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Creep strength and microstructure of a modified P911-type steel weld joint

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Abstract. The creep strength and microstructure of the weld joint of the modified P911-type steel has been studied. The creep rupture time of the welded joint at 650° of 1375 h is close to that of the base metal. The heat affected zone -is found to be the weakest area due to the increased size and relatively high coarsening rate of precipitates. The increased boron content in the weld steel effectively stabilizes the $M_{23}(C,B)_6$ particles and is beneficial for the creep strength of the weld joint in the fusion zone.

1. Introduction

Modified 9-12%Cr martensitic steels are promising materials for high temperature components of modern power plants. Gas tungsten arc welding (GTAW) of these steels is widely used to join different components of the power units. However, the creep strength of welded joints is significantly lower as compared to the base metal (BM) due to the microstructural changes caused by heat input during the welding process. Thus, the design of appropriate welding consumables to prevent degradation of the creep properties of high-chromium martensitic steel weldments is important. The main reason for the microstructural degradation during creep is the coarsening of precipitates, leading to a decrease in pinning forces, lath widening and the formation of a coarse subgrain structure [1]. It has been observed that an increased boron content in 9-12%Cr steels is beneficial for improving the dispersion and stability of $M_{23}(C,B)_6$ precipitates [2-4]. However, the effect of the addition of boron to the filler material of the 9%Cr steel welds on the overall creep strength and microstructure in different weld zones is not well established.

In this work, we investigate the creep strength of a weld joint of grade P911 steel obtained with a modified 9%Cr steel consumable with high B and low N contents.

2. Materials and methods

Plates of 9Cr-1Mo-1W (P911) steel with a double-V butt joint configuration were preheated to ~250°C and welded by the gas tungsten arc welding (GTAW) method using a 9% Cr steel with high boron and low nitrogen contents. The chemical compositions of the base material and the welding wire are shown in Table 1.

Table 1. Chemical compositions of base and filler materials (wt.%).

	Fe	C	Si	Mn	Cr	Co	Mo	W	V	Nb	B	N
Base metal	bal.	0.11	0.06	0.36	9.09	-	1.02	1.11	0.22	0.09	0.005	0.050
Filler metal	bal.	0.10	0.12	0.41	9.05	2.86	0.58	1.8	0.20	0.05	0.012	0.007

Then the welded joint was cooled to ~100 °C and subjected to post-weld heat treatment (PWHT), which was carried out at 760 °C for 2 h.

Flat creep specimens with a length of 25 mm and a cross section of 7×3 mm^2 were subjected to tensile creep tests in air under initial applied stresses of 140, 120, and 100 MPa at 650 °C using ATS2330 lever arm machines.

The microstructures and dispersed particles in different zones of the weld joint were investigated by transmission electron microscopy (TEM) using a Jeol JEM-2100 microscope operating at 200kV, equipped with an INCA energy-dispersive X-ray (EDX) spectrometer. The dislocation densities were estimated by counting individual dislocations in the lath interiors per unit area on arbitrarily selected TEM images. Extraction carbon replicas were prepared to determine the size and chemical composition of precipitates. The volume fractions of precipitates were determined using the Thermo-Calc software with the TCFE7 database for Fe-based alloys.

3. Results and discussion

Figure 1 shows the stress vs. rupture time relation for the studied weld joint at 650 °C in comparison with that for the base metal of grade P911.The creep fracture of the specimens occurred in the softened heat affected zone (HAZ) near the fusion zone (FZ). The estimated creep rupture strength of the weld joint at 100,000 hours and T=650 °C is lower by 10 MPa as compared to that of P911 steel.

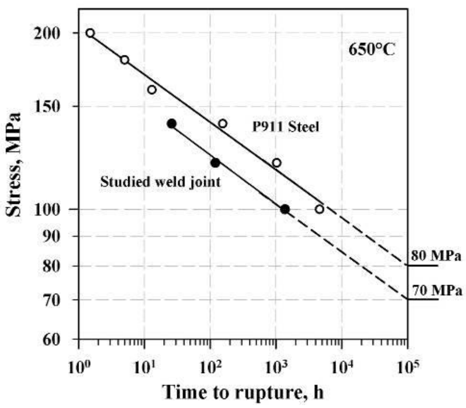

Figure 1. Creep rupture properties of the studied weld joint and aP911 steel.

All studied zones of the weld joint after PWHT had a tempered martensite lath structure with a high density of $M_{23}C_6$ and MX precipitates [5]. The crept microstructures of the studied weld joint in HAZ and FZ are shown in Figure 2 together with base metal in the grip portion, aged for 1375 h.

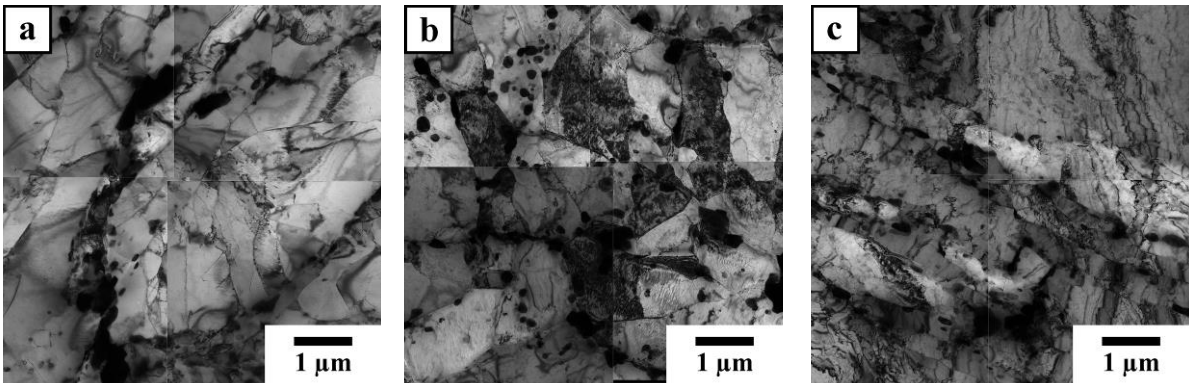

Figure 2. Microstructure of the studied weld joint after creep at 100 MPa in FZ (a); in HAZ (b) and base metal in the grip portion of the sample aged for 1375 h (c) at 650 °C.

