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Fractal and probability analysis of creep crack growth behavior in 2.25Cr–1.6W steel incorporating residual stresses

Mengjia Xu, Jijin Xu*, Hao Lu, Jieshi Chen, Junmei Chen, Xiao Wei

School of Materials Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China

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ABSTRACT

In order to clarify creep crack growth behavior in 2.25Cr–1.6W steel incorporating residual stresses, creep crack tests were carried out on the tension creep specimens, in which the residual stresses were generated by local remelting and cooling. Residual stresses in the specimens were measured using Synchrotron X-ray diffraction techniques. The fracture surface of the creep specimen was analyzed using statistical methods and fractal analysis. The relation between fractal dimension of the fracture surface and fracture mode of the creep specimen was discussed. Due to different fracture mechanisms, the probability density functions of the height coordinates vary with the intergranular crack percentage. Good fitting was found between Gaussian distribution and the probability function of height coordinates of the high percentage intergranular crack surface.

1. Introduction

2.25Cr–1.6W steel (HCM2S, T23/P23) is usually used to manufacture water wall, superheater and reheater tubes, and main steam pipe in the Ultra Super Critical (USC) Power Plants with the benefit of enhancing thermal efficiency. Components employed in power plants are continually exposed to both high temperatures and high steam pressures. The safety and performance of a thermal power plant are highly dependent on the integrity of its welded joints [1]. Welding residual stresses arise as a consequence of the heterogeneous application of energy and localized melting [2,3]. The welding residual stresses would be superimposed on any applied loads, such as high steam pressures, and generate a complex stress state on in-service components. They may accelerate creep damage development and cracking initiation at high temperature on these components. Hence, understanding the combined effects of welding residual stress and primary loads on the creep damage and crack initiation plays an important role in assessing the reliability of high-temperature structural components [4–9].

It is very difficult to obtain an accurate structural integrity assessment on actual components with residual stresses due to the complexity in geometry, residual stresses state, microstructure and local multiaxial creep ductility [4,5]. Therefore, such assessment was usually investigated under closely controlled laboratory conditions [4–13]. A new design for a compact tension (CT) specimen can introduce a tensile residual stress field into the CT notch root area. The residual stress is generated in compact tension (CT) specimen by pre-compressing and then unloading [4,6,5]. The crack growth in this work is driven solely by the residual stress with no external stress applied at all. The stresses state of welding can affect the damage process during creep; however, there is insufficient information on the effects of welding residual stresses on fracture mode. For this purpose, a novel experimental investigation is required to characterize the fracture surface quantitatively.

The concept that the fractal dimension is related to irregular objects with a self-similar property provides a basis for the quantitative characterization of the tortuosity of fracture surfaces. Since the fracture surface roughness is predetermined by morphological features which are dependent on the toughness of the material, it can be deduced that fracture toughness might also affect fracture surface roughness [14]. Ever since Mandelbrot et al. first introduced this concept to materials science in 1984 [15], a number of studies have focused on the fractal characteristics of fracture surfaces and their microstructure [14,16–25]. It should, however, be noted that the reported correlation between fractal dimension of fracture surfaces and the fracture toughness in steel could be negative [14,16–22] or positive [23,24]. Such divergent results have been pointed out to be dependent on the

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* Corresponding author.
E-mail address: xujijin_1979@sjtu.edu.cn (J. Xu).

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Table 1
Chemical compositions of 2.25Cr–1.6W steel (mass, %).

C	Mn	P	S	Si	Cr	Mo	W	V	Nb	N	Al	B	Ni	Ti	Ti/N
0.06	0.37	0.012	0.002	0.28	2.32	0.08	1.56	0.22	0.044	0.0035	<0.015	0.0026	0.05	0.009	3.9

