Materials and Design 34 (2012) 566–575

Contents lists available at ScienceDirect

Materials and Design

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

Numerical investigation of factors affecting creep damage accumulation in ASME P92 steel welded joint

Lei Zhao, Hongyang Jing, Lianyong Xu *, Junchao An, Guangchun Xiao

School of Materials Science and Engineering, Tianjin University, Tianjin 300072, China
Tianjin Key Laboratory of Advanced Joining Technology, Tianjin 300072, China

ARTICLE INFO

Article history:
Received 15 February 2011
Accepted 7 May 2011
Available online 14 May 2011

Keywords:
D. Welding
H. Failure analysis
I. Creep

ABSTRACT

The present study mainly investigated Type IV cracking occurring in the fine grained heat affected zone (FGHAZ) in the welded joint of ASME P92 steel at high temperature and low applied stress by numerical simulation method. Based on the modified Karchanov–Rabotnov constitutive equation, the user defined material subroutine (UMAT) was complied and the creep damage accumulation was carried out by finite element method using ABAQUS codes for the welded joint at 650 °C and 70 MPa. Calculated results revealed that the most severe creep damage and the highest equivalent creep strain occurred in the FGHAZ because of high maximum principle stress and high maximum principle stress. Furthermore, the effect of groove angle and HAZ width on the creep damage accumulation was investigated. It indicated that a small groove angle and a narrow FGHAZ width could deteriorate the creep damage accumulation because of the degradation of maximum principle stress and stress triaxiality in the FGHAZ.

1. Introduction

In order to improve the thermal efficiency and to reduce the CO_2 emission in modern ultra-supercritical (USC) fossil-fired power, the operating temperature and pressure have to be increased [1,2]. The development of a new type of heat resistant steel is necessary to satisfy the working conditions of steam operating temperature above 600 °C and steam pressure above 20 MPa. High Cr ferritic heat resistant steel is often regarded as the most potential material [3,4]. ASME P92 steel (9Cr–1.8 W–0.5Mo–NbV in wt.%) is a typical high Cr ferritic steel and has been used as structural materials for boiler components at 600 °C and 25 MPa due to its good mechanical properties, especially the high creep rupture strength, which is the most important property for high pressure and temperature application [5,6].

However, when the power plant steam pipe is in-service under high temperature and high pressure, creep cracks often occur in the fine grained heat affected zone (FGHAZ) of welded joints, known as Type IV cracking [7–9]. It would lead to a short creep life of the welded joint compared to that of the base metal. Recently, some researchers have investigated the causes of Type IV cracking [10,11]. Type IV cracking is mainly caused by the accumulation of the creep damage (creep voids) and often occurs in the position with the most severe creep damage. However, the creep damage accumulation, stress distribution and the relationship between these two phenomena have not been investigated in detail. In the present study, a fine element method coupled with continuum damage mechanics is used to investigate the mechanism of Type IV cracking and to determine the major factors affecting the creep damage accumulation.

The calculation of the creep damage accumulation using the finite element method (FEM) can be used to predict the most severe damage position, the failure lifetime of the components, and to assess the growth of the creep damage in the structure [12]. In continuum damage mechanics, a damage parameter is defined ranging from 0% (no damage) to 100% (full damage) and then the parameter is monitored throughout the creep time. The creep rupture time is defined as the time taken for the continuum damage level to reach 99.9–100% in most elements in a given zone. Previous researches have shown that FEM predictions of creep rupture time for many practical applications are in good agreement with experimental results [13,14].

In the present study, based on modified Karchanov–Rabotnov constitutive equation, the user defined material subroutine (UMAT) is complied, and the creep damage accumulation in a welded joint of ASME P92 steel at 650 °C and 70 MPa is calculated by ABAQUS. Additionally, simulations on welded joints with various groove angles and various HAZ widths are also carried out to determine factors affecting Type IV cracking in ASME P92 steel.

* Corresponding author at: School of Materials Science and Engineering, Tianjin University, Tianjin 300072, China. Tel./fax: +86 022 27402439.
E-mail address: xulianyong@tju.edu.cn (L. Xu).

0261-3069/$ - see front matter
doi:10.1016/j.matdes.2011.05.009

2. Creep damage constitutive equation and material properties

2.1. Creep damage constitutive equation used in UMAT

Several different forms of creep damage constitutive equations have been proposed to predict the creep damage and the fracture life of the engineering component operated at high temperature [14–18]. In the present study, a modified Karchanov–Rabotnov equation for the creep damage is used to calculate stress distribution and creep damage accumulation of a welded joint creep specimen serviced at 650 °C and 70 MPa, and the constitutive equation can be expressed in the multi-axial form as follows [16]:

$$\frac{d\varepsilon_{ij}^c}{dt} = \frac{3}{2}B\sigma_e^{n-1}S_{ij}(1-\rho+\rho(1-D)^{-n}) \quad (1)$$

$$\frac{dD}{dt} = g \cdot \frac{A}{\phi+1} \cdot \frac{(\alpha\sigma_1 + (1-\alpha)\sigma_e)^{v}}{(1-D)^{\phi}} \quad (2)$$

$$D_{cr} = 1-(1-g)^{(1/(\phi+1))} \quad (3)$$

where ε_{ij}^c is the creep strain tensor; σ_e and σ_1 are the equivalent stress and the maximum principal stresses, respectively; S_{ij} is the stress deviation tensor; D is the damage variable; D_{cr} is the critical damage, while $D/D_{cr} = 1$ means that the material is damaged completely; α is the multiaxial stress parameter ($0 < \alpha < 1$); B, n, A and v are the material constants related to the minimum creep strain rate and rupture behavior; g, ρ and ϕ are the constants accounting for the inhomogeneity of the damage where ρ represents the volumetric ratio of the damage phase.

