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High Temperature Fatigue Properties of Dissimilar Welded Joints of SUPER304H™

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Abstract

Austenitic stainless steel SUPER304H™, which has been used for the super-heater and reheater tubes of coal-fired power plant boilers as a world standard, is recently used also for the heat recovery steam generators (HRSGs) of combined cycle power plants, which operate at increasingly higher temperature for higher power generation efficiency. Since HRSGs start and stop more frequently than coal-fired boilers, their tubes are subjected to a great number of heat cycles. Accordingly, when SUPER304H™ is used for the high-temperature parts of HRSGs and ferritic steel for the low-temperature parts, dissimilar welded joints between the two materials are required to be highly resistant to repetitive thermal stress due to the difference in thermal expansion coefficients between them. Through thermal fatigue tests, dissimilar welded joints between SUPER304H™ and ferritic steel proved capable of withstanding a great number of heat cycles.

1. Introduction

Nippon Steel & Sumitomo Metal Corporation's austenitic stainless steel for boiler tube use, SUPER304H™ (equivalent to KA-SUS304J1HTB, ASTM A213 S30432, and ASME SA213 Code Case 2328),[1] has been widely used for super-heaters and reheaters for coal-fired power plant boilers. On the other hand, combined cycle power plants have increased over the last years, and their heat recovery steam generators (HRSGs) are operated at increasingly higher temperature. In this situation, SUPER304H™ is now used for the heat transfer tubes of the HRSGs, replacing conventionally used ferritic heat resistant steel.

Austenitic stainless steel such as SUPER304H™ is stronger at high temperature and more resistant to steam oxidation than ferritic heat resistant steel, and for this reason, the former is used mainly for high-temperature parts of power generation boilers and the latter for low-temperature parts. Consequently, there are welded joints between the austenitic and ferritic steels (such joints being referred to as dissimilar welded joints) at the interface between the high- and low-temperature sections of the boilers. Since the coefficient of thermal expansion of austenitic steel is higher than that of ferritic steel, when a dissimilar welded joint is heated, thermal stress occurs owing to the difference. Because of the quick start-up ability of combined cycle power plants superior to that of coal-fired boilers, the HRGSs are started and stopped frequently, and the dissimilar welded joints are subjected to repeated thermal stress. When austenitic steel is used for the heat transfer tubes of HRSGs, therefore, it is important to secure good fatigue properties of the welded joints with ferritic steel.

The present paper reports the results of a creep fatigue test, thermal fatigue test and thermal stress analysis of dissimilar welded joints between SUPER304H™ and ferritic steel conducted for the purpose of studying the applicability of SUPER304H™ to HRSGs.

2. Creep Fatigue Test of Dissimilar Welded Joints of SUPER304H™

To examine the basic fatigue properties of dissimilar welded joints of SUPER304H™ at high temperature, the creep fatigue test was conducted at a constant 600°C using specimens of dissimilar welded joints of SUPER304H™ (18Cr-9Ni-3Cu-Nb-N) with ferritic heat resistant steel T91 (9Cr-1Mo-V-Nb, equivalent to KA-STBA28, ASTM A213 T91, and ASME SA213 T91). **Figure 1** shows the coefficients of thermal expansion of SUPER304H™ and T91. Here, it

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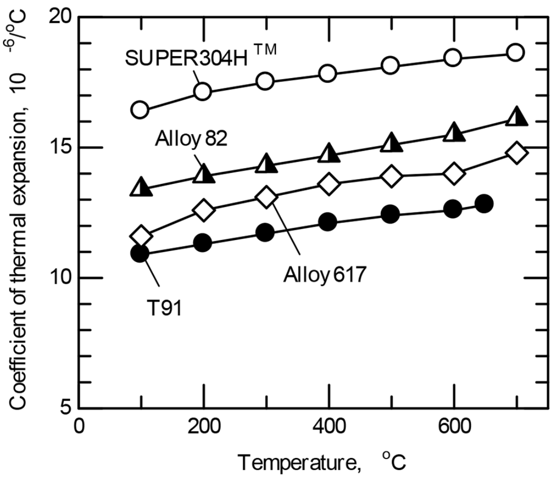


Fig. 1 Coefficient of thermal expansion of SUPER304H™ and T91

is clear that SUPER304H™ has a thermal expansion coefficient roughly 1.5 times that of T91. Weld metals of Ni-base alloys are commonly used as the weld metal to join these two materials. The coefficients of thermal expansion of typical two of such weld metals, Alloy 82 (AWS A5.14 ERNiCr-3) and Alloy 617 (AWS A5.14 ERNiCrCoMo-1), are also given in Fig. 1; as seen here, the coefficients of thermal expansion of these weld metals are between those of SUPER304H™ and T91.

