Reduction of Creep Strength in T91 Superheater Tubes due to Thickening of Steam Oxide Scale on Internal Tube Surface

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Abstract

The design life of T91 superheater tubes is based on creep rupture life which depends on operating temperature and stress. However, exposure to high temperatures for a long duration will cause the formation of oxide scale layer on the tube surface which probably will accelerate the tube damage and subsequently shorten its life. The main objective of this paper is to quantify the reduction of creep rupture life in T91 superheater tubes prior to exposure to steam at temperature of 540ºC in the oxidation test rig and boiler environments. A specimen that was exposed to a boiler environment for 80,000 hours was found having 191µm thickness of the oxide scale before creep test as measured using an optical microscope scale. While specimen exposed to steam in oxidation test rig at the same temperature for 1000 hours having oxide scale thickness of 35.8 µm. Both specimens were then subjected to a uniaxial creep test at 650ºC and 100MPa. Time to rupture for specimens with 191µm and 35.8µm oxide scale thickness is 212 hours and 290 hours respectively. This result shows that a 27% reduction of creep strength in the specimen with 191µm oxide scale thickness as compared to the specimen with oxide scale thickness of 35.8µm. This finding shows the creep strength in the T91 superheater tube is reduces as oxide scale layer thickening. Therefore, it is important to examine the progress of oxide scale thickening to evaluate the current health condition of T91 superheater tubes.

Keywords: *T91; Creep; high-temperature oxide scale*

1. Introduction

Superheater T91 tubes in subcritical boiler exposed to steam at temperature between 500ºC to 580ºC. Operates in this range of temperature at Hoop stress approximately 100MPa will cause T91 superheater tube susceptible to creep [1]. Therefore, it is important to evaluate the progressing of creep in T91 superheater tubes during scheduled outage. In order to evaluate creep progressing, T91 superheater tubes need to be cut out for sampling and test in the laboratory using creep testing machine. However, the sampling process for destructive testing may not be a practical practice for most of the power plant due to high cost for repair and replacement of the cut region. Therefore, non-destructive testing (NDT) has been the most appropriate method to evaluate the health condition of T91 superheater tubes. The most common method to evaluate creep on T91 superheater tubes is through in-situ replication and hardness measurement. These methods required

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skillful operator and metallurgist to prepare replicated microstructure and interpret the microstructure changes. Therefore, Ultrasonic Testing (UT) has proposed and introduced a method to measure the internal thickness of oxide scale thickness.

2. Laboratory Test

Two types of test were conducted in the laboratory to evaluate the reduction of creep strength due to the thickening of internal oxide scale. The as-received T91 samples were subjected to oxidation and creep tests, while T91 superheater tubes that were exposed in a boiler for 80,000hours was subjected to creep test only.

2.1 Sample Preparations

An unexposed T91 superheater tube sample was exposed to steam at a temperature of 540ºC for 1000hours in steam oxidation tester. The oxidized samples were machined into standard creep test samples according to ATSM E8 as shown in Figure 1. Thickness oxide scale on the internal surface of T91 superheater before creep testing was found approximately 15µm, 191µm and 38.5µm for unexposed, exposed to boiler environment and exposed to oxidation tester respectively. The oxide scale consists of hematite and magnetite layers which are intact to each other as well as to base material as shown in Fig. 2. The samples machining process was conducted without damaging the oxide scale layer on the internal surface. This is to ensure oxide scale condition can be compared before and after creep test.

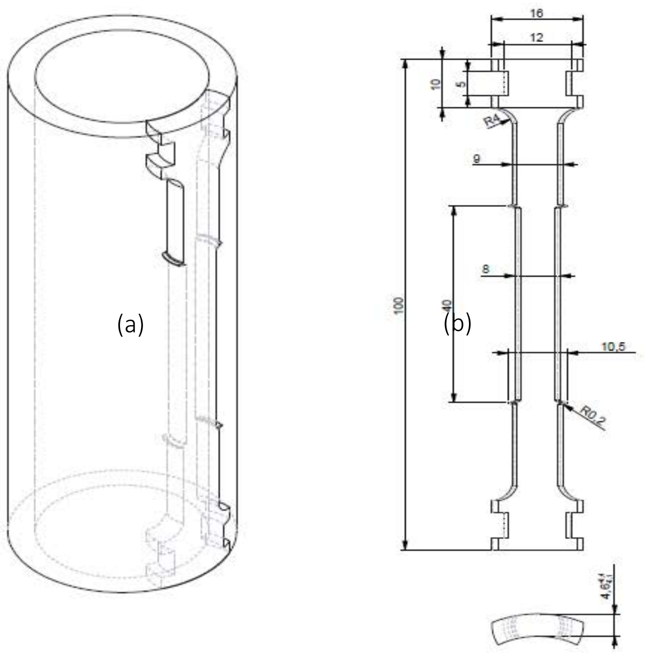


Figure. 1. Standard creep test sample, (a) Extraction location from oxidized T91 superheater tubes that were exposed in boiler and oxidation tester, (b) Sample dimension view from top and front.

