\{\sinh(\alpha\sigma)\}$ plots [18,23,24]. Some authors [25] consider α as the inverse stress at which the power law breaks (Eq. (2)). This power-law description is preferred for relatively low stresses. Conversely, the exponential law (Eq. (3)) is suitable for high stresses. However, the hyperbolic sine law (Eq. (4)) can be used for a wide range of temperatures and strain rates. Using the definition of the Zener–Hollomon parameter, Eq. (4) can be rewritten as:

$$\dot{\varepsilon} = A[\sinh(\alpha\sigma)]^n \exp(-Q/RT) \quad (5)$$

Although the constants of this equation (A, α, n, and Q) depend on the material being considered, they are also usually referred to as apparent values, because no account is generally taken of the internal microstructural state and they are only derived from an Arrhenius plot with a linear range and the assumption that the microstructure remains constant. Therefore, this method is called the "apparent approach" throughout this paper. Cabrera et al. [25–28] showed that when the dependence of Young's modulus (E) and the self-diffusion coefficient of austenite (D) on temperature are taken into account, a constant creep exponent $n = 5$ and self-diffusion activation energy (Q_{sd}) can be used to describe the appropriate stress. The latter is true as long as the deformation mechanism is controlled by the glide and climb of dislocations. Accordingly, the unified relation can be expressed as:

$$\dot{\varepsilon}/D(T) = B[\sinh(\alpha'\sigma/E(T))]^5 \quad (6)$$

where $D(T) = D_0 \exp(-Q_{sd}/RT)$ (with D_0 a pre-exponential constant) and $E(T)$ describes the dependence of the Young's modulus on temperature. The values of D_0 and Q_{sd} can be taken from the tables given by Frost and Ashby [29,30]. In these tables, the dependence of the shear modulus (G) on temperature in the form of $G(T) = G_0\left(1 - \frac{T_M}{G_0}\frac{dG}{dT}\frac{(T-300)}{T_M}\right)$ is also available. Here, G_0 is the shear modulus at 300 K, $\frac{T_M}{G_0}\frac{dG}{dT}$ is the temperature dependence of modulus, and T_M is the melting temperature of the material. According to the relation of shear and Young modulus, the values of $E(T)$ can be calculated. This method is referred to as the "physically based approach".

In this paper, the apparent and the physically based approaches are used to derive the constitutive equations of a 17–4 PH stainless steel during hot compression testing. Both methods are critically discussed and some modifications and easy-to-apply methods are also introduced. 17–4 PH (AISI 630) is more common than any other type of precipitation- hardened stainless steel. Industrial hot deformation processing such as forging for this steel is conducted in the temperature range at which the austenite phase is stable. The ability of 17–4 PH alloy to develop very high strength without catastrophic loss of ductility and its superior corrosion resistance compared to other steels of similar strength, have made it very attractive to engineers.

2. Experimental materials and procedures

A 17–4 PH stainless steel with chemical composition of 0.03 wt.% C–15.14 wt.% Cr–4.53 wt.% Ni–3.4 wt.% Cu–0.25 wt.% Nb was used in this work. Single-hit hot compression tests at high strain rates were performed using a Baehr DIL-805 deformation dilatometer, while for tests at low strain rates, an Instron 4507 universal deformation machine was used. However, some tests were performed at intermediate strain rates using these two machines in order to check if both testing systems offered similar results. Therefore, in order to cover a wide range of temperatures (900–1150 °C) and strain rates (10^{-4}–$10\ s^{-1}$), and to check the reproducibility of our results, these two types of deformation machines were used and both sets of resultant flow curves were used simultaneously for constitutive analyses.

2.1. Hot compression tests using the Baehr DIL-805 machine

Specimens 10 mm high and 5 mm in diameter were prepared. In order to minimize the occurrence of inhomogeneous compression due to the existence of friction between the anvils and the specimen surface, the Rastegaev design [24] was used, in which the entire end face of the specimen was machined away except for a small rim to form a reservoir. Subsequently, these reservoirs were filled with glass powder as a lubricant material and the specimen was placed between Al_2O_3 anvils in the vacuum chamber. Inductive heating and Ar gas quenching were used for thermal treatments. The specimen was austenitized at 1180 °C for 10 min and cooled down at a rate of 1.5 °C s^{-1} to the deformation temperature and held there for 5 min before hot compression testing. Single-hit hot compression tests were carried out at temperatures of 950–1150 °C with strain rates of 10^{-3}–$10\ s^{-1}$.

2.2. Hot compression tests using the Instron 4507 machine

Cylindrical specimens, 11.4 mm in height and 7.6 mm in diameter, were prepared for hot compression testing using the Instron 4507 universal deformation machine. Tantalum foils and boron nitride solution were used to reduce friction in this case. The specimen was austenitized at 1100 °C for 15 min and cooled down at a rate of 1.5 °C s^{-1} to the deformation temperature and held there for 5 min before hot compression testing. After deformation, the samples were immediately quenched in water. Single-hit hot compression tests were carried out at temperatures of 900–1100 °C with strain rates of 10^{-4}–$0.1\ s^{-1}$.