Evaluation of Creep Damage and Fracture in High Cr Steel Welds

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Abstract Creep strength of high Cr ferritic steel welds decreases than base metals due to Type-IV creep damages formed in the heat affected zone (HAZ) during long-term use at elevated temperatures. In the present study, microstructural changes and damage evolution behaviors in HAZ during creep were investigated for the ASME Gr.91 and Gr.122 steel weld joints. Creep voids formed at an early stage of life and coalesced to form a macro crack at 0.8 of life for the Gr.91 steel weld. On the other hand, for the high strengthened Gr.122 steel weld, small amounts of Type-IV creep voids formed at 0.5 of life, increased slightly until 0.9 of life and rapid crack growth occurred after that. KAM and grain boundary length of fine-grained HAZ obtained by EBSD decreased and saturated till 0.2 of life in the Gr.91 steel weld, whereas they decreased after 0.5 of life in the Gr.122 steel weld. It was found that the recovery of dislocation structures in HAZ was completed at early stage of life for the Gr.91 steel weld, whereas it occurred after recrystallization at the later stage of life for the Gr.122 steel weld. These differences of microstructural changes was considered to relate to the differences of Type-IV creep damage behavior; early initiation of creep voids at 0.2 of life in the Gr.91 steel weld and later damage evolution after 0.5 of life in the Gr.122 steel weld. From these results the methods for remaining life assessment of high Cr steel welds were discussed.

Keywords High Cr ferritic steel, Welded joint, Creep, Type-IV creep damage, EBSD

1. Introduction

In order to improve the efficiency of power generation, the pressure and temperature conditions of steam in thermal plant have been continuously increased. In 1990s, the high Cr ferritic heat resisting steels were applied to the boiler components in 600 ˚C class ultra super critical (USC) thermal power plants in Japan. The base metals of these steels with tempered martensite structures have excellent high temperature strength; however, fine-grained structures without lath-martensite are formed in the heat-affected zone (HAZ) during weld thermal-cycle and the creep strength of welds decreases than the base metals. The Type-IV failure along the inter-critical and fine-grained HAZ of weld joints is caused through the nucleation and growth of creep voids and cracks during long-term services at high temperatures [1-8]. Recently, it was recommended to take the weld strength reduction factor (WSRF) into account for the high temperature design using high Cr steels [9, 10]. It is important to understand the microstructural changes and damage evolutions in HAZ during creep for the remaining life assessment of weld components.

In the present paper, aiming to elucidate the Type-IV failure mechanisms of Gr.91 and Gr.122 steel welds, we have evaluated the Type-IV creep damage evolutions and microstructural degradations through interrupting creep tests of the large-scale welded joint specimens. Remaining life assessment methods of high Cr steel welds were discussed based on the experimental results.

2. Experimental procedure

The materials investigated are the Gr.91 steel (9Cr-1Mo-VNb steel) plate with a thickness of 25mm and the Gr.122 steel (11Cr-0.4Mo-2W-CuVNb steel) plate with a thickness of 30mm. The plates were welded by gas tungsten arc (GTA) welding using a double U groove. After welding, a post-weld heat treatment (PWHT) was conducted at 745 ˚C for 60 min for the Gr.91 steel weld and for 75 min for the Gr.122 steel weld.

The simulated fine-grained HAZ (f-HAZ) specimens were produced using a weld simulator (a Gleeble testing machine) by rapid heating to a peak temperature of 900 ˚C for the Gr.91 steel and 950 ˚C for the Gr.122 steel, respectively. Creep tests of the base metal and simulated f-HAZ were conducted using smooth bar specimens and those of the welded joints were conducted using smooth plate type specimens of 17.5 × 5 mm^2 in cross-section and 100 mm in gauge length (S-welded joint) at 550, 600 and 650 ˚C [7].

