Materials and Design 47 (2013) 677–686

Contents lists available at SciVerse ScienceDirect

Materials and Design

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

Evaluating of creep property of distinct zones in P92 steel welded joint by small punch creep test

Lei Zhao [a,b], Hongyang Jing [a,b], Lianyong Xu [a,b,*], Yongdian Han [a,b], Junjie Xiu [a,b], Yaxia Qiao [c]

[a] School of Materials Science and Engineering, Tianjin University, Tianjin 300072, China
[b] Tianjin Key Laboratory of Advanced Joining Technology, Tianjin 300072, China
[c] China Electric Power Research Institute, Beijing 100055, China

A R T I C L E I N F O

Article history:
Received 27 October 2012
Accepted 13 December 2012
Available online 22 December 2012

Keywords:
Small punch creep testing
Uniaxial creep
Welded joint
Creep damage

A B S T R A C T

Small punch creep tests were carried out on four different micro zones in P92 steel welded joint: base metal, welded metal, fine grain heat affected zone and coarse grain heat affected zone. In addition to the creep rupture times, the full deflection curves during creep were also obtained, from which the creep properties of different welded joint micro zones could be derived. Furthermore, finite element method (FEM) analysis implanted with continuum damage mechanics was performed to investigate the variation of the creep damage, stress and strain during the test process. The validity of FEM results was certified by the agreement with experimental results. Then, on the basis of the experimental data, FEM results and theoretical models, the relationship of load in small punch creep test and stress in uniaxial creep test and the correlation of deflection and strain were established, respectively. According to these relations, the creep properties of the different distinct zones in P92 steel welded joint were obtained.

1. Introduction

Nowadays, reducing the consumption of energy by improving the efficiency of thermal power plants and developing the clean energy by reducing the emission of CO_2 have become an important issue in the development of modern materials [1,2]. Advanced foil power plants need to use higher working temperatures above 600 °C and higher steam pressures above 30 MPa to achieve these purposes, and this requires materials with superior properties that can operate under such conditions [2,3]. P92 steel (9Cr–0.5Mo–1.8W–VNb) due to high creep strength and high corrosion resistance at elevated temperature has been widely applied in these advanced foil power plant components such as main steam pipes, superheaters and reheaters [4–6]. Since the pipe systems of the power plants are very complex and have many integrated locations, these high temperature components are mainly fabricated by the welding process. However, premature failures at welded joints which always occur in the fine grain heat affected zone (FGHAZ) adjacent to the base metal (BM), known as Type IV cracking, have recently become the most severe problems for advanced high chromium ferritic steels [7,8]. Therefore, determining the creep properties of the distinct zones in P92 steel welded joint is extremely important for assessing the integrity of the in-service components.

* 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 © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.matdes.2012.12.032

Previous researches on P92 steel welded joint have focused on: investigating the failure type and Type IV cracking mechanism by the cross weld uniaxial creep specimen [9,10]; investigating the properties of heat affected zone (HAZ) by the heat simulated uniaxial creep specimens according to the welding thermal cycles [11,12]. However, the size of the actual HAZ is narrow and the welding thermal cycle of HAZ is complicate, so the above mentioned approaches have limitations to assess the welded joint integrity.

To overcome the limitations of specimen size problem, the small punch testing technique has been recently developed and is expected to reduce the influence of sampling on the component. Furthermore, this technique is also a nondestructive test for the in-service components by using a miniaturized disc specimen with a thickness of 0.25–0.5 mm and a diameter of 8–10 mm [13–16]. For the past three decades, the small punch test had been successfully employed to measure the ductile–brittle transition temperature [17], to estimate the fracture toughness [15], and to evaluate the susceptibility to environmental embrittlement [18]. In particular, a small punch creep (SPC) test has been developed to determine the fracture properties and creep properties at high temperature [19,20]. Because the size of this SPC specimen is smaller than that of conventional uniaxial creep specimen, this technique can be used to measure the creep properties of the distinct zones in the welded joint such as the fine grain heat affected zone (FGHAZ) and the coarse grain heat affected zone (CGHAZ). In particular, this technique can be used to directly assess the creep residual life of the in-service components in a nondestructive way. Recently, some researchers had employed this technique to assess the creep properties at elevated temperature. Izaki et al. [21] had studied the creep properties of the 2.25Cr–1Mo steel boiler pipe; Dobeš and Milička [19,22] and Blagoeva and Hurst [23] had obtained the creep properties of the P91 steel and the Al–C–O alloys; Zhou et al. [24] and Zhai et al. [25] had analyzed the factors affecting the SPC results by numerical simulation. These investigations revealed that SPC was the novel and useful method to determine the creep properties. However, the SPC tests on micro zones of P92 steel welded joint have not been studied in detail, which has crucial value in life prediction of P92 steel components operating at high temperatures and high pressures. Furthermore, the relationship between the SPC tests and conventional uniaxial creep tests also needs to be studied deeply.