The microstructure parameters and the mean size of precipitates in different portions of the crept specimens are summarized in Table 2. It is seen that the lath structure of the tempered martensite evolves into a subgrain structure during creep. The formation of the intermetallic Laves phase particles was observed in the base and weld metals, but their size in HAZ is almost twice that found in the fusion zone. An increase in the creep duration leads to a significant drop in the dislocation density in the FZ from 2.15×10^{14} m^{-2} after creep for 26 h to 0.45×10^{14} m^{-2} after creep for 1375 h.

Table 2. The microstructure parameters in the different portions of crept specimens of the studied weld joint.

	140 MPa, 26 h			100 MPa, 1375 h		
	Base metal in grip portion	Heat affected zone	Fusion zone	Base metal in grip portion	Heat affected zone	Fusion zone
Lath width, μm	0.61±0.02	0.69±0.03	0.65±0.01	0.69±0.02	0.94±0.10	0.90±0.04
Dislocation density, $\times10^{14}$ m^{-2}	1.05±0.20	0.80±0.20	2.15±0.25	0.80±0.20	0.45±0.10	0.45±0.15
Average size of $M_{23}C_6$, nm	140±9	162±14	118±7	171±13	190±14	130±8
Average size of MX, nm	55±4	60±7	43±8	59±6	67±8	46±5
Average size of $Fe_2(W,Mo)$, nm	207±9	242±11	127±5	380±14	394±18	234±9

It is suggested that the increased creep strength of the weld metal in the FZ is due to the increased stability of the $M_{23}C_6$ particles and the Laves phase particles. These particles were found to effectively prevent migration of (sub)grain boundaries [2,3]. The determined eequilibrium volume fractions of different precipitates are listed in Table 3.

Table 3. Equilibrium volume fractions of precipitates in the base and filler steels calculated by Thermo-Calc.

	Base metal	Filler metal
Volume fraction of $M_{23}(C,B)_6$, %	2.69	2.16
Volume fraction of (Nb,V)(C,N), %	0.39	0.09

Volume fraction of $Fe_2(W,Mo)$, %	0.57	0.96

The overall equilibrium volume fraction of precipitates at 650 °C in the base and the weld steel is nearly the same. The volume fraction of $M_{23}(C,B)_6$ in the base steel is somewhat higher than that in the weld metal. The relatively low volume fraction of (Nb,V)(C,N) in the weld metal is attributed to the low N content in the consumable steel filler wire. The well-known Zener equation was used to estimate the pinning pressure from precipitates at the (sub)grain boundaries in HAZ and FZ of the weld joint [6]:

$$P_Z = \frac{3\gamma F_V}{d} \quad (1)$$

where γ is the boundary energy per unit area, Fv is the volume fraction of precipitates and d is the mean diameter of particles. Figure 3 displays the changes of the pinning pressures exerted by precipitates in HAZ and FZ during creep exposure. After PWHT, the steel in HAZ is characterized by increased stability as compared to the weld metal due to pinning from (Nb,V)(C,N) particles. However, the precipitation of $Fe_2(W,Mo)$ particles in the weld metal during creep significantly increases the pinning pressures in the FZ. Since $Fe_2(W,Mo)$ and $M_{23}(C,B)_6$ particles in FZ are characterized by relatively low coarsening rate, they effectively stabilize the (sub)grain boundaries during creep exposure.

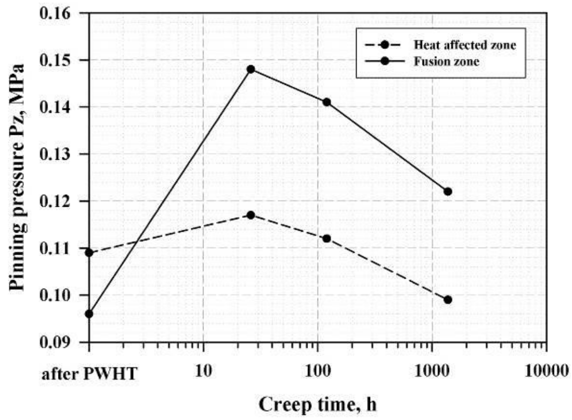

Figure 3. The evolution of Zener pinning pressures exerted by precipitates in HAZ and FZ of the studied weld joint during creep exposure.

4. Conclusions

The creep strength and microstructure of the modified P911-type steel weld joint has been studied. The main results can be summarized as follows:

1. The creep strength of the modified P911-type steel weld joint at T=650 °C is lower by ~10 MPa as compared to that of the base P911 steel due to the softening of the base metal in the HAZ.
2. The decreased strength of the base steel in HAZ is attributed to the increased size and relatively high coarsening rate of the $M_{23}(C,B)_6$ and (Nb,V)(C,N) particles.
3. The formation of relatively small particles of $Fe_2(W,Mo)$ and reduced coarsening rate of $M_{23}(C,B)_6$ particles in the weld metal results in the increased creep strength of the studied weld joint in the FZ.

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