Creep interruption tests were conducted using a large-scale thick plate type specimen (L-welded joint) of 21 × 21 mm^2 in cross-section and 100 mm in gauge length for the Gr.91 steel weld and of 24.5 × 24.5 mm^2 in cross-section and 120 mm in gauge length for the Gr.122 steel weld, which included the full original plate thickness close to the structural components [7, 8]. Creep tests were conducted using several L-welded joint specimens at 600 ˚C and interrupted at several time steps. Because creep voids formed inside the specimen, we cut the specimens in the center of width after interruption of creep tests, and observed the creep voids in HAZ using SEM or laser-microscope. The area and number of creep voids were measured using the image processing software. Changes of microstructures in fine-grained HAZ were investigated by measuring KAM (Kernel average misorientation) and grain boundary length using EBSD (Electron backscatter diffraction).

3. Results and discussion

3.1. Creep strength of welded joints

Figure 1 and 2 show the creep test results for the base metal, simulated f-HAZ and welded joints of the Gr.91 steel and Gr.122 steel, respectively. The failure locations of the welded joint specimens are indicated with the subscripts attached to the plots, where BM means failure in base metal and HAZ means Type-IV failure in the fine-grained HAZ. In the Gr.91 steel weld, the Type-IV failure occurred after 10,000h at 550 ˚C and 1,000h at 600 ˚C. The differences in creep rupture times between welded joint and base metal tended to widen with decreasing stress. The creep rupture times of the simulated f-HAZ were more than one order shorter than those of the base metal for the same stresses at all temperatures. The creep rupture times of the welded joint approached those of the simulated f-HAZ for low stresses at all temperatures.

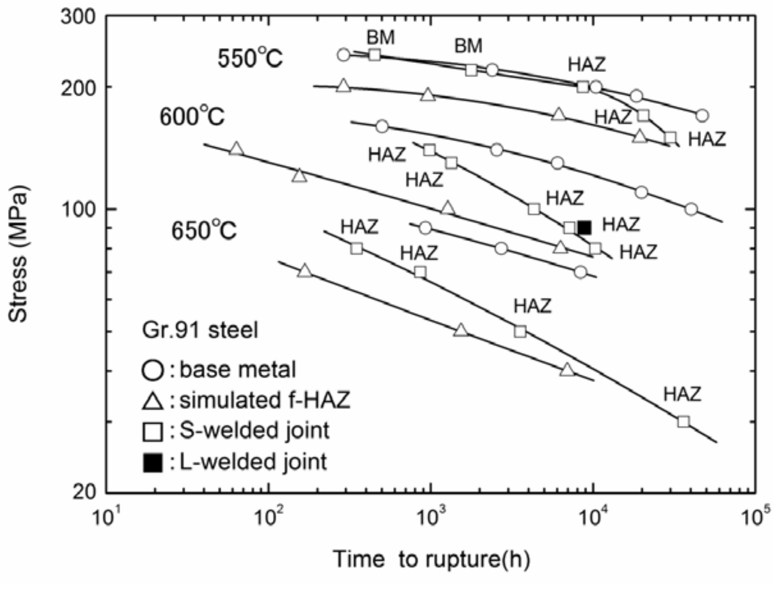

Figure 1. Creep rupture times of the base metal, simulated f-HAZ and welded joints of the Gr.91 steel.