When a welded joint of the two materials is configured as SUPER304H™+weld metal+T91 so that the coefficient of thermal expansion changes gradually, the differential thermal expansion between the materials is smaller than in the case of direct contact, and thermal stress is expected to decrease. Specimens for the creep fatigue test were prepared as follows: plates of the two steels were welded together by automatic TIG welding using Alloy 82 weld metal, and then subjected to post weld heat treatment by holding at 740°C for 30 min and cooling in the atmosphere. Round-bar test pieces, 10 mm in diameter of the parallel portion, were cut out from the joints of the plates, and subjected to the test at 600°C.

Here, the test pieces were subjected to repeated strains in the PP (fast-fast) and CP (slow-fast) waveforms shown in parts (a) and (b) of **Fig. 2**; the strain was controlled here using an extensometer attached to the gauge section of the test piece. The strain rate was set at 0.8%/s on the fast side (P side) and 0.01%/s on the slow side (C side). Under the strain rate of 0.8%/s on the fast side, the creep strain during the loading is negligibly small, and under that of 0.01%/s on the slow side, creep strain generates during the loading. Accordingly, at the test using the PP waveform (hereinafter referred to as the PP test), no creep strain is generated in the test piece, but elastic and plastic strains are imposed in repetition, and at the test using the CP waveform (hereinafter referred to as the CP test), in contrast, creep strains are imposed on the test piece in repetition on the tensile side only, in addition to elastic and plastic strains. Generally speaking, when creep strains, especially tensile creep strains, are imposed repeatedly, the fatigue life of the material is adversely affected. In consideration of this, the test was conducted under two conditions: with and without creep strains. The strains were applied at a total strain range of 0.5% (repetition of 0.25% tensile strain and 0.25% compressive strain alternately).

Photo 1 shows the appearances of the test pieces after the creep fatigue test. At either of the PP and the CP tests, the failure occurred