Hence, in the present study, the SPC tests were carried out on a set of specimens extracting from the base metal (BM), the welded metal (WM), the coarse grain heat affected zone (CGHAZ) and the fine grain heat affected zone (FGHAZ) of P92 steel welded joint at 650 °C to investigate the applicability of the SPC test. In addition, the effect of microstructure change in P92 steel welded joint on the creep properties was also investigated. The SPC rupture data were correlated with the results obtained from the standard uniaxial creep tests, so that the SPC results could be applied to evaluate the creep life of P92 steel welded joints servicing at high temperature. Furthermore, a finite element method (FEM) analysis coupled with the continuum damage mechanics was carried out to investigate the evolution of the creep deflection, creep strain and creep damage during SPC tests to interpret it in detail.

2. Experimental procedures

2.1. Materials employed

Advanced heat resistant chromium steel-P92 steel with a composition (in wt.%): 0.10 C, 0.47 Si, 0.40 Mn, 0.001 S, 0.008 P, 8.77 Cr, 0.12 Ni, 0.18 Mo, 1.48 W, 0.16 V, 0.054 Nb, 0.001 B, 0.02 Al, 0.043 N and Fe balance was used for the experiments and was taken from the virgin main steam pipes with inside diameter of 390 mm and wall thickness of 80 mm. The pipes with the J-type groove were welded by Gas Tungsten Arc (GTAW) for the root and Shielded Metal Arc Welding (SMAW) for the rest with appropriate deposit metals. Subsequently, the welded joint was tempered for 4 h at 760 °C in order to relieve the internal stresses.

2.2. Creep tests

In the present study, conventional uniaxial creep (UC) tests as well as small punch creep (SPC) tests were all performed at 650 °C, and subsequently their results were compared. The dimension and size of the standard uniaxial creep test specimens and the SPC test specimens employed in this paper are shown in Fig. 1a and b, which are designed according to ASTM: E 139-011 and ASTM: E 8M-11 and CEN code [26]. The typical uniaxial creep test specimen is a rod type with a diameter of 10 mm and a gauge length of 100 mm (see Fig. 1a) while the SPC test specimen is a disc type with a diameter of 10 mm and a thickness of 0.5 mm [26]. Small punch creep specimens which represented BM, WM, CGHAZ and FGHAZ were retrieved from P92 steel welded joint, as shown in Fig. 2. Furthermore, the conventional uniaxial creep specimens with BM and WM materials were also machined from the welded joint. Specimen surfaces should be ground and mechanically polished up to 0.05 μm alumina powder finish. In particular, the thickness of SPC specimens was finally adjusted to 0.5 ± 0.01 mm. Conventional uniaxial creep tests and SPC tests were carried out at 650 °C with the precision of ±1 °C in accordance with ASTM: E 139-11 and CEN code [26].

Fig. 3 shows the schematic illustration of the SPC test equipment. It is composed of a heat resistant superalloy punch, the upper and lower heat resistant superalloy specimen holders, a ceramic ball with diameter of 2.5 mm, a loading mechanism, a gas purging mechanism and a data acquisition unit. During testing, a constant load was applied to the center of specimen through the ceramic ball using the electric servo motor. The central deflection of the specimen was then monitored by measuring the displacement of the compression puncher using a linear variable displacement transformer. The SPC tests were carried out under constant loads ranging from 225 N to 350 N and were conducted in argon gas atmosphere at 0.3 L/min to prevent severe oxidation of the specimen. The standard uniaxial creep tests were also carried out to verify the validity of the creep rupture strength evaluated by the SPC tests.

3. Finite element method analyses

3.1. Finite element model

Taking advantage of the rotational symmetry of the experimental equipment and the shape and deformation of the SPC specimen, an axisymmetric model was developed as shown in Fig. 4, the components of which are the same as those illustrated in Fig. 3. In this model, the punch ball and the supported holders were implemented as rigid bodies and then surface-to-surface contacts were assigned at all contacting interfaces, i.e. interface between the upper surface of specimen and the ball surface and interface between the specimen and the clamping surface of the low die. Friction coefficient at the contact interfaces was assumed to be 0.2. The SPC specimen was considered as a deformable body and was then modeled with 2000 axisymmetric linear reduced integration elements. This element was adopted since it was particularly appropriate to embody bending effect and contact interaction problems and could be used to prevent converge problems due to shear and volume locking caused by severe shear and torsion [27]. According to the experimental situations, the encastre constrains were assigned to the supported dies and the symmetric constrains were applied to the corresponding edges of the SPC specimen while the punch ball was defined to only move vertically.

3.2. Material model

Due to large deformation occurring in the SPC test, an elastic–plastic–creep approach was employed to analyze the creep behavior. According to the thermal elastic–plastic mechanics, the total strain ε^t can be considered as:

$$\varepsilon^t = \varepsilon^e + \varepsilon^p + \varepsilon^c \tag{1}$$

where ε^e, ε^p and ε^c are elastic, plastic and creep strain components, respectively. The elastic and plastic strains are considered to be independent of strain rate. The material is assumed to be isotropic and homogenous and linear elastic up to the yield strength and post-yield the material which obeys the von Mises stress potential and associated J2 flow theory.

In addition, to obtain the whole creep deformation and the damage accumulation, a continuum damage mechanics was implanted in the analyses. The alternative creep damage model proposed by Liu and Murakami was used in the present study [28]. This model could overcome the convergence problems which were caused by the very high creep damage rates and the corresponding high creep strain rate when the creep damage reached to the unit