Materials Science and Engineering A 526 (2009) 1–6

Contents lists available at ScienceDirect

Materials Science and Engineering A

journal homepage: www.elsevier.com/locate/msea

A thermo-viscoplastic constitutive model to predict elevated-temperature flow behaviour in a titanium-modified austenitic stainless steel

Dipti Samantaray, Sumantra Mandal*, Utpal Borah, A.K. Bhaduri, P.V. Sivaprasad[1]

Materials Technology Division, Indira Gandhi Centre for Atomic Research, Kalpakkam 603102, India

ARTICLE INFO

Article history:
Received 4 February 2009
Received in revised form 21 May 2009
Accepted 6 August 2009

Keywords:
Austenitic stainless steel
Constitutive model
Johnson–Cook model
Zerilli–Armstrong model
Flow stress

ABSTRACT

The experimental stress–strain data from isothermal hot compression tests over a wide range of temperatures (1073–1473 K), strains (0.1–0.5) and strain rates (0.001–1 s^{-1}) were employed to formulate a suitable constitutive model to predict the elevated-temperature deformation behaviour in a Ti-modified austenitic stainless steel (alloy D9). It was observed that the Johnson–Cook (JC) model in its original form is inadequate to provide good description of flow behaviour of alloy D9 in the above hot working domain. This has been attributed to the inadequacy of the JC model to incorporate the coupled effects of strain and temperature and of strain rate and temperature. A modified constitutive model based on the Zerilli–Armstrong model has been proposed for considering the effects of thermal softening, strain rate hardening and isotropic hardening as well as the coupled effects of temperature and strain and of strain rate and temperature on flow stress. The proposed modified constitutive model could predict the elevated-temperature flow behaviour of alloy D9 over the specified hot working domain of alloy D9 with good correlation and generalization.

1. Introduction

Austenitic stainless steels, such as AISI type 316 and its modifications, have been used as materials for fuel clad tubes and fuel sub-assembly wrappers in fast breeder reactors owing to their superior elevated-temperature mechanical properties, compatibility with liquid sodium and adequate resistance to void swelling. For India's 500 MWe Prototype Fast Breeder Reactor (PFBR), a 15Cr–15Ni–2.2Mo Ti-modified austenitic stainless steel (alloy D9) has been developed [1]. Alloy D9 is processed through various thermo-mechanical treatments before being fabricated into the final component, and estimation of the appropriate forming load is a major consideration. This load depends on the flow stress of material, the geometry of the die, and friction at the tool–work piece interface. Therefore, prediction of hot deformation behaviour of the materials, namely its flow stress as a function of strain, strain rate and temperature is necessary for accurate prediction of forming load [2].

Constitutive equations, which represent the material's flow behaviour, are used in computer codes to model the material's response under specified loading conditions [3]. In the recent past, several empirical, semi-empirical and physically based constitutive models have been proposed [4–11]. Although, physically based models like Mechanical Threshold Stress (MTS) model [7] and Bammann–Chiesa–Johnson (BCJ) model can represent the deformation behaviour with greater accuracy over a wide range of temperatures and strain rates [12], these are not always preferred as physically based models often require more data from precisely controlled experiments [13,14]. More importantly, these models involve large number of material constants and properties than empirical models which may not be readily available [15–17]. Ideally, a constitutive equation should involve a reasonable number of material constants, which can be evaluated using limited number of experimental data, and should be able to predict the flow behaviour with adequate accuracy and reliability over a wide range of temperature and strain rate.

Amongst the empirical and semi-empirical models, the Johnson–Cook (JC) [8,18] and Zerilli–Armstrong (ZA) [9] models are part of many commercially available finite element (FE) software. The JC model, which has been successfully used for various materials [8,19] for different ranges of temperature and strain rate [17,20], has been revised several times to incorporate adiabatic temperature rise during material deformation [21] and for materials with different strain rate sensitivity [16,22]. The Original JC model has been extensively used as it requires less number of experimental data for evaluation of the materials constants. On the other hand, the ZA model has been used for different fcc and bcc materials over different strain rates at temperatures between room temperature and $0.6T_m$ [23–26]. ZA model is preferred to JC model as it couples the effects of strain rate and temperature [27–29]. However

* Corresponding author. Tel.: +91 44 27480118; fax: +91 44 27480075.
E-mail address: sumantra@igcar.gov.in (S. Mandal).
[1] Formerly with Materials Technology Division, Indira Gandhi Centre for Atomic Research, Kalpakkam 603102, India.

0921-5093/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.msea.2009.08.009

Table 1
Chemical composition (in wt%) of the 15Cr–15Ni–2.2Mo Ti-modified austenitic stainless steel (alloy D9) used.

C	Mn	Si	S	P	Cr	Ni	Mo	Ti	B	Co	N
0.052	1.509	0.505	0.002	0.011	15.051	15.068	2.248	0.31	0.001	0.01	0.006

, it is particularly not suitable for prediction of flow stress at temperatures above $0.6T_m$ and at lower strain rates [30].

Hence, the objective of this work is to find out a suitable constitutive equation to model the elevated-temperature flow behaviour of alloy D9 over a wide range of temperature, strain and strain rate based on the data obtained from hot compression tests. First, the experimental stress–strain data were used to determine the material constants to relate flow stress, strain, strain rate and temperature as per the JC model. Subsequently, a modified model, based on the original ZA model, is formulated to predict the flow behaviour of alloy D9 over its entire hot working regime. This paper demonstrates the inadequacy of the JC model, and shows the appropriateness of our proposed modified-ZA model for predicting the flow behaviour during hot working of alloy D9.