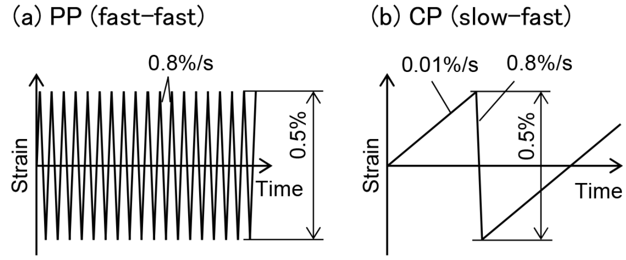


Fig. 2 Strain waveforms for the creep-fatigue test

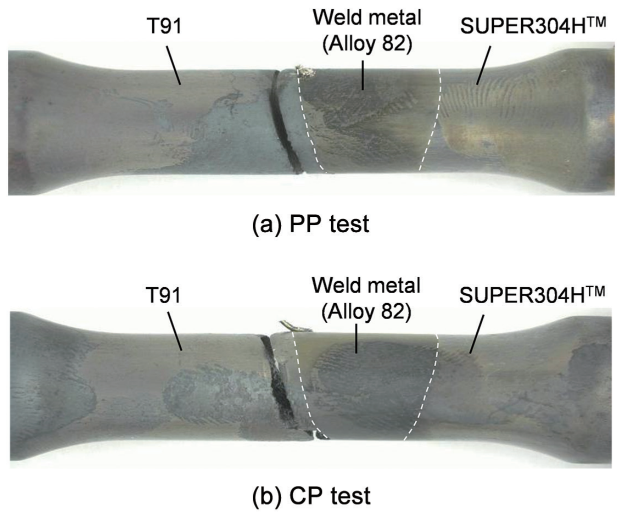


Photo 1 Appearance of the specimens after the creep-fatigue test

at the heat affected zone (HAZ) slightly apart from the weld metal on the T91 side. The fracture started in the PP test from the softest region of the HAZ, and in the CP test from the fine-grained HAZ. **Figure 3** compares the fatigue life of the dissimilar joint with that of T91 steel; in this test, the fatigue life of the dissimilar joint proved to be substantially the same as that of T91. It became clear from the above that, when repetitive strain is imposed on a dissimilar welded joint of SUPER304H™ and T91 at high temperature, no damage such as crack is inflicted on SUPER304H™, regardless of whether creep strain is imposed, and the weakest portion of the joint is the HAZ on the T91 side. It has been proven also that the creep fatigue life of the dissimilar joint is not significantly lower than that of the T91 base metal.

3. Thermal Cycle Test of Dissimilar Welded Joints of SUPER304H™ Tubes

Since the creep fatigue test described in the previous Section 2 was conducted at constant temperature, no repetitive thermal stress or strain due to the difference in the thermal expansion coefficients between the two base metals and the weld metal was imposed on the joint. To study the fatigue characteristics of dissimilar welded joints under the temperature change of power plants, we conducted the test to subject dissimilar welded joints to heat cycles to apply repetitive thermal stress and strain; the test conditions and the result are explained below.

Specimens of dissimilar welded joints between tubes of SUPER304H™ and T91, each 45 mm in outer diameter and 7 mm in wall thickness, were prepared by automatic TIG welding using Alloy 82 as the weld metal. At the test, the specimens were heated

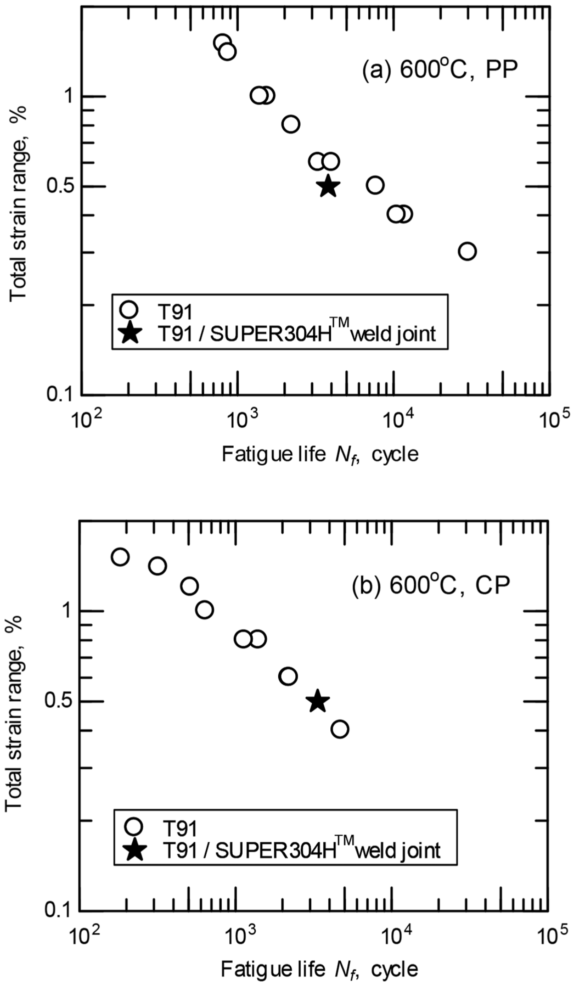


Fig. 3 Comparison of creep fatigue life of dissimilar welded joints under different strain waveforms

