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Effect of welding on creep damage evolution in P91B steel

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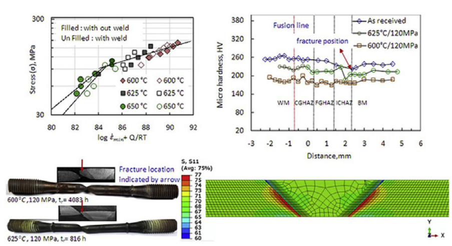
HIGHLIGHTS

- Comparison of creep properties of welded and virgin specimens of P91B steel.
- At lower stresses (<100 MPa) welded samples show higher minimum creep-rate.
- Creep rupture at inter-critical heat affected zone (IC-HAZ) in welded specimens.
- FEA showing accumulation of creep strain in weld/base metal interface.
- Precipitate free soft ferrite matrix accumulates strain and weakens IC-HAZ.

GRAPHICAL ABSTRACT



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ABSTRACT

Study of creep behavior of base metal (without weld) and welded specimens of P91B steel over a range of temperatures (600–650 °C) and stresses (50–180 MPa) showed similar values of minimum creep-rates for both specimens at higher stress regime (>100 MPa) whilst, significantly higher creep rates in the case of welded specimens at lower stress regime. Considering that welded specimen is comprised of two distinct structural regimes, i.e. weld affected zone and base metal, a method has been proposed for estimating the material parameters describing creep behavior of those regimes. Stress–strain distribution across welded specimen predicted from finite element analysis based on material parameters revealed preferential accumulation of stress and creep strain at the interface between weld zone and base metal. This is in-line with the experimental finding that creep rupture preferentially occurs at inter-critical heat affected zone in welded specimens owing to ferrite-martensite structure with coarse $Cr_{23}C_6$ particles.

1. Introduction

P91 grade (ASTM A-387) 9Cr-1Mo steel is widely used in thermal power plants and petrochemical industries because of low thermal expansion, high thermal conductivity, high corrosion resistance, good weld-ability and excellent creep resistance [1–4]. After several years of its use, there has been a growing concern about creep damage accumulation and rupture life degradation of structural components made of P91 steel at elevated temperatures. Most of the in-service problems have been found to be associated with the mismatch between the creep behaviors of the base metal, the weld joint and the heat affected zone (HAZ) [5,6]. Creep rupture strength of the welded region of this steel has been found to be lower than that of the base metal. Lower rupture life of the weldment has been attributed to the formation of a soft micro-structural region covering fine-grain heat affected zone (FG-HAZ) and inter-critical heat affected zone (IC-HAZ) [7]. Microstructural changes and damage accumulation in this region, under creep condition,

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Abbreviations and symbols

BM	Base metal
CG-HAZ	Coarse grain heat affected zone
FG-HAZ	Fine grain heat affected zone
IC-HAZ	Inter critical heat affected zone
W, WM,WAZ	Weld/Composite, Weld metal, Weld affected zone
MMAW	Manual metal arc welding
PWHT	Post weld heat treatment
A, Ao	Material constants
T, Q, R	Temperature in Kelvin, Activation energy, Universal gas constant
σ	Stress
$\dot{\varepsilon}$, $\dot{\varepsilon}_c$, $\dot{\varepsilon}_m$	Creep rate, Creep strain rate, Minimum creep rate
n, m	Norton stress exponent, time exponent
ε_W, ε_{BM}, ε_{WAZ}	Creep strain for composite/weld, Base metal, Weld affected zone
f	Volume fraction of the weld affected zone
ρ, b, x	Dislocation density, Burgers vector, Average inter particle spacing
t_c, t_g	Time required by a dislocation to climb and glide
t, t_r	Time, rupture time

leads to premature failure. This type of failure is commonly known as Type-IV fracture [7–13].