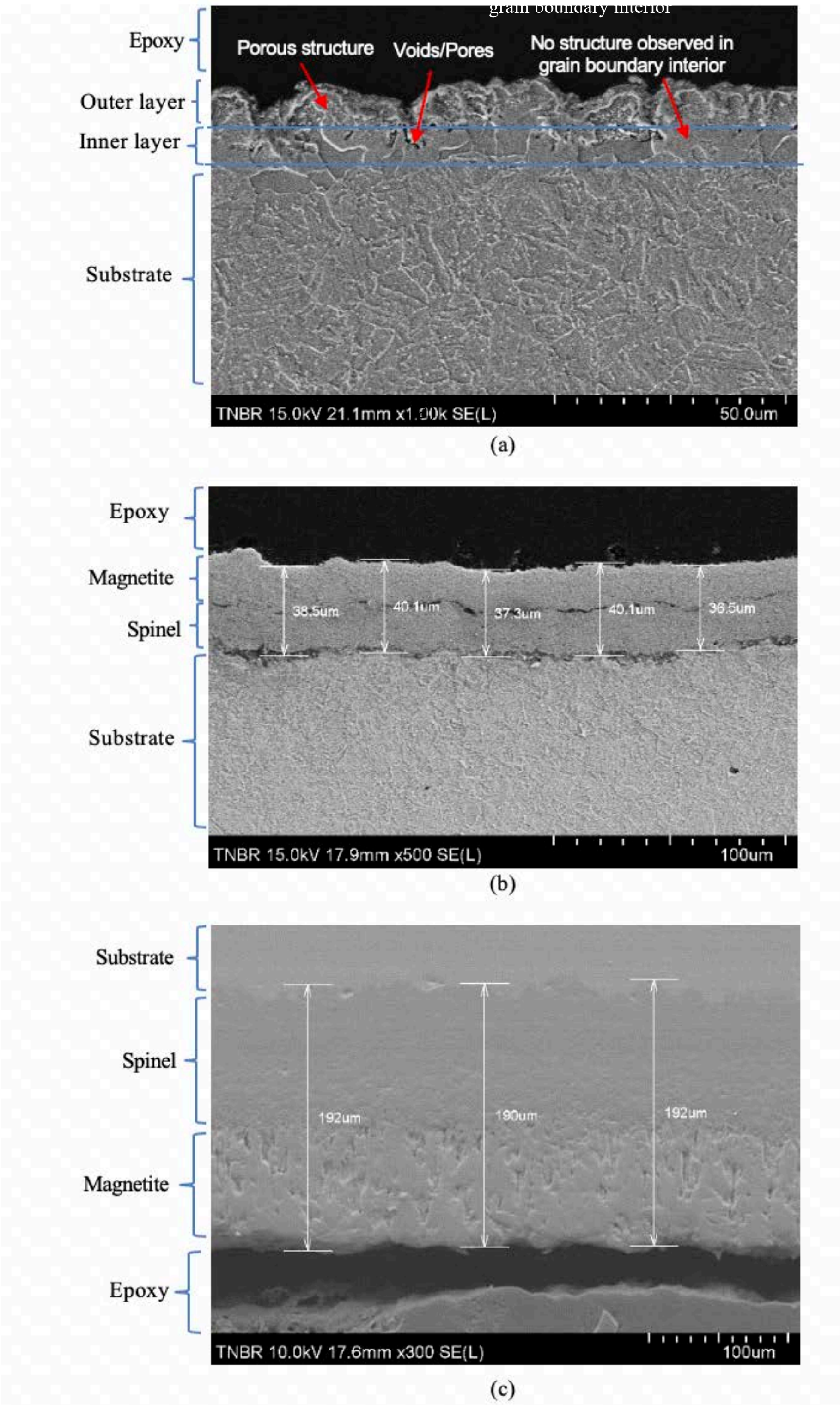


Figure 2. FE-SEM micrographs showing the condition of internal oxide scale exposed to steam at a temperature of 540ºC, (a) Unexposed T91 tube, (b) T91 tube which was oxidized in steam oxidation tester for 1000hours, (c) T91 tube which was oxidized in a boiler for 80,000hours.