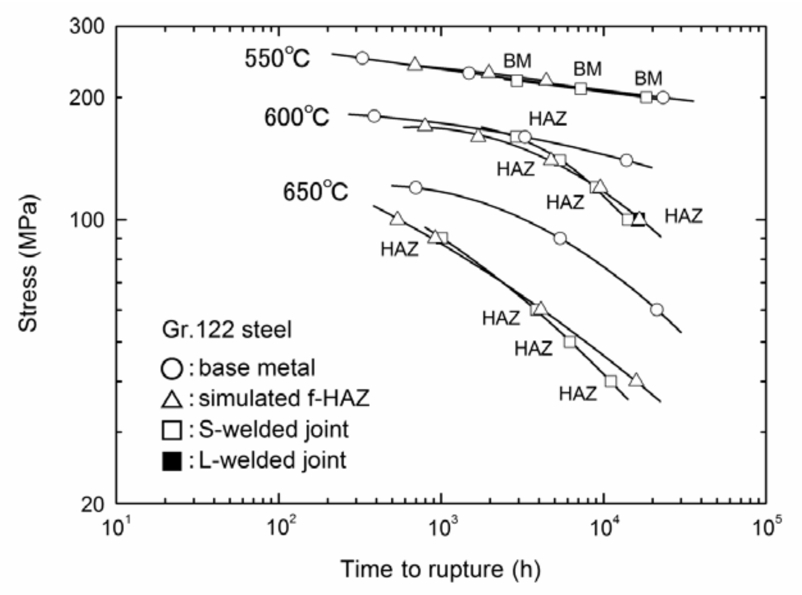

Figure 2. Creep rupture times of the base metal, simulated f-HAZ and welded joints of the Gr.122 steel.

For the Gr.122 steel welds, Type-IV failure did not occur at 550 ˚C within this test stress. It was observed after 5,000 h at 600 ˚C. The creep rupture times of the simulated f-HAZ were nearly the same as the base metal at 550 ˚C; they decreased than the base metal after 5,000 h at 600 ˚C. The differences in creep rupture times between base metal and simulated f-HAZ were more than one order at all test conditions for the Gr.91 steel, whereas they appeared at lower stresses than 140 MPa at 600 ˚C for the Gr.122 steel. At these test conditions, the simulated f-HAZ of the Gr.122 steel revealed void- type inter-granular failure and its creep ductility decreased.

3.2. Evolution of Type-IV creep damage

Creep rupture times of the L-welded joints were 8,853 h at 600 ˚C and 90 MPa for the Gr.91 steel and 16,340 h at 600 ˚C and 100 MPa for the Gr.122 steel; they also showed the Type-IV failure and their rupture times were slightly longer than the S-welded joints as shown in Figs. 1 and 2. We have conducted the creep interruption tests using the L-welded joints for both steels at these test conditions and investigated the processes of Type-IV damage and fracture. Figure 3 shows the binary images of creep voids and cracks observed in HAZ of the central cross-section of the L-welded joints of the Gr.91 steel creep-interrupted at 600 ˚C and 90 MPa. It was found that a small number of creep voids formed at about 0.2 of creep rupture life, and the number of voids increased with time, and then coalesced to form a crack at 0.8 of life. Creep voids and cracks were mostly observed in the area about 20% below the plate surfaces.

The area fraction of creep voids in the HAZ of the Gr.91 and Gr.122 steel welds are plotted against the life ratio (t/t_r) in Fig. 4. In this figure, the area fraction of creep voids in the area about 20% below the plate surfaces where it shows the highest value is plotted. It was found that the Type-IV damage behavior and amounts of creep voids were considerably different for both steel welds. In the Gr.91 steel weld, Type-IV creep voids formed at the early stage 0.2 of creep life and increased gradually with elapse of time. On the other hand, in the Gr.122 steel weld, only a small amount of creep voids formed at 0.5 of creep life and slightly increased till 0.9 of life. Type-IV crack was not observed till 0.92 of life; it was observed in the specimen interrupted at 0.98 of life as shown in Fig. 4. The formation and growth of creep voids were suppressed during steady-state condition;

