Creep Rupture Properties of Welded Joints of Heat Resistant Steels*

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Abstract
In this study, the high-temperature mechanical and creep rupture properties of Grade 91/Grade 91 (Mod. 9Cr–Mo) similar welded joints and Grade 91/Inconel 82/SUS304 dissimilar welded joints were examined. The effects of temperature and stress on the failure location in the joints were also investigated. Creep rupture tests were conducted at 823, 873, and 923 K; the applied stress ranges were 160–240, 80–160, and 40–80 MPa, respectively. The creep rupture strengths of the specimens with welded joints were lower than those of the specimens of the base metal at all temperature levels; in addition, these differences in creep strength increased with temperature. After being subjected to long-term creep rupture tests, the fracture type exhibited by the dissimilar welded joints was transformed from Types V and VII to Type IV. It was estimated that the fracture type exhibited by the dissimilar welded joints after 100,000-h rupture strength tests at 823 K and 873 K was Type IV fracture.

Key words: Similar Welded Joint, Dissimilar Welded Joint, Creep Rupture Property, Fracture Type

1. Introduction
In structural components subjected to long-term service at high temperature, fracture mainly occurs not in the base metal part but in the weldments. SUS304 and Grade 91 steels (Mod. 9Cr–1Mo) steels are used mostly in thermal/nuclear power plants owing to their high strength at high temperatures \(^{(1-9)}\). Recently, fracture due to the nucleation and propagation of creep cracks (now recognized as Type IV fracture), which occurs after long-term service in the fine-grained heat affected zone (HAZ) of Grade 91 welded joints, has attracted wide-spread scientific attention aimed at mitigation of this phenomenon for high-Cr ferritic heat-resisting steels. In addition, many researches have been conducted to predict the creep life and residual life of the base metal of Grade 91 steel \(^{(1-13)}\). In the present study, the creep rupture properties and microstructural changes were examined by conducting long-term creep rupture tests on specimens of Grade 91/Grade 91 similar welded joints and SUS304/Grade 91 dissimilar welded joints. The relationship between the changes in the microstructure and the nucleation and propagation of creep cracks occurring during creep deformation of dissimilar welded joint specimens were studied. The results of these investigations have shown that Type IV fracture occurs in welded joint specimens in lower-stress creep regions.
2. Experimental Procedures

2.1. Preparation of welded joints and sampling of welded joint specimens

The material used was a 9Cr–1Mo–V–Nb steel plate (ASME SA-387/SA-387M Grade 91) with a thickness of 25 mm. The creep properties of the base metal of this steel may be found in NRIM Creep Data Sheet No.43 (12). The similar welded joints were created using gas tungsten arc welding (GTAW). TGS-9CB (Kobe Steel) was used as a welding wire. The chemical compositions of the base metal and the weld metal are shown in Table 1.

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<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>Nb</th>
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<td>0.004</td>
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<td>0.004</td>
<td>9.21</td>
<td>0.94</td>
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Fig. 1. Cross-sectional view of similar welded joint

Post-weld heat treatment (PWHT) was then conducted at 1016 K for 8.5 h. Figure 1 shows the cross-sectional view of similar welded joint.

18Cr-8Ni (JIS G 4304 SUS 304-HP) and 9Cr-1Mo-V-Nb steel plates, each with a thickness of 25 mm, were used to manufacture the dissimilar welded joints. WEL-82 ((Nippon Welding Rod) wire was used for buttering and butt welding. The 9Cr–1Mo–V–Nb steel plate was first buttered using the wire, and then subjected to PWHT at 1003 K for 8.4 h. Next, it was butt welded with the SUS304-HP steel plate using the same type of wire. Both buttering and butt welding were performed using GTAW. The chemical compositions of the base metal and the weld metal are shown in Table 2. Figure 2 shows the macrostructure of a cross-section of the welded joint. X-ray inspection of the welded joints revealed no defects. Next, smooth plate-type creep specimens—5 mm in width, 17.5 mm in thickness, and 100 mm in gauge length—were sampled in the direction perpendicular to the weld line so that the weld metal was located at the centre of the specimen along the gauge length. Figure 3 shows the sampling location of the smooth plate-type creep specimens.
Fig. 2. Cross-sectional view of dissimilar welded joint