3. Creep Test Results and Discussion

Creep test was conducted on 12 samples which were cut out from T91 superheater tubes that were oxidized in boiler and steam oxidation tester at 540ºC. Uniaxial creep tests were conducted at 650ºC with four different stress which is 100MPa, 110MPa, 120MPa and 130MPa. Correlation between oxide scale thickness and creep rupture life were analysed to evaluate the effects of oxide scale thickness to creep life. An increased in oxide scale thickness is believed to reduce creep life and this has been proven by creep test results as shown in Fig 3. The results show that specimens exposed to boiler environments for 80,000 hours at a steam temperature of 540ºC with oxide scale thickness approximately 191 μm had a lower creep rupture life as compared to specimens oxidized in steam oxidation test rig at same steam temperature for 1000 hours with an oxide scale thickness of 35.8 μm. This finding show that thicker oxide scale reveals shorter creep life even though exposed to the same steam temperature.

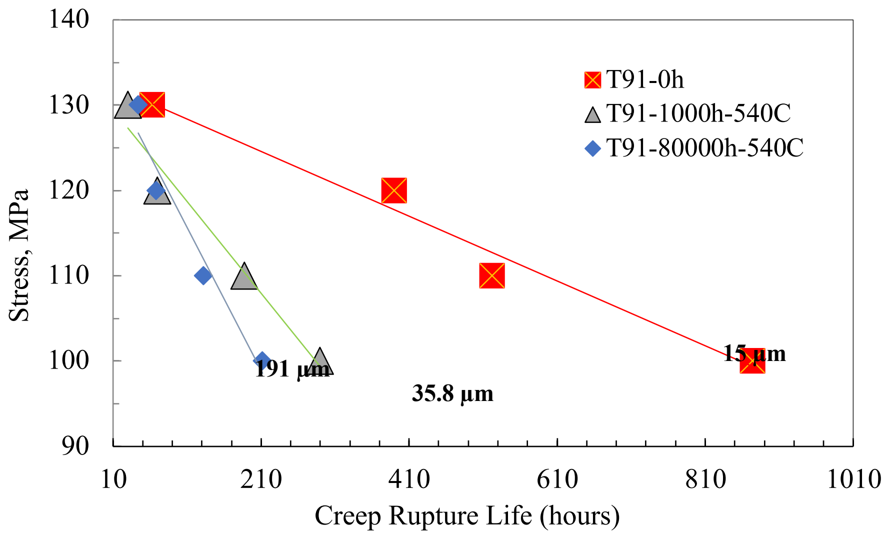


Figure 3. Comparison of creep rupture life of T91 superheater tubes which consist of different oxide thickness

Measurement of oxide scale thickness was found to be more reliable for life assessment of superheater tubes as compared to metal or wall thickness measurement [2]. This is due to the relationship between oxide scale thickness and metal temperature. This is proven by the obtained creep test result in Fig 3 which show that the creep rupture life of T91 specimens that were exposed to steam oxidation was found to be reduced significantly on specimens oxidized at temperature 540ºC as compared to unexposed specimens which have been proven by creep testing results obtained. The relationship between oxide scale thickness and creep rupture life is found to be consistent for specimens oxidized at the same temperature for different durations.

The microstructural examination was conducted on creep tested specimen. The interested area of examination was on specimen's grip which was subjected to minimal stress as compared to the gauge length. This is because the oxide scale condition in this region is only influenced by temperature and damage is not subjected to stress. Conditions of oxide scale before and after creep test were observed through micrographs in Fig. 4. Specimen oxidized at 540ºC in steam oxidation test rigs and boiler were observed found to contain cracks after being subjected to creep test at a temperature of 650ºC as illustrated in Figures 4(a) and (b) respectively. Cracks were observed formed between spinel and magnetite layer for both specimens.

Formation of cracks on specimens oxidized in the boiler has created an air gap of about 10µm in thickness between oxide scale and metal. This observation is also similar to specimen oxidized in steam oxidation test rig with different severity. Specimens oxidized in steam oxidation test rig were found to experience few isolated cracks while specimen oxidized in the boiler was observed to experience continues cracking. The crack location and orientation are similar to the findings reported by [3] on specimens exposed to laboratory air for 10,000 hours at 625ºC. The behaviour of cracking almost was also found to be about the same as the separation mechanism reported by [4].