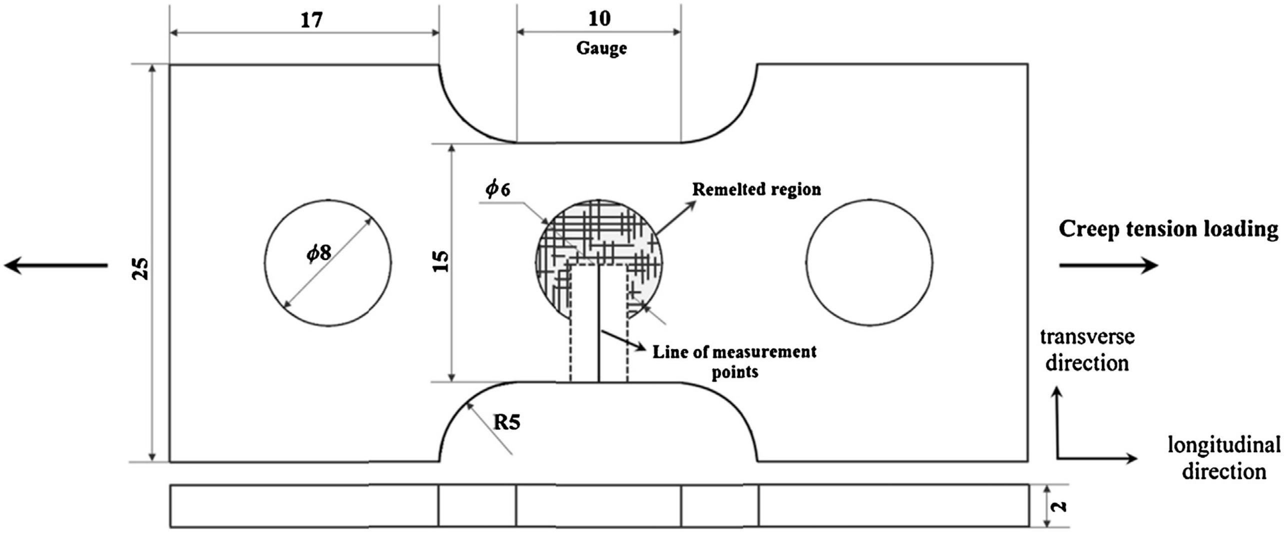

Fig. 1. Geometry of the employed creep specimens.

microstructure of fractured materials and measurement methods [21,25]. For instance, Strnadel et al. [21] reported that causes could be the differences between the fractal character on different scaling levels and the random character of initiation of fracture mechanisms. In most previous cases, the fractal dimensions of fracture surfaces were calculated based on the profile of the section perpendicular to the fracture surface. In recent years, the fractal characterization of fracture surfaces of steels has been presented by means of image processing (IP), for example, by Tang et al. [23,24]. The image used for IP was obtained from scanning electron microscopy (SEM). However, errors are introduced by noise superimposed onto the material signal when using image analyses from SEM [25]. Strnadel et al. [21] have estimated the fractal dimension of the drop-weight tear test (DWTT) specimen fracture surfaces using a three-dimensional (3D) photographing and box-counting method. However, studies on 3D fractal analysis of the creep test specimen fracture surface in Cr–Mo heat-resistant steel were rarely reported.

The aim of the present study is to investigate the creep crack growth behavior and fracture mode of 2.25Cr–1.6W steel incorporating residual stresses. The residual stress was generated in a tension creep specimen by local remelting followed by cooling. A quantitative fractographic analysis of fracture surfaces of the creep specimens was performed in order to investigate the creep fracture characteristics when taking consideration of the effect of residual stress distribution. The results of this study will provide possibilities for an objective and quantitative determination of cracking growth process and fracture mechanisms in Cr–Mo heat-resistant steel.

2. Experimental material and test procedures

While creep cracking has been observed in welded engineering structures exposed to long-term elevated temperature conditions, laboratory studies of this failure mechanism have to rely on complex welded specimens with welding residual stresses [4,6,5]. This type of specimen is far from ideal in that the residual stress field is operator-dependent, difficult to predict and that the microstructure varies locally. Our aim is to develop a laboratory creep test specimen into which welding residual stresses could be introduced, and in which the microstructure could represent the actual welding structure.

The specimens for the creep test were cut from the 2.25Cr–1.6W steel. Table 1 presents chemical compositions for 2.25Cr–1.6W steel. Fig. 1 shows the adopted geometry and dimensions of the creep specimen. A circular region of 6 mm diameter at the center of the specimen was remelted completely along the through-thickness orientation by TIG (tungsten inert-gas arc) welding at current of 150 A and voltage of 20 V for 5 s and then cooled in air. When the remelted region solidified, welding residual stresses arose as a consequence of structure constraint. In this case, remelting treatments were carried out in an identical manner in two creep tension specimens (labeled T1 and T2).

The specimen T1 was tested under a constant nominal tensile stress of 330 MPa and a temperature of 550 ± 1 °C using a lever arm high temperature creep machine until it broke. The specimen T2 was tested under the same load and temperature condition, but the test was halted after 180 h. This time was chosen because the time to failure for specimen T1 was 191 h. The intent was to stop the test at a point after cracking had initiated and close to failure. The change of gauge was monitored of two specimens during creep test using the linear variable differential transducers, as shown in Fig. 2.

Before creep testing, the specimen T1 was used to measure the residual stresses in the longitudinal direction (the creep tension direction). The experiment was carried out using synchrotron X-ray diffraction at BL14B beam line of the Shanghai Synchrotron Radiation Facility (SSRF), in Shanghai, China. The conventional $\sin^2\psi$-method was applied. The specimen T1 was irradiated by a X-ray beam of 23 keV energy, with an approximate dimension of 0.3 mm × 0.3 mm, positioned in the center line of the remelted specimen as shown in Fig. 1. The interval between the measured points was 1 mm. Measurements were made the {2 1 1} reflection. The inclination angle ψ was varied between 0° and 45°, using five