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Research Paper

Influence of temperature on the oxide spallation of T91 alloy superheater tubes in power plant

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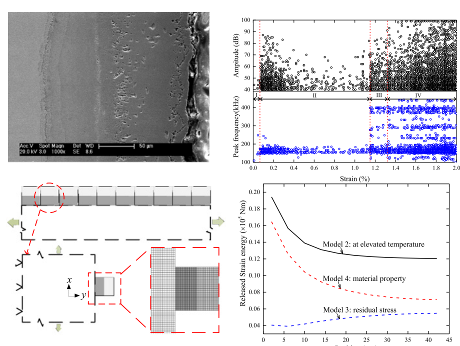
HIGHLIGHTS

- Acoustic emission features can be used to distinguish oxide failure evolution.
- Oxide failure behavior is sensitive to the test temperature.
- Strain energy in oxide scale and substrate decreases with increasing temperature.
- The substrate material property is one of key factors influencing oxide spallation.

GRAPHICAL ABSTRACT



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ABSTRACT

The spallation of steam-side oxide scale on boiler tubes can seriously influence the safety of power plants. In this work, the failure behavior of oxide scale formed on T91 alloy superheater tubes was investigated using a uniaxial tension test at room temperature and at elevated temperature (300 °C). Acoustic emission (AE) equipment was employed to monitor the failure evolution of oxide scale. The AE features associated with the metallographic investigation were adopted to detect the onset of each oxide failure type. The experimental results showed that oxide spallation occurred only at room temperature. For the elevated temperature test, no oxide spallation was found even at the maximum strain of 2%. An elastic-plastic finite element model was developed to understand the influence of temperature on the oxide failure. Results of the simulation revealed that the material property was one of key factors influencing the oxide spallation. Since the substrate yield strength decreased with increasing temperature, oxide spallation could be prevented at elevated temperature in the field.

1. Introduction

The formation of protective steam-side oxide scale enables T91 alloy tubes to survive prolonged service in the aggressive environment of power plant [1–3]. However, the oxide scale is often spalled from the tube surface after a period of oxidation [4,5]. The driving force for oxide spallation is the residual stress. This can be oxide growth stress and thermal stress arising from the thermal expansion mismatch between the oxide scale and the substrate [6–8]. Oxide failure destroys the barrier function, and steam direct access to the metal resulting in increased oxidation rate [9]. In addition, scale exfoliation can cause plugging, steam starvation and local overheating of tubes [10]. Thus, the mechanical behavior of steam-side oxide scale should be investigated to prevent oxide failure during the power plant operation.

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One preferred method to investigate the oxide failure was to mimic the practical operation environment in the laboratory condition. However, the driven force for oxide failure was complicated, which was difficult to be measured in the laboratory test [11]. Substantial mechanical tests have been applied to study the failure behavior of oxide scale [12–16]. Chandra-Ambhorn et al. [12] used the tension test in the SEM to determine the mechanical adhesion energy of oxide scale on AISI 430Ti alloy at room temperature. Bruns et al. [13] applied a four-point bending test to measure the mechanical properties of NiO on pure nickel at oxidation temperature. Renusch et al. [14] investigated the failure behavior of oxide scale formed on 2.25–24% Cr steels during the isothermal exposure and the cooling process. Oxide failure was difficult to be detected due to numerous crack sites within oxide scale. Acoustic emission (AE), produced by oxide failure event, can be used to monitor the real-time failure evolution of the oxide scale [17–20]. The AE measurement has been used to investigate the failure characteristics of oxide scale under many tests, such as the four-point bend test [21], the tension test [22] and the thermal test [14,23,24]. Huang et al. [25] studied the failure mechanism of oxide scale on T22 by the tension test and AE equipment at room temperature. However, since oxide failure always occurs at the intermediate temperature of the cooling process, tests performed at room temperature would provide different failure behaviors than that at elevated temperature. The contribution factors that influence oxide failure at elevated temperature have not been fully understood. In addition, experimental study focused on the oxide scale formed on T91 is still insufficient.

Our previous work has investigated the failure behavior of steam-side oxide scale on T22 alloy at room temperature [25]. In this paper, the uniaxial tension test and the acoustic emission technique were employed to investigate the oxide failure on T91 alloy at room temperature and at elevated temperature. The oxide failure process was divided into four stages by the evolution of AE features (AE amplitude and peak frequency), and the influence of temperature on oxide spallation was analyzed by the experimental results. Finally, finite element model was developed to assess the key factors that influence oxide failure at elevated temperature.