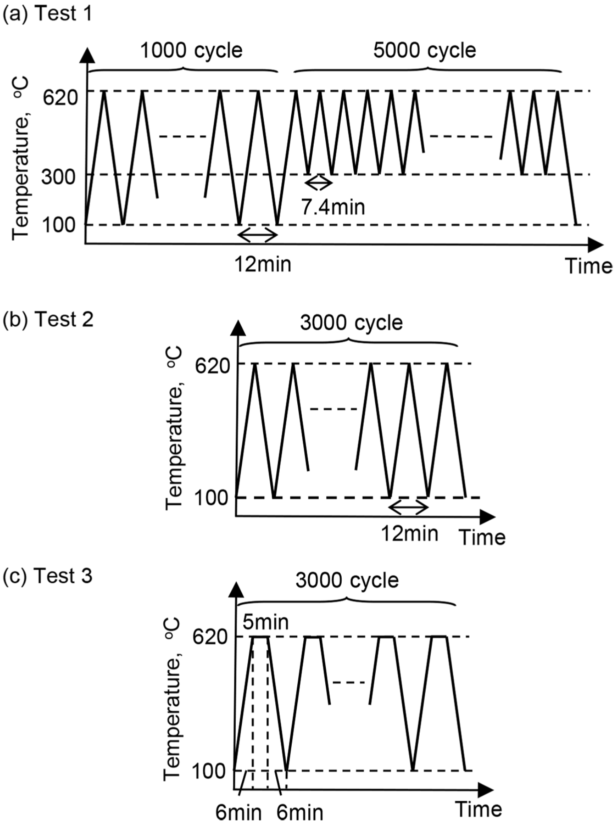


Fig. 4 Temperature cycles for the thermal fatigue test

by high-frequency induction heating and then cooled by blowing air through the inside and to the outer surface; **Figure 4** shows the heat cycle patterns. In Test 1, the specimens were subjected to 1000 times of heat cycles from 100 to 620°C and then 5000 times of cycles from 300 to 620°C (see part (a)): the temperature of the former heat cycle was meant to simulate the weekly start and stop (WSS) operation of a combined cycle plant, whereby a HRSG is stopped at weekends, and the latter to simulate the daily start and stop (DSS) operation, whereby it is stopped every night. When the DSS is assumed to be practiced every weekday, and the WSS every weekend, the DSS will be repeated 5000 times and the WSS 1000 times, approximately, in 20 years of plant operation.

Test 1, therefore, is meant to reproduce the thermal stress that a HRSG undergoes in 20 years of operation. Test 2 is intended to evaluate the effect when a HRSG undergoes an increased number of the heat cycles from 100 to 620°C than in Test 1 (see part (b)), and the heat pattern of Test 3 includes a 5-min holding time at each peak at 620°C of Test 2 (see part (c)); this is for evaluating the effect when the plant is sometimes held at high temperature.

Figure 5 shows the measured temperature at and near the welded joint during the heat cycles from 100 to 620°C. Although it is not easy to heat nonmagnetic austenitic steel and magnetic ferritic steel uniformly to the same temperature by high-frequency induc-

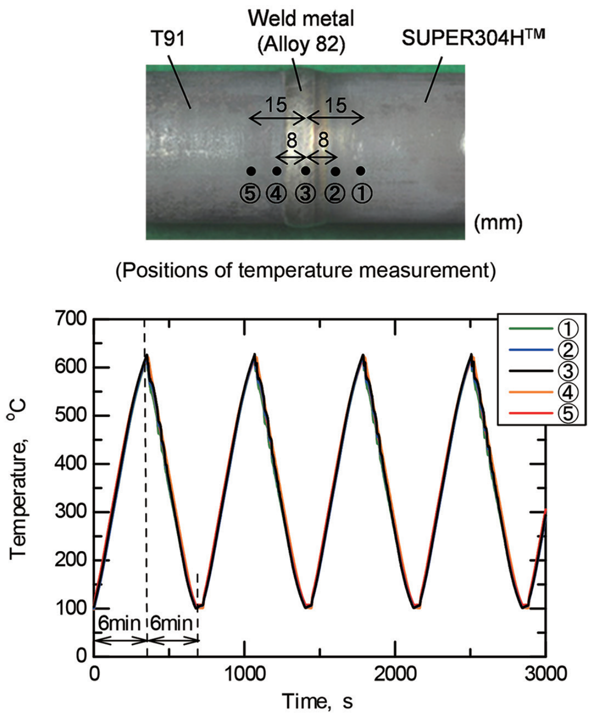
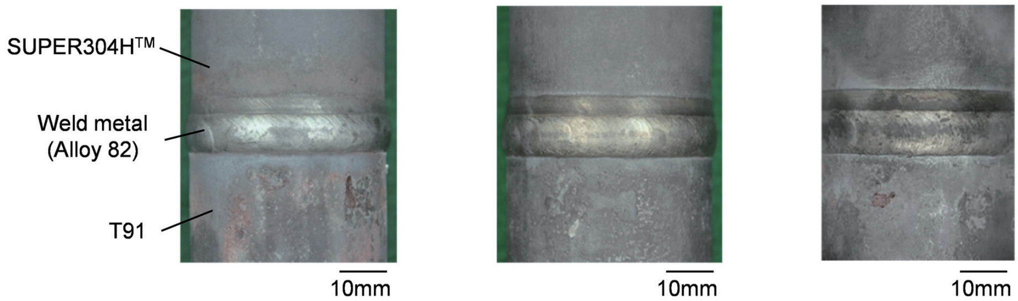
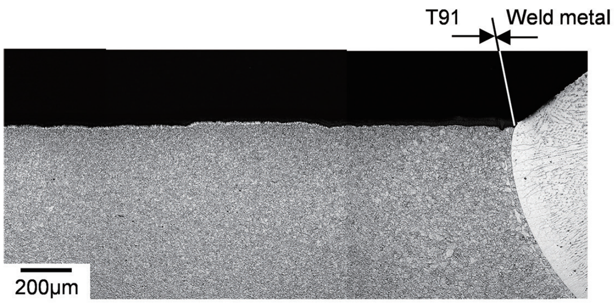