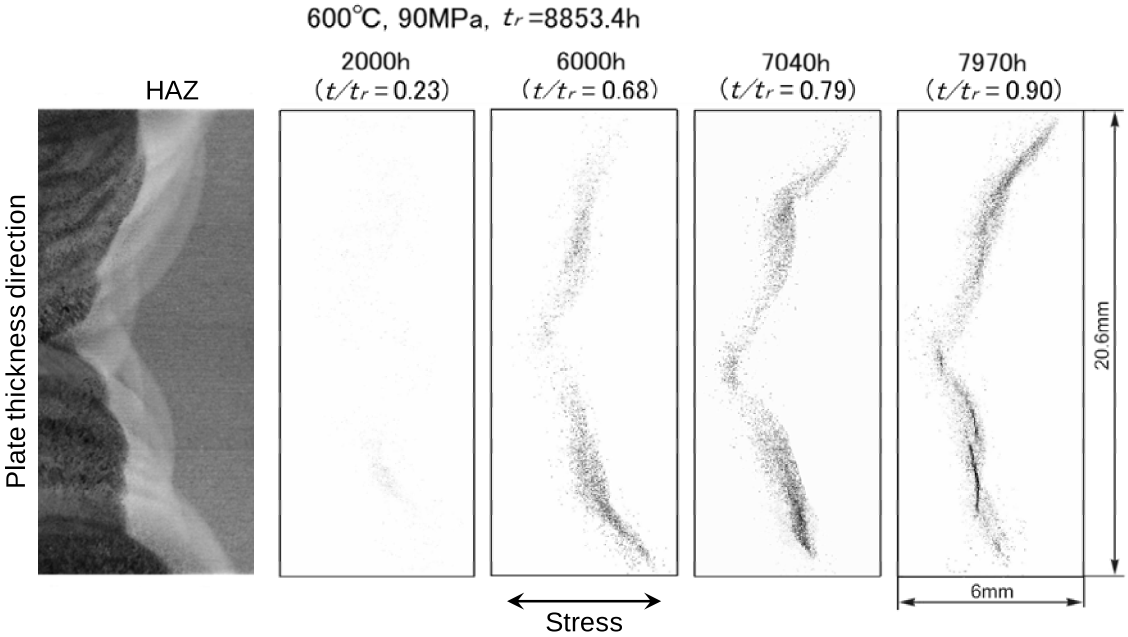

Figure 3. Binary images of creep voids and cracks observed in the HAZ of a central cross-section of the L-welded joints for the Gr.91 steel crept at 600 ˚C and 90 MPa.

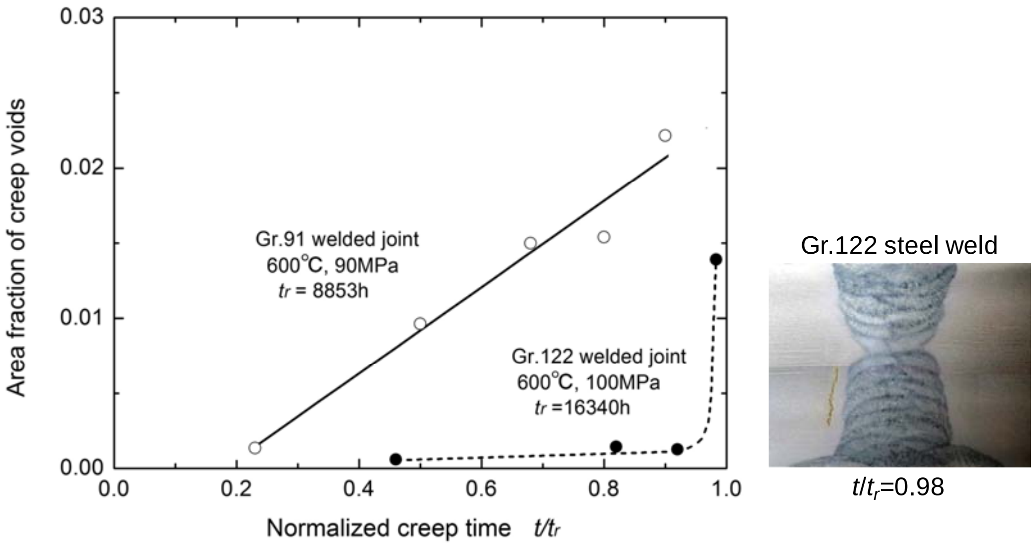

Figure 4. Changes of the area fraction of creep voids in HAZ during creep of the Gr.91 and Gr.122 steel welds at 600 ˚C.

however, the crack growth rate in the accelerated stage was high for the high strengthened Gr.122 steel. The lower creep ductility of the Gr.122 steel is related to these damage behavior.