The formation of cracks are generally due to the changes in temperature exposure from 540ºC to room temperature and heated up again to 650ºC. Differences in thermal expansion between oxide scale and substrate have caused cracking during the heating and cooling process [5]. This formation of cracks as found on both specimens are most probably similar to the spallation behaviour that generally occurs during service exposure after the oxide scale thickness has grown up to its critical thickness of 225µm [6].

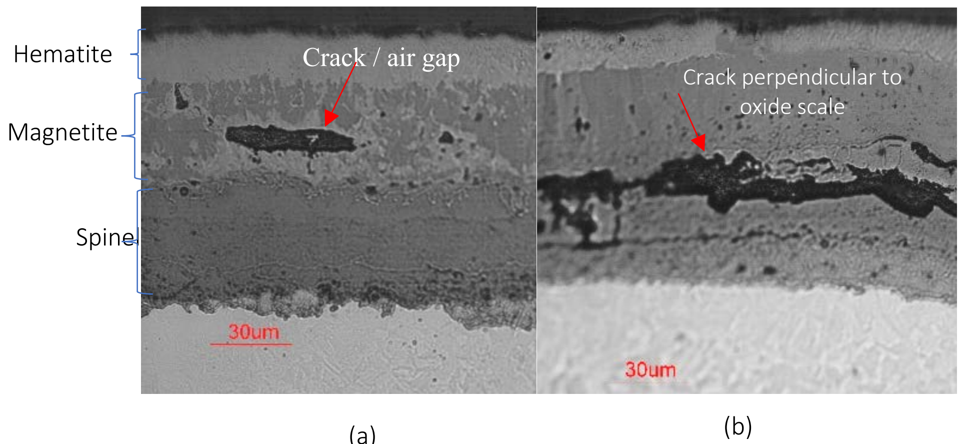
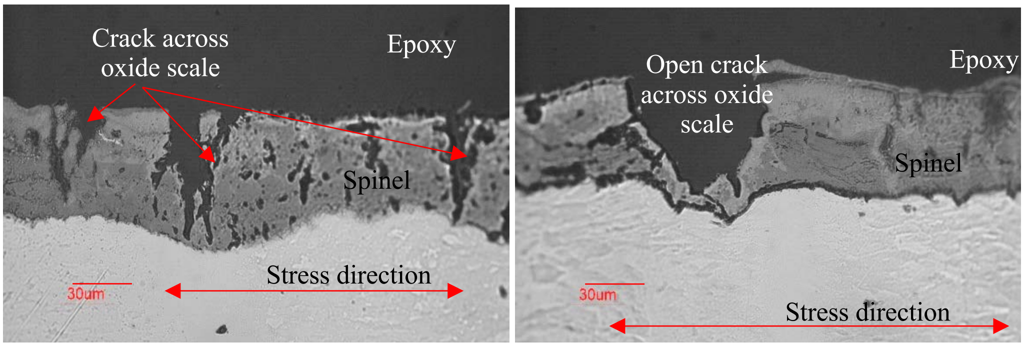


Figure 4. Micrograph showing oxide scale condition on creep specimens at grip area (a) after creep testing for specimens oxidized at 540ºC in steam oxidation test rig, (b) after creep testing for specimens oxidized at 540ºC subcritical boiler.

In addition, the microstructure examination on gauge length of the creep tested specimens showed that thinner oxide scale was found surrounding the ruptured area as compared to the grip area. The remaining oxide scale was detected as spinel by EDX analysis with detection of Fe, Cr and O elements. This finding has confirmed that the iron oxide scale has been spalled off during testing. Severe cracks were observed across the spinel layer around the ruptured area which is believed to be due to the highest stress concentration. This is further supported by evidence of cracks orientation across the oxide scale which is perpendicular to stress direction as marked in Figure 5.



(a) (b)

Figure 5. Micrograph showing cracks across spinel layer surrounding the ruptured area of creep tested specimens which were (a) oxidized in boiler and (b) steam oxidation test rig at 540ºC prior to creep test.

4. Conclusion

Creep rupture life of T91 superheater tubes oxidized at temperatures of 540ºC for 1000 hours and 80,000 hours is 290 hours and 212 hours respectively. The rupture life for both samples was found significantly shorter as compared to the unexposed specimen which is 874 hours for creep tested at 650ºC and 100MPa. The reduction of creep life was found consistent with thickening of the oxide scale which is 38.5µm and 191µm for sample exposed to steam oxidation and boiler environment respectively. Based on the results, it is concluded that for T91 steel, which exposed to steam at 540ºC, the thickening of oxide scale will cause a reduction in creep life. Therefore, it is important to monitor the thickening of the internal oxide scale to evaluate the health condition of the T91 superheater tubes.

5. References

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