2. Experimental

The chemical composition of alloy D9 used in this work is given in Table 1. Cylindrical specimens of 10 mm diameter and 15 mm height were used for isothermal hot compression tests on a computer-controlled servo-hydraulic testing machine (DARTEC, Stourbridge, UK) with a maximum loading capacity of 100 kN. This machine is equipped with a control system to impose exponential decay of the actuator speed to obtain constant true strain rate. A resistance heating split furnace with SiC heating elements is used to surround the platens and specimen. The specimen is coated with a borosilicate glass paste that acts as a lubricant and also as a protective coating.

The testing temperatures were in the range of 1073–1473 K at an interval of 50 K, while the imposed constant true strain rates were 0.001, 0.01, 0.1 and 1 s^{-1}. The adiabatic temperature rise was recorded with a transient recorder. The specimens were deformed and subsequently quenched in water. The load vs. stroke data were processed to obtain true stress (σ) vs. true plastic strain using standard equations. The flow stress data obtained at different temperatures (T), strains and strain rates were corrected for adiabatic temperature rise, if any, by linear interpolation between $\ln\sigma$ and $1/T$.

3. Results and discussions

3.1. Johnson–Cook (JC) model

According to the JC model, the flow stress is expressed as:

$$\sigma = (A + B\varepsilon^n)(1 + C \ln \dot{\varepsilon}^*)(1 - T^{*m}), \quad (1)$$

where σ is the (Von Mises) flow stress, A is the yield stress at reference temperature and reference strain rate, B is the coefficient of strain hardening, n is the strain hardening exponent, ε is the plastic strain, $\dot{\varepsilon}^* = \dot{\varepsilon}/\dot{\varepsilon}_0$ is the dimensionless strain rate with $\dot{\varepsilon}$ being the strain rate and $\dot{\varepsilon}_0$ the reference strain rate, and T^* is the homologous temperature and expressed as:

$$T^* = \frac{T - T_{ref}}{T_m - T_{ref}} \quad (2)$$

with T as the current absolute temperature, T_m the melting temperature (1673 K for alloy D9) and T_{ref} as the reference temperature ($T \geq T_{ref}$). The minimum temperature of the test matrix is taken as the reference temperature. C and m are the material constants that represent the coefficient of strain rate hardening and thermal softening exponent, respectively. The JC model considers isotropic hardening, strain rate hardening and thermal softening, but as three independent phenomena whence these can be isolated from each other. Thus, the total effect of strain hardening, strain rate hardening and thermal softening on flow stress can be calculated by multiplying these three terms, i.e. the first, second and third parentheses in Eq. (1). This model is appropriate for materials where flow stress is moderately dependant on strain rate and temperature [14].

To predict the flow behaviour of alloy D9 employing the JC model, 1073 K (minimum temperature of test matrix) is taken as reference temperature and 1 s^{-1} the reference strain rate. The material constants of the JC model for alloy D9 are given in Table 2. The procedure for calculation of these parameters is described below.

At reference temperature 1073 K and reference strain rate 1 s^{-1}, Eq. (1) will reduce to:

$$\sigma = A + B\varepsilon^n. \quad (3)$$

The value of A is calculated from the yield stress (i.e. the stress at 0.002 strain) of the flow curve at 1073 K and 1 s^{-1}. Substituting the value of A in Eq. (3) and using the flow stress data at various strains for the same flow curves, $\ln(\sigma - A)$ vs. $\ln\varepsilon$ is plotted. B is calculated from the intercept of this plot while n is obtained from the slope. At reference temperature, there is no flow softening term as $T^* = 0$. So, Eq. (1) can be expressed as:

$$\sigma = (A + B\varepsilon^n)(1 + C \ln \dot{\varepsilon}^*). \quad (4)$$

Using the flow stress data for a fixed strain at various strain rates, C is obtained from the slope of $\{\sigma/(A + B\varepsilon^n)\}$ vs. $\ln \dot{\varepsilon}^*$ plot. Similarly, at reference strain rate ($\dot{\varepsilon} = 1\ s^{-1}$), thermal softening effect on flow stress can be isolated since $\ln \dot{\varepsilon}^* = 0$. So, Eq. (1) can be expressed as:

$$\sigma = (A + B\varepsilon^n)(1 - T^{*m}). \quad (5)$$

Using the flow stress data for a particular strain at different temperatures, the graph of $\ln[1 - \{\sigma/(A + B\varepsilon^n)\}]$ vs. $\ln T^*$ is plotted. The material constant m is obtained from the slope of this graph. It should be noted here that material constants C and m of the JC model are determined using the least-square method. A constrained optimization procedure is used to find their optimised values. This optimisation is done by minimising the average absolute error (δ) between the experimental and predicted flow stress expressed as:

$$\delta = \frac{\sum_{i=1}^{K} |(\sigma_{exp} - \sigma_{cal})/\sigma_{exp}|}{k}, \quad (6)$$

where σ_{exp} and σ_{cal} are the experimental and predicted flow stresses, respectively, and k is the total number of data points.

Using the parameters summarised in Table 2, the flow stress data for alloy D9 are predicted for various processing conditions, and compared with experimental data for similar loading conditions. Comparison between the experimental and predicted flow stress data (Fig. 1) clearly shows that the deviation in prediction for most of the loading conditions is unacceptable. The correlation

Table 2
Parameters of the Johnson–Cook model for alloy D9.

Parameter	A (MPa)	B (MPa)	n	m	C
Value	120	465.79	0.308	0.75 ± 0.003	0.1 ± 0.002