Fig. 5 Temperature measurement at different positions of dissimilar welded joint during heat cycles

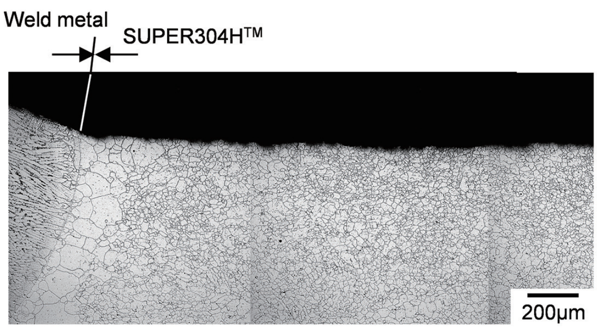


(a) Test 1 (b) Test 2 (c) Test 3

Photo 2 Appearances of dissimilar welded joints after thermal fatigue test



(a) T91 side, outer surface



(b) SUPER304H™ side, outer surface

Photo 3 Cross section of dissimilar welded joint after thermal fatigue test

tion heating, it was made possible in the present test to heat SUPER304H™, T91 and the weld metal to substantially the same temperature by adequately designing the shape of the induction coil. In addition, by adjusting the air blow, the temperature of the joint and adjacent portions was kept nearly even during cooling, and as a result, desired heat cycles were applied to the joint and the adjacent portions.

Photo 2 shows the appearances of the welded joints of the test pieces after the test. No cracks or other defects were found visually at the joints. No defects were found, either, at the outer and inner surfaces of the joint at the ultrasonic inspection conducted after Test 1. To examine the effects of the heat cycles on the welded joint in more detail, the specimen tubes were cut longitudinally across the welded joint after Test 1, and the metallographic structure was observed at the section surface. **Photo 3** shows examples of the sectional photomicrographs: the frame of part (a) was taken at the T91 side of the joint, and that of part (b) at the SUPER304H™ side. There were no cracks or other defects in either of them.

These test results demonstrate that dissimilar welded joints of SUPER304H™ and T91 tubes are capable of withstanding many heat cycles, which indicates that, when these materials are used for HRSGs, operating under repeated heat cycles of many starts and stops, the equipment will be able to operate for a long time. Thus, SUPER304H™ is expected to contribute to the high-temperature operation of HRSGs, consequent improvement in power generation efficiency and the reduction of environmental loads.

