International Journal of Pressure Vessels and Piping 88 (2011) 501–506

Contents lists available at ScienceDirect

International Journal of Pressure Vessels and Piping

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

Prediction of high temperature flow stress in 9Cr–1Mo ferritic steel during hot compression

S.A. Krishnan, C. Phaniraj*, C. Ravishankar, A.K. Bhaduri, P.V. Sivaprasad [1]

Materials Technology Division, Indira Gandhi Centre for Atomic Research, Dept of Atomic Energy, Kalpakkam 603102, Tamil Nadu, India

ARTICLE INFO

Article history:
Received 20 June 2010
Received in revised form
13 July 2011
Accepted 25 July 2011

Keywords:
9Cr–1Mo steel
Hot deformation
Constitutive equation
Strain rate compensation

ABSTRACT

Constitutive analysis was performed on the experimental true stress-true strain data obtained from hot isothermal compression tests on 9Cr–1Mo steel in a wide range of temperatures (1173–1373 K, i.e. 900–1100 °C) and strain rates (0.01–100 s^{-1}). The constitutive equation for hot deformation is represented by a hyperbolic–sine Arrhenius type equation relating flow stress, strain rate and temperature, and could be described by the Zener–Hollomon parameter in an exponential type equation. The influence of strain was incorporated in the constitutive equation by considering the variation of material constants as a function of strain. It is observed that the compensation for strain could not accurately predict the flow stress for the entire strain rate and temperature regime. The constitutive equation was revised incorporating compensation for both strain and strain rate by suitably modifying the Zener–Hollomon parameter and the modified constitutive equation is found to give good prediction of flow stresses for most strain rate and temperature combinations.

1. Introduction

The understanding of material flow behavior through modeling [1–10] in hot deformation is important in the analysis and optimization of metal forming processes. Constitutive equations are used to represent flow behavior of materials that can be used in Finite Element Analysis to model the material response under various loading conditions. At high temperatures, the dependence of flow stress on strain rate and temperature may be obtained from hot compression, torsion and tensile tests. The hot working tests need to be performed under conditions similar to those encountered in industrial forming processes where strain and strain rate may vary and strain rate may be as high as 100 s^{-1} [1]. Though large strains are achieved in hot torsion tests, the strain varies along the specimen radius hindering a strain dependent analysis. Hot tension tests are not favorable because necking makes the deformation inhomogeneous and the strain achievable is often insufficient to cover the range of strains observed in industrial forming processes. Hot compression tests are widely employed in evaluating the hot working behavior of materials since uniform deformation can be obtained even at high strain rates as those encountered in industrial practice.

Many researchers have attempted to develop constitutive equations of materials using a hyperbolic–sine Arrhenius type equation [1,3–7,9,10]. The hyperbolic–sine equation is suitable for analysis of flow stress data obtained over a wide range of strain rate and temperature, as it combines both power-law and exponential dependences in the low and high stress limits, respectively. By taking into account the effect of strain and deformation history, Rao *et al.* [3] proposed a new methodology based on the modified hyperbolic–sine Arrhenius equation to predict the flow stress under varying conditions of temperature and strain rate. Sloof *et al.* [6] found that a strain dependent parameter in the hyperbolic–sine equation yielded a good prediction of flow stresses for a wrought magnesium alloy. The successful use of a strain dependent term for Ti–Al based alloys has been reported by Pu *et al.* [7]. Recently, it has been shown by Lin *et al.* [9] and Mandal *et al.* [10] that the strain dependent term in the hyperbolic–sine Arrhenius constitutive equation is not sufficient in accurately predicting the flow behavior. Hence, a revised method with compensation for strain rate in the Zener–Hollomon parameter was developed by Lin *et al.* [9] and was followed by Mandal *et al.* [10] to accurately predict flow curves for a wide range of strain rate and temperature.

9Cr–1Mo ferritic steel and its modified versions such as P91 (modified by addition of Nb and V) and P92 (modified by reduced Mo with W addition) are the materials of choice for steam generator applications in new generation power plants [11–14]. This is because they possess excellent creep strength and ductility at elevated temperatures, and have a proven resistance to stress

* Corresponding author. Tel./fax:+91 44 27480118.
E-mail address: phani@igcar.gov.in (C. Phaniraj).
[1] Formerly with Indira Gandhi Centre for Atomic Research, Kalpakkam, India.

0308-0161/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijpvp.2011.07.009