<table>
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<tr>
<th>Materials</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
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<tr>
<td>9Cr-1Mo-V-Nb</td>
<td>0.10</td>
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<td>0.001</td>
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<td>Inco.82 (WEL-82)</td>
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<td>0.21</td>
<td>2.99</td>
<td>0.003</td>
<td>0.001</td>
<td>73.74</td>
<td>18.54</td>
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<tr>
<td>SUS 304</td>
<td>0.06</td>
<td>0.52</td>
<td>0.93</td>
<td>0.029</td>
<td>0.008</td>
<td>8.89</td>
<td>18.32</td>
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</table>

Table 2. Chemical compositions of 9Cr-1Mo-V-Nb, Inconel 82 and SUS 304 steels for dissimilar welded joint.

Fig. 3. Sampling location of test specimen from welded joint

2.2. Creep test and observation of microstructures

Creep rupture tests were conducted at 823, 873, and 923 K with applied stress ranges of 160–230, 80–130, and 40–80 MPa, respectively. Microstructural observations of the as-received material, which were called “virgin condition” here, and creep ruptured specimens were conducted using an optical microscope and a scanning electron microscope (SEM). In addition, the average linear expansion coefficients of the three steels used in this study were measured using thermal analysis equipment.

3. Results and Discussion

3.1. Creep rupture properties and failure location of the similar welded joint specimens

The stress–creep rupture time curves for the base metal and similar welded joint specimens are shown in Fig. 4. The figure also shows the failure locations of the welded joint specimens. As seen in the figure, the creep rupture strengths of the welded joint specimens were lower than those of the base metal specimens at all temperatures and stresses tested. All the welded joint specimens fractured in the weld metal at 823 K. At
873K, in the region of higher stress and shorter rupture time, fracture occurred in the weld metal. For rupture times over 4000 h, however, the failure location shifted to the HAZ. Furthermore, at 923 K, though fracture occurred in the weld metal for rupture times below 1000 h, the failure location shifted to the HAZ for rupture times over 7000 h. The cause of the fracture occurring in the weld metal at 823 K and at higher stress at 873 and 923 K could be attributed to the lower creep strength of the weld metal as compared with that of the base metal.

Figure 5 shows the profiles of the welded joint specimens having the longest creep rupture time at each temperature. In the specimen that fractured at 160 MPa at 823 K and after 13748.5 h, fracture occurred in the weld metal (Fig. 5 (a)). In the specimen that fractured at 80 MPa at 873 K and after 12414.8 h, brittle fracture was observed in the HAZ (Fig. 5 (b)). In the specimen that fractured at 40 MPa at 923 K and after 7687.7 h, though large deformation was observed in the weld metal (Fig. 5 (c)), the fracture occurred in the HAZ, as also for the welded joint specimen ruptured at 873 K. All the specimens that ruptured in the HAZ showed Type IV fracture.

Fig. 5. Profiles of welded joint specimens having the longest creep rupture time at 823, 873, and 923 K.
3.2. Creep rupture properties and failure location of the dissimilar welded joint specimens

In general, there were significant differences between the linear expansion coefficients of the ferritic and austenitic steels. As a result, surface cracking occurred when the dissimilar welded joints connecting these dissimilar types of steel came into direct contact with heat. The average coefficients of linear expansion for the three types of steel at around the service temperature are shown in Fig. 8. The coefficients of linear expansion for each type of steel increased with temperature. Furthermore, the coefficients were in the order 9Cr-1Mo-V-Nb > Inconel 82 > SUS304. Thus, Inconel 82, which was used as the welding material (i.e., a cushioning material) for this experiment, had a mean coefficient of linear expansion that was intermediate to those of the 9Cr-1Mo-V-Nb and SUS304.
Fig. 8. Comparison of average expansion coefficients of the three materials at different temperatures

In this section, we describe the creep rupture properties of the dissimilar welded joints and the rupture location of all ruptured specimens, after long-term exposures to elevated temperature. The stress–creep rupture time curves of the dissimilar welded joints and the base metal of 9Cr-1Mo-V-Nb steel are shown in Fig. 9. The creep rupture strength of the dissimilar welded joint specimen was less than that of the base metal specimen at each temperature. Furthermore, the differences in creep strength between the specimens tended to increase with temperature.