4. FE-Analysis of Dissimilar Welded Joints of SUPER304H™ Tubes

Through the test described in the previous Section 3, the welded joints of SUPER304H™ and T91 were confirmed to withstand many heat cycles. To examine the effects of thermal loads on the dissimilar joints in more detail, we analyzed the stress and strain under thermal loads by the finite element method (FEM). Welded tubes shown in **Fig. 6** comprising SUPER304H™ and T91 tubes, 45 mm in outer diameter and 8.5 mm in wall thickness each, were defined as the analysis objects: Tube A was made by directly joining the two by welding, and Tube B had a short tube of a Ni-base alloy, HR6W (23Cr-45Ni-7W-Ti-Nb, equivalent to ASTM B167-UNS N 06674 or ASME SB167 Code Case 2684),[2)] between the two. This short tube, which is called a transition piece and made of a Ni-base alloy having an intermediate coefficient of thermal expansion between those of the two materials meeting at the joint, is inserted when thermal fatigue defects are feared to occur at the welded joint owing to the differential thermal expansion between austenitic and ferritic steels, to mitigate the thermal stress. To confirm the effectiveness of the transition piece, the strains at the joints of Tubes A and B were estimated by the FEM analysis and compared with each other. Here, the weld metal was Alloy 617 for both Tubes A and B.

Since tubes are axially symmetric, two-dimensional models of the longitudinal sections of the specimen tubes were devised, and the analysis was conducted using axially symmetric elements. As an example of such analysis models, **Fig. 7** shows the finite element mesh of the welded joint and adjacent parts of Tube A. The properties of ferritic T91 steel change near the joint owing to the welding heat. In the present analysis, the T91 steel up to 3 mm from the weld metal was defined as the HAZs, and the HAZ was divided further into three zones, each 1 mm in thickness: the one adjacent to the weld metal was defined as the hardening zone, and another adjacent to the T91 base metal as the softening zone. Based on the results of a separate test using specimens simulating HAZs, a stress equivalent

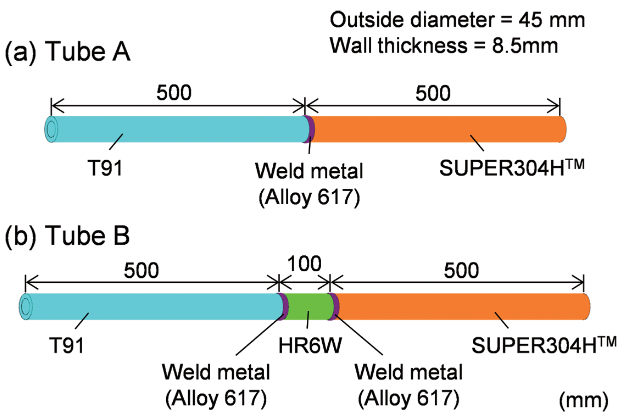


Fig. 6 Dissimilar welded tube of SUPER304H™ for FE-analysis

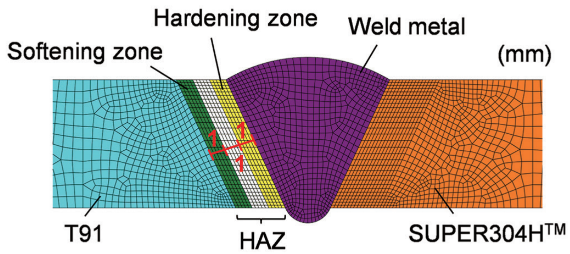


Fig. 7 FE-model of dissimilar welded joint

to a stress-strain relation 1.6 times that in the base metal and a creep-strain rate 1/50 times that in the base metal were applied to the hardening zone, and a stress equivalent to a stress-strain relation 0.9 times that in the base metal and a creep-strain rate 50 times that in the base metal to the softening zone. The 1-mm zone between the hardening and softening zones was assumed to have the same mechanical properties as the base metal.