3.3. Micro-structural changes in HAZ

Changes of microstructures of HAZ in the creep-interrupted L-welded joints was observed and KAM and grain boundary length were measured using EBSD. Figure 5 shows the changes in the grain boundary length in the fine-grained HAZ during creep for both steel welds. Here, length of grain boundaries with misorientation from 5˚ to 65˚ is plotted as prior austenitic boundaries. For the f-HAZ in the Gr.91 steel weld, the grain boundary length decreased till 0.2 of life and saturated after that. On the other hand, for the f-HAZ in the Gr.122 steel weld, the grain boundary length increased till 0.5 of life, and then decreased after that. The decrease of grain boundary length occurs due to the recovery of microstructures during creep.

Figure 6 shows the changes in the micro-hardness and KAM of fine-grained HAZ during creep for both steel welds. Here, average value of KAM is plotted excluding the points whose misorientation is larger than 5° in order to investigate the changes of dislocation structures. For the f-HAZ in the Gr.91 steel weld, hardness and KAM decreased till 0.2 of life and saturated to constant value, whereas they did not change till 0.5 of life and then decreased after that for the Gr.122 steel weld. The decrease of KAM and hardness occurs due to the recovery of dislocation structures. Because the grain boundary length increased without changing KAM and hardness till 0.5 of life, dynamic recrystallization was considered to be occurred in the fine-grained HAZ of the Gr.122 steel.

These differences of microstructural changes are considered to relate to the differences of creep damage behavior between two steels. In the Gr.91 steel weld, the recovery of dislocation structures of f-HAZ occurs at early stage of life, and then early initiation and evolution of Type-IV creep voids occur. In the Gr.122 steel weld, the recovery of dislocation structures occurs after the recrystallization of f-HAZ, and then damage evolution occurs at later stage of life.

From these experimental results, we consider about the methods for the residual life assessment of weld components as follows. For the Gr.91 steel weld, ultrasonic nondestructive testing is available for residual life assessment because creep voids and cracks increase gradually inside the plate thickness. Hardness measurement and microstructural observation are not available because their changes saturate in the early stage of life. Local necking on the specimen surface in HAZ is also available because the creep ductility is high for the Gr.91 steel. For the Gr.122 steel weld, ultrasonic testing may be difficult to detect Type-IV creep damages because the amount of voids are small and crack grows rapidly after 0.9 of life. Evaluation of hardness and dislocation structures (KAM) are available because they change largely in the latter half of life. Local necking on the specimen surface was scarcely observed for the Gr.122 steel weld with low creep ductility.

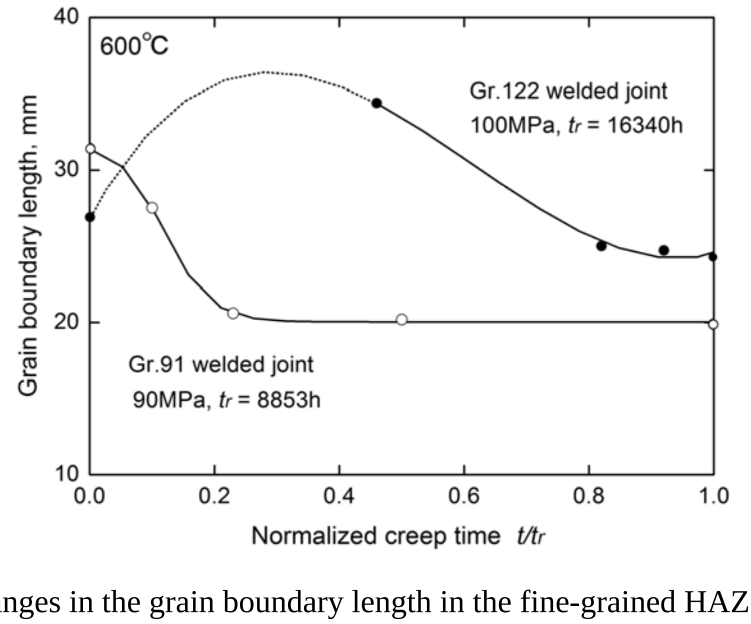

Figure 5. Changes in the grain boundary length in the fine-grained HAZ during creep for the Gr.91 and Gr.122 steel welds measured by EBSD.