2. Experimental procedures and results

2.1. Experimental procedures

The alloy used in this study was T91 with composition (wt.%): 8.9Cr, 0.9Mo, 0.4Mn, 0.24Si, 0.121Ni, balance Fe [26]. Prior to testing, T91 alloy tubes were peroxided by exposing in one boiler for 6700 h at the temperature of 550 °C. SEM observations indicated that the oxide scale consisted of two compact sublayers: an inner Fe-Cr spinel and an outer magnetite sublayer (Fig. 1), as with our previous study conducted on T22 alloy [25]. The structure and composition of the oxide scale on T91 have been studied in detail by previous work [27,28]. The outer magnetite layer was generated by the reaction between outward diffusing iron ions and the oxygen at the oxide/steam interface. While the inner Fe-Cr spinel was produced by inward diffusing oxygen ions and metal at the oxide/substrate interface [29]. Then the T91 alloy tube was cut into tension test specimen by an electrical discharge machine (Fig. 2). Four specimens (named A–D) were prepared to analyze the oxide failure behavior.

The predominant contribution to oxide failure was the thermal stress, which increased with decreasing temperature [30]. Thus, oxide scale was susceptible to failure at room temperature. Our previous work has been conducted to study oxide failure at room temperature [25]. However, during the power plant operation, oxide failure always occurred at the intermediate temperatures of the cooling process [7]. Testing performed at room temperature always cannot fully reflect the oxide failure behavior in the practical operation environment of boiler. To understand the influence of temperature on oxide failure, experimental fixtures shown in Fig. 3 was applied to conduct the room temperature test and the elevated temperature test (300 °C). A MTS-SANS CMT5105 universal testing machine was used to perform the tension test at the velocity of 0.05 mm/min. TMR-211 dynamic digital recording system combined with a strain gauge was employed to record the tensile strain, and a Physical Acoustic PCI-2 system associated with a waveguide was used to monitor AE signals throughout the test. AE signals produced by oxide failure were transmitted from the specimen via the waveguide to the sensor (Nano30) at the threshold of 40 dB. Noises, arising from the localized plastic deformation around the pin holes, cannot be discriminated by the TDOA method [31], because of the small specimen dimension and the uncertainty of the waveguide length.

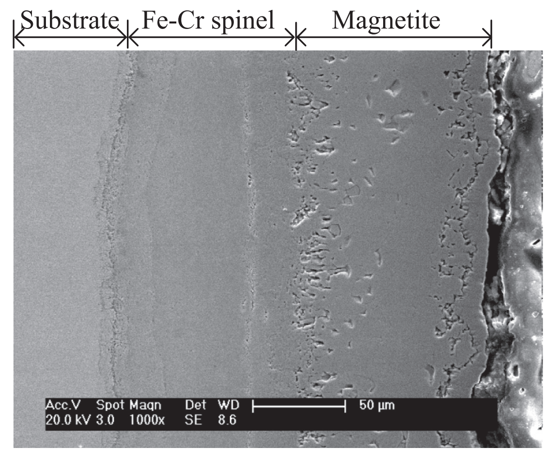

Fig. 1. SEM image of oxide scale grown on T91 alloy tube.

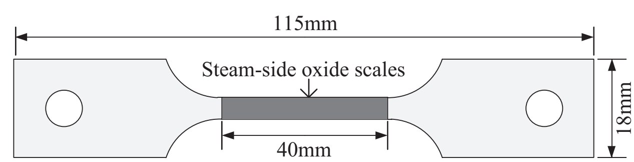

Fig. 2. Schematic of pin-loaded tension test specimen.

2.2. Experimental results at room temperature

The metallographic investigation was adopted to observe the specimen surface after the tension test. The microscopic observations revealed that oxide failure was sensitive to the test

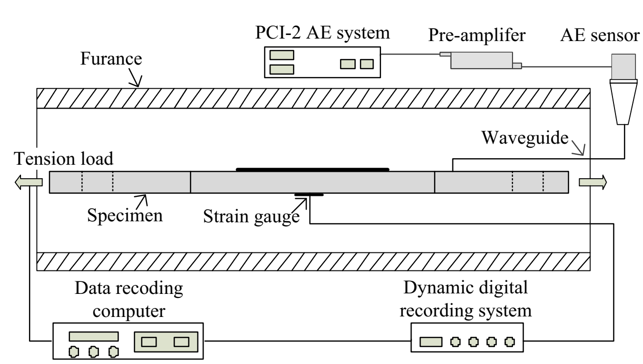

Fig. 3. Schematic illustration of the test system at elevated temperature.