A heat cycle from 100 to 620°C with a holding time of 10 min at 620°C was repeated 10 times in the analysis; here, the heating time from 100 to 620°C and the cooling time from 620 to 100°C were set at 10 min each. **Figure 8** shows the results of the analysis of the creep strain occurring at the dissimilar welded joints of Tubes A and B. The creep strain occurred mainly at the HAZ on the T91 side, while the creep strain in the SUPER304H™ and HR6W was small; this is because the resistance to creep deformation of T91 is the lowest of the three. From a comparison of Tubes A and B, the creep strain of T91 is smaller in Tube B with the transition piece. **Figure 9** shows the relationship between the number of heat cycles and the creep strain at the weld toe on the T91 side on the outer surface, where the creep strain was largest. Because of the transition piece, the creep strain was lower in Tube B by roughly 40% than in Tube A. With both Tubes A and B, creep strain mainly generated during the first cycle, but additional strain during the second cycle and thereafter was smaller, and gradually decreased cycle after cycle.

As stated above, when dissimilar welded joints of SUPER304H™ and T91 tubes undergo heat cycles, creep strain accumulates on the T91 side of the joint, but additional strain at every cycle thereafter decreases gradually. The reason for the absence of cracks and other defects in the joint after the repetition of many thermal loads described in Section 3 is presumed to be this gradual decrease of additional creep strain. The creep strain of the dissimilar welded joint is

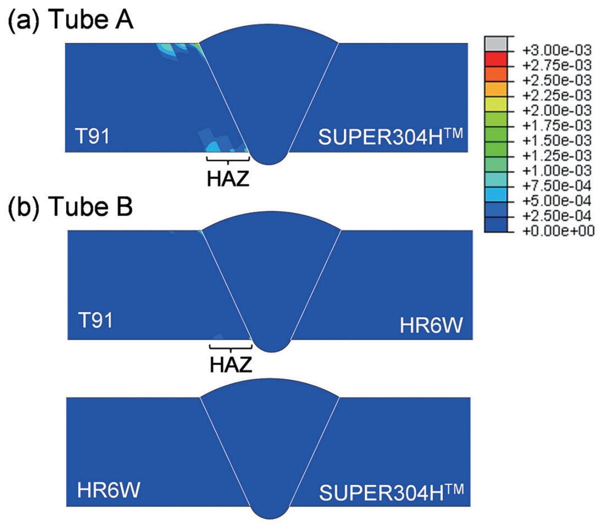


Fig. 8 Calculated distribution of creep strain near dissimilar welded joints

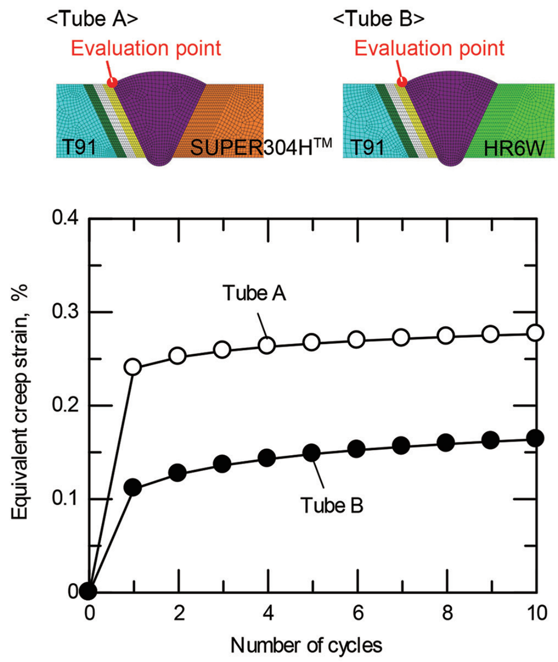


Fig. 9 Relationship between equivalent creep strain and number of cycles at the weld toe in T91

also reduced by inserting a transition piece of a Ni-base alloy between SUPER304H™ and T91 tubes, and the resistance to heat cycles is further enhanced.

5. Conclusion

The present paper reported the high-temperature fatigue properties of dissimilar welded joints between tubes of SUPER304H™, austenitic stainless steel for boiler tube use (corresponding to KA-SUS304J1HTB, ASTM A213 S30432, and ASME SA213 Code Case 2328), and ferritic steel. The present study exhibited excellent thermal fatigue resistance of dissimilar welded joints of SUPER304H™, which has been used widely for coal-fired boilers of thermal power plants. The results of the present study will help expand the applications of the steel to heat recovery steam generators operated at increasingly higher temperatures. The material is thus expected to contribute to the enhancement of power generation efficiency and the reduction of environmental loads.

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