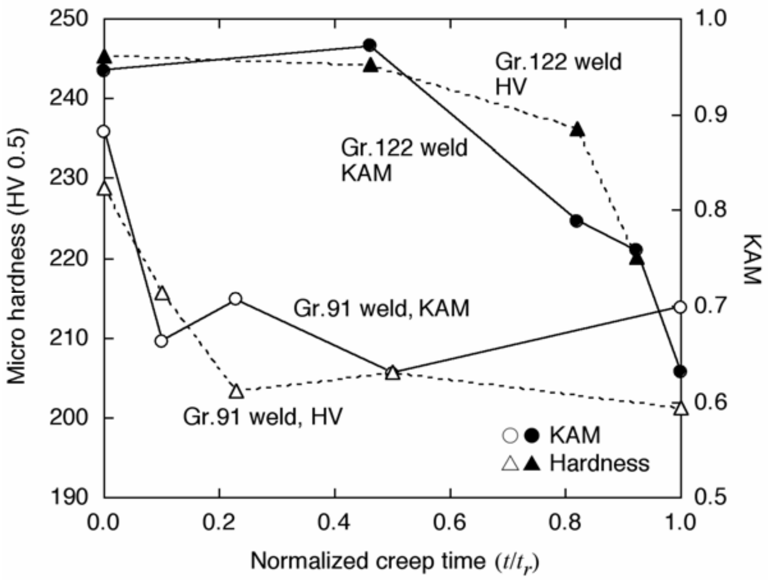

Figure 6. Changes in the micro hardness and KAM in the fine-grained HAZ during creep for the Gr.91 and Gr.122 steel welds measured by EBSD.

4. Conclusions

In the present paper, creep strength, Type-IV damage evolution and microstructural change during creep in the Gr.91 and Gr.122 steel welds were investigated quantitatively using the large-scale welded joint specimens. The results are summarized as follows:

(1) In the Gr.91 steel weld, the Type-IV failure occurred after 10,000h at 550 ˚C and 1,000h at 600 ˚C. In the Gr.122 steel weld, Type-IV failure did not occur at 550 ˚C; it occurred after 5,000 h at 600 ˚C.

(2) Type-IV creep voids in the Gr.91 steel weld formed at the early stage 0.2 of creep life, increased with elapse of time, and then coalesced to form a macro crack after 0.8 of life.

(3) In the Gr.122 steel weld, a small number of Type-IV creep voids formed at 0.5 of life, increased slightly until 0.9 of life, and then rapid crack growth occurred after that. The area fraction of creep voids in the Gr.122 steel weld was much smaller than that in the Gr.91 steel weld.

(4) In the Gr.91 steel weld, the recovery of dislocation structures of fine-grained HAZ occurred at early stage 0.2 of life, and was followed by early initiation and evolution of Type-IV creep voids. In the Gr.122 steel weld, the recovery of dislocation structures occurred after recrystallization of fine-grained HAZ, and then damage evolution occurred at later stage of life.

(5) Form the above experimental results, for the Gr.91 steel weld; it is considered that ultrasonic nondestructive testing etc. is available for the residual life assessment because creep voids and cracks increase gradually inside the plate thickness. Hardness measurement and microstructural observation of fine-grained HAZ are not available because their changes saturate in the early stage of life.

(6) For the Gr.122 steel weld, ultrasonic testing is considered to be difficult to detect Type-IV creep damages because the amount of voids are small and crack grows rapidly after 0.9 of life. Evaluation of hardness and dislocation structures (KAM) are available for the residual life assessment because they change largely after 0.5 of life.

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