The relation between B, n, A, v and the minimum creep strain rate and the rupture behavior can be described as follows:

$$\dot{\varepsilon}_{min}^c = B\sigma^n \quad (4)$$

$$t_f = \frac{1}{A\sigma^v} \quad (5)$$

where $\dot{\varepsilon}_{min}^c$ is the minimum creep strain rate; t_f is the rupture time; σ is the applied stress under the uniaxial creep test.

2.2. Creep material properties

According to the different thermal cycles during welding, the microstructure regions of a welded joint can be divided into four different zones: welded metal (WM); coarse grained heat affected zone (CGHAZ), which is the region near the fusion boundary that reaches a temperature well above Ac_3 during welding; fine grained heat affected zone (FGHAZ), which is away from the fusion boundary where the peak temperature (T_p) is lower, but still above Ac_3; base metal (BM). The mechanical properties of CGHAZ, WM, BM, and FGHAZ are different due to the different welding thermal cycles. It is known that the variation in mechanical properties in real weld joints is continuous. However, in order to reduce model complexity, the weld joint is considered to consist of WM, CGHAZ, FGHAZ, and BM, and only four kinds of mechanical properties are used in this study. The quantification of the mechanical properties of HAZ is much more challenging compared to the base material and the welded metal, because of the heterogeneity of the microstructure in the HAZ in a rather narrow range. The mechanical properties of FGHAZ and CGHAZ can in principle be studied by subjecting bigger steel samples to the expected thermal cycles which correspond to the actual thermal cycles undergone by the FGHAZ and the CGHAZ during welding process, in order to produce homogeneous microstructures of the FGHAZ and the CGHAZ [19].

The minimum creep strain rate versus applied stress and the rupture time versus applied stress are shown in Figs. 1 and 2 respectively for different micro-zones in the welded joint of ASME P92 steel. The test results show that FGHAZ exhibits a higher creep strain rate compared to BM, CGHAZ, and WM. It is implied that creep failure may occur in the FGHAZ because of low creep strength. Further, the material constants (B, n, A, v) can be obtained. Fig. 3 shows the nonlinear fitting line of material constants

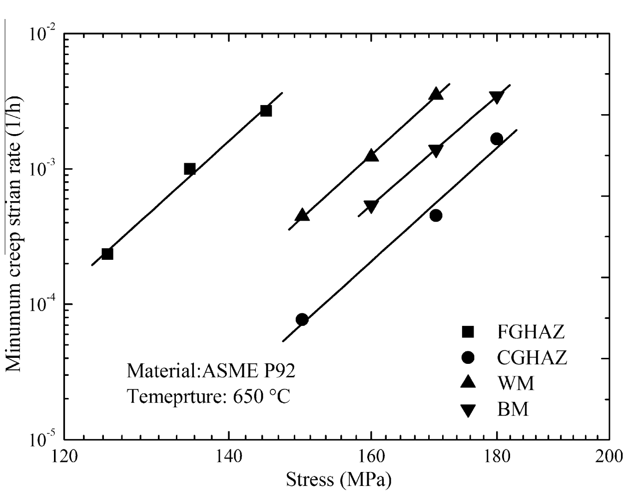

Fig. 1. Minimum creep strain rate versus applied stress of ASME P92 steel at 650 °C.

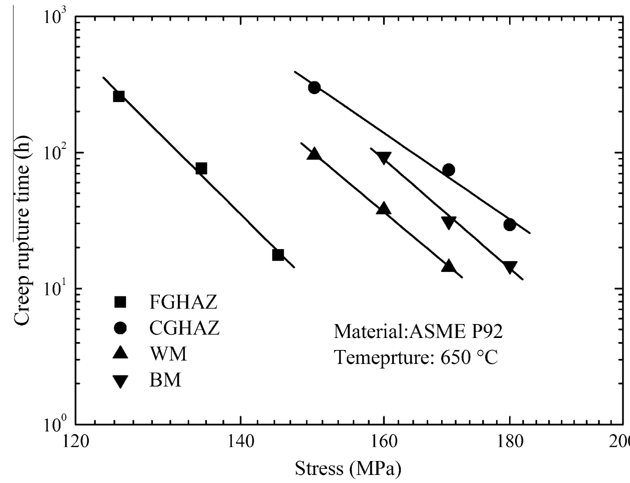

Fig. 2. Rupture time versus applied stress of ASME P92 steel at 650 °C.

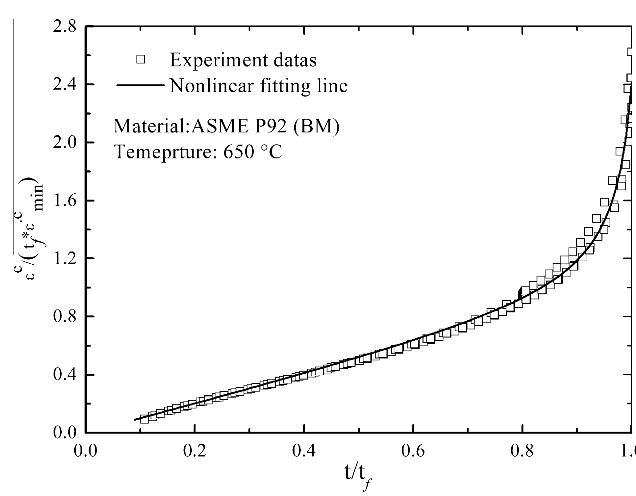

Fig. 3. Nonlinear fitting line of material constants for modified Karchanov–Rabotnov equation.