Fig. 9. Stress vs. rupture time curves of the dissimilar welded joint and base metal

Figure 10 shows the overall appearance and structure of a cross-section taken at a ruptured region following failure at 823 K under 160 MPa of stress and after 17198 h. There was no significant deformation of the ruptured specimen and the rupture appeared to be due to brittle fracture; a flat fracture surface was observed on each section (Fig. 10 (a), (b), and (c)). In addition, examination of the structure of the ruptured region under an optical microscope revealed that the fracture occurred at the interface between the HAZ of the 9Cr–1Mo–V–Nb steel and Inconel 82 in each case.
Fig. 10. Fracture surface and micro structure of creep specimen tested at 823 K and 160 MPa; the rupture time was 17,198 h

Fig. 11. Schematic showing fracture type of welded joints

The weld-zone fracture types of the similar and dissimilar welded joints are schematically illustrated in Fig. 11. Conventionally, the rupture types are classified based on the rupture location in the weld zone of similar welded joints:

Type I: Rupture due to cracks generated only in the weld metal
Type II: Rupture due to cracks generated across the weld metal and in the coarse region of the base metal HAZ
Type III: Rupture due to cracks generated only in the coarse region of the base metal HAZ
Type IV: Rupture due to cracks generated only in the fine-grained region of the base metal HAZ.

However, the rupture locations for dissimilar welding joints are different. Thus, new classifications—Types V through VII—are expediently defined as follows:

Type V: Rupture due to cracks generated only in the base metal of 9Cr-1Mo-V-Nb steel
Type VI: Rupture due to cracks generates across the region from the interface of the 9Cr-1Mo-V-Nb steel HAZ and Inconel 82 to the 9Cr-1Mo-V-Nb steel HAZ and the base metal 9Cr-1Mo-V-Nb steel
Type VII: Rupture due to cracks generated at the interface between the 9Cr-1Mo-V-Nb steel HAZ and Inconel 82
Figure 12 shows the fracture type of the dissimilar welded joint specimens subjected to different temperature/stress treatments, as determined microscopic observations of the fracture surfaces. At 823 K and 240/200 MPa, the rupture was of Type VI. At 160 MPa, the rupture was of Type VII. At 873 K and 160 MPa, the rupture was of Type V; and at less than 120 MPa, the rupture was of Type IV. Under lower stress, i.e., 80 MPa, the rupture was a mixture of Types III and IV. At a higher temperature of 923 K, the rupture was of Type IV. Thus, at given temperatures and stress levels, the fracture type of the dissimilar welded joints transformed from Types V and VII to Type IV fractures.

Figure 13 shows the relationship between the creep rupture properties and fracture types of the dissimilar welded joints (estimated using the Larson–Miller parameter). The fracture type of the dissimilar welded joints was predicted to be of Type IV at 823 K and 873 K after 100,000 h.

4. Conclusions

The creep rupture properties and microstructural changes of 9Cr-1Mo -V-Nb steel were examined by conducting long-term creep rupture tests on similar and dissimilar welded joints specimens at 823, 873, and 923 K. The relationships between the changes in the microstructure and the nucleation and propagation of creep cracks in the welded joint specimens were investigated. The results are summarized as follows:
1) The creep rupture strengths of the welded joint specimens were lower than those of the
base metal specimens at all temperatures tested. The rupture locations were found to shift from the weld metal at higher stresses to the HAZ at lower stresses (longer rupture times) at 873 and 923 K. Furthermore, the fracture type of the specimens that ruptured in the HAZ was found to be Type IV fracture; i.e., the crack initiated in the fine-grained HAZ adjacent to the base metal.

2) Type IV fracture occurred in the fine-grained HAZ about 400-500 µm away from the boundary between the base metal and HAZ, where the hardness was minimum. The Type IV creep crack in the present welded joints nucleated in the curved part of the groove and propagated toward the top of the V-groove. It was found that the voids and cracks were initiated inside the plate and not on the surface.

3) The creep rupture strengths of the dissimilar welded joint specimens were less than those of the base metal specimens at all temperature levels. In addition, these differences in creep strength tended to increase with temperature.

4) The fracture type of the dissimilar welded joints observed in the creep rupture tests transformed from Types V and VII to Type IV.

5) The fracture type of the dissimilar welded joints was predicted to be Type IV at 823 and 873 K after 100,000 h.

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References


