Low-cycle fatigue properties of USC boiler tube materials at elevated temperatures

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1. Abstract

The improvement of the efficiency of power generation and reduction of exhaust gas are essentially required in thermal power technology. Increase of operating steam temperature and pressure is one of the most viable strategies to meet these demands. Exposure to such harsh conditions, however, will cause unexpected damages to materials used, in particular thermal stress in heat exchanger tubes due to the regular shutdowns and irregular stops of thermal power plant for the purpose of maintenance and retrofit. Therefore, low-cycle fatigue properties of materials should be carefully considered in material's selection. In this study, low-cycle fatigue properties of two ultra-supercritical (USC) boiler tube materials, T91 ferritic steel and Super304H austenitic steel, were explored in the temperature range of 550 to 650 °C [1]. A fatigue life prediction model, applicable to a wide range of temperature, was developed using fatigue parameters, plastic strain amplitude and plastic strain energy density.

2. Introduction

Recently, in order to reduce fine dust, many researchers are studying a variety of renewable energy to replace the fossil fuels. However, it is impossible to replace thermal power, which accounts for a large amount of renewable energy supply, for a short period of time. Therefore, it is essential to develop thermal power generation technology to produce more energy with less fuel. The most fundamental way to improve power generation efficiency is to increase main steam temperature and pressure of the boiler system [2].

In many developed countries, researches on USC power plants are actively being carried out. Especially, the most important problem to be solved for utilizing the main steam of 600 °C or more is focusing on efforts to secure commercial alloy materials that can be used at this condition [3].

Depending on boiler tube components, the conditions of operating temperature and pressure are different. Therefore, it is important to select suitable materials considering various factors such as lifespan and economical efficiency.

In order to adopt the candidate materials, low-cycle fatigue characteristics of T91 ferritic and Super304H austenitic steels were analyzed and compared.

3. Experimental details

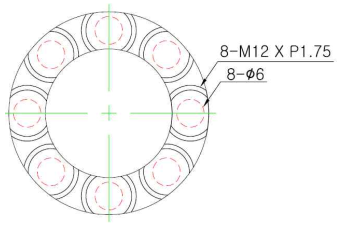
The heat exchanger tubes, made out of T91 ferrite steel and Super304H austenitic steel, used in the thermal power generation boiler was cut into the specimens in the manner as shown in Fig. 1a and b. Low-cycle fatigue experiments were conducted at a constant strain rate of $5 \times 10^{-3} s^{-1}$ under a strain control mode with a triangular waveform. Test temperature was controlled by an electrical furnace in accordance with ISO 6892-2 standard [4]. The total strain amplitude used in the test ranged from 0.25% to 0.8% and test temperature varied from 550℃ to 650℃. The sampling rate was set to acquire 200 data of load, displacement, and strain per each cycle. Low-cycle fatigue life was defined as the 30% load drop point of the peak stress with respect to that at half-life.

In order to predict the fatigue life, a separated strain method is used with elastic strain and plastic strain using the Coffin-Manson model [5] and Basquin model [6, 7] in stress-train hysteresis curve at half-life. The Coffin-Manson model is the life equation that shows the relationship between plastic strain amplitude and fatigue life in the low-cycle fatigue region and the Basquin model is the life equation that shows the relationship between elastic strain amplitude and fatigue life in the high-cycle fatigue region. Generally, two models are combined to get the relationship between total strain amplitude and fatigue life.

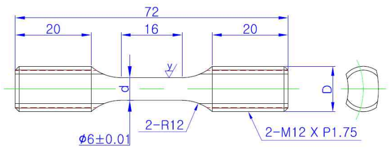
4. Results and discussion

Fig.2 shows the low-cycle fatigue life curves of T91 and Super304H steels, where the predicted lives from the Basquin and Coffin-Manson models are inserted for comparison. At a given temperature, fatigue life of T91 steels decreases drastically with increasing total strain amplitude, while the change in the fatigue life of Super304H is relatively small. For the temperature range of 550 to 650 °C, T91 steel exhibits a superior fatigue resistance, compared to Super304H, at high strain amplitudes beyond 0.7%, but it becomes reversed at low strain amplitudes of less than 0.6%.

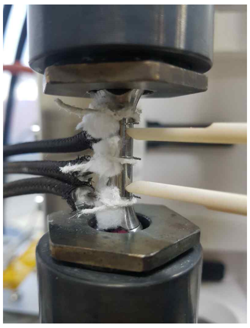
Most thermal power plants are designed to withstand the low-cycle fatigue cycles of more than 2,000. According to Fig. 2, the strain amplitude corresponding to the fatigue life of 2,000 cycles is ~0.6% for both steels and below 0.6%, the fatigue resistance of Super304H is superior to that of T91. This indicates that for the USC temperature condition of >550 °C, Super304H austenitic steel is recommended for a boiler tube material.



(a) The locations of test specimen collection in a USC heat exchanger tube (cross-sectional view)



(b) Low-cycle fatigue test specimen



(c) The photo showing the experimental setup of the low-cycle fatigue test at elevated temperature, where a uniaxial extensometer and three type K thermocouples are attached on the specimen surface.

Fig.1 Test specimen and experimental setup for the low-cycle fatigue test at elevated temperature.

5. Conclusions

The low-cycle fatigue tests of two USC boiler tube materials, T91 ferrite and Super304H austenitic steels, were carried out at elevated temperatures ranging from 550℃ to 650℃ and in a wide range of total strain amplitude from 0.25% to 1.1%, and the following conclusions are obtained.

(1) The fatigue resistance of both steels decreased with increasing strain amplitude and temperature, but the loss of the fatigue resistance with increasing strain amplitude was much severe in T91 ferritic steel compared to Super304H austenitic steel.

(2) The transition in fatigue resistance between T91 and Super304H steels occurred at ~0.6%, which corresponds to the fatigue life of 2,000 cycles. Therefore, considering the boiler tube design guideline requiring the fatigue resistance of more than 2,000 cycles, Super304H austenitic steel appears to be suitable for USC boiler tube materials.

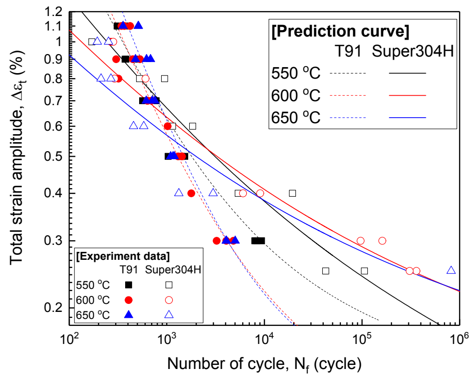


Fig.2 Low-cycle fatigue life curves of T91 ferritic steel and Super304H austenitic steel at 550, 600, and 650 °C.

Acknowledgment

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