Addition of a small amount of boron (50–100 ppm) to the parent metal is reported to be an effective way to overcome such a problem [11,13–27]. The boron addition retards the onset of tertiary stage of creep. It reduces the coarsening rate of $M_{23}C_6$ carbides at the prior austenite grain boundaries and thereby delays the recovery of martensite during creep [16]. It is reported that boron atoms occupy vacancies in the vicinity of the interfaces between growing carbide particles and the martensite matrix (near prior austenite grain boundaries) [17,18]. As a result the accommodation of local volume change associated with the coarsening of carbide particles becomes difficult.

By now the beneficial effect of B addition on the creep resistance of weld joint of 9Cr-1Mo steel has been established. In recent studies, the present authors have reconfirmed this aspect by performing long term creep tests on the base metal and cross-weld specimens of P91B steel [28,29]. However, earlier studies were primarily focused around the effect of B addition on the microstructural parameters and their effects on the creep properties of 9Cr-1Mo steel. Hence, there is a serious need for analytical work towards the prediction of creep life of B added P91 steel, not only of base metal but also of weld joint. The present work is an extension of the earlier studies [28,29] in this direction. This study provides a background for developing a predictive approach for long-term creep life estimation of high temperature engineering components made of B added 9Cr-1Mo steel, which is required for structural design to ensure safety and reliability.

2. Experimental procedure

2.1. Material

Modified 9Cr-1Mo steel plates (12 mm thickness), containing a small amount of boron (designated as P91B steel), in hot-rolled, normalized and tempered condition was used in the present study. The chemical composition and heat treatment conditions of as-received steel are listed in Table 1. Heat treated plates were welded by manual metal arc welding (MMAW) using E9016 B9 electrode. The plates were preheated and inter-pass temperature of 200–250 °C was maintained during welding. Parameters used for welding are given in Table 2. After welding, the weld pads were held at 250 °C for 30 minutes to eliminate diffusible hydrogen from the welded region. Radiographic examination was used to detect weld defects. The plates that passed the test were used in this investigation. Post weld heat treatment (PWHT) was carried out in a furnace at 760 °C for 3h to relieve the residual stresses generated during welding.

Table 1
Chemical composition (wt. %) and the heat treatment conditions of investigated P91B steel.

C	Si	Mn	P	S	Cr	Mo	V	Nb	Ni
0.1	0.4	0.3	0.005	0.002	8.5	1.04	0.09	0.1	0.02
Al	N	B	Fe	Normalizing		Tempering			
0.03	0.0021	0.01	Balance	1050 °C/1 h air-cool		760 °C/3 h air-cool			

Table 2
Welding parameters used for preparing the weld joint of P91B steel.

Welding method	Current (A)	Voltage (V)	Heat input (kJ/mm)
MMAW	100	25	1.0

2.2. Creep test

Creep tests on base metal and cross-weld specimens were performed using MAYES constant load creep testing machine (Model TC 30) having automatic lever leveling facility. The dimension and orientation of the specimens used for the creep testing are schematically shown in Fig. 1. Tests were conducted at 600 °C, 625 °C and 650 °C and 180-50 MPa stress. The strain was measured by an extensometer–LVDT assembly. The test temperature was controlled with an accuracy of ±2 °C.

2.3. Microstructural examination and hardness testing

Metallographic examinations on as-received and creep tested specimens were carried out using Zeiss EVO60 Scanning Electron Microscope (SEM) and JEOL® JEM-2100 and FEI-TECNAI G220S-TWIN transmission electron microscopes (TEM). The micro-hardness measurements were taken before and after the creep testing, using Vickers micro-hardness tester (Micromet 5103, Buehler Ltd, USA) with 100 gf (0.98 N) load for 15s dwell time. TEM examination was used to study the effect of creep exposure on the microstructures of P91B steel. Thin foils were prepared from the base metal, weld metal and different regions of HAZ using CM-12 ion-miller. Secondary phases were identified using energy dispersive X-ray spectroscopy (EDS) and selected area electron diffraction analysis (SAED).

3. Results and discussions

3.1. Comparison of creep properties between specimens with and without weld joint

Cross-weld specimens are tested in the present study to compare the creep behavior of base metal and welded P91B steel and for developing an analytical approach for prediction of long term creep life of P91B steel components. A specimen having a weld zone aligned along the loading direction could be assumed to be a