# Creep Strength of Dissimilar Welds for Advanced USC Boiler Materials

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**Abstract** The research project aiming to commercialize 700˚C class pulverized coal power system; advanced ultra-super critical (A-USC) pressure power generation has been conducted in Japan from 2008. In A-USC boilers, Ni base or Ni-Fe base alloys are used for high temperature parts at 650-700˚C and advanced high Cr ferritic steels are planning to be used at the temperatures lower than 650˚C. Because the high B-9Cr steel developed in National Institute for Materials Science (NIMS) has improved creep strength in welds, it is one of the candidate materials for A-USC boilers. In the present paper, the creep tests of the dissimilar welds between Ni base alloy and high B-9Cr steel for A-USC boilers were conducted at 650˚C. In the heat affected zone (HAZ) of the high B-9Cr steels, fine-grained microstructures were not formed and grain size of the base metal was retained. Free boron on the grain boundaries is considered to affect the mechanisms of the α-γ transformation during weld thermal cycle. Consequently, the Type-IV failure was not occurred in the present dissimilar welds and their creep rupture lives were 5-10 times longer than those of the conventional 9Cr steel welds at 650˚C.

**Keywords** A-USC boiler, High B-9Cr steel, Dissimilar weld, Creep

## 1. Introduction

Research project aiming to commercialize 700 ˚C class pulverized coal power system; A-USC power generation, with 46-48 % power generation efficiency, and to reduce $CO_2$ emissions more than 10 % has been conducted from 2008 in Japan. In the A-USC boiler, Ni base or Ni-Fe base alloys such as Alloy 617, Alloy 263 and HR6W are planning to be used for high temperature parts at 650-700 ˚C, and advanced high Cr ferritic steels are planning to be used at the temperatures lower than 650 ˚C. In the dissimilar weld between Ni base alloy and high Cr steel, Type-IV failure and thermal-fatigue (creep-fatigue) are the major concerns. Because the 9Cr-3W-3Co-VNb steel containing higher boron and lower nitrogen (high B-9Cr steel) developed in NIMS has improved creep strength in the HAZ and weld joint [1, 2], it is one of candidate materials for A-USC boilers [3].

In the present paper, creep tests of the dissimilar welds between high B-9Cr steels and Ni base alloys for A-USC boilers (Alloy 617 and Alloy 263) were conducted at 650 ˚C. Microstructures and creep damages in the welds were investigated.

## 2. Experimental procedure

Two kinds of the high B-9Cr steels; MARBN10 steel (9Cr-3W-3Co-VNb-0.01B-0.003N) and MARBN12 steel (9Cr-2.6W-3Co-VNb-0.01B-0.007N) were prepared. The chemical compositions are shown in Table 1. In the present steels, about 0.01% boron was added aiming to strengthen the grain boundaries. Nitrogen content was lower than 0.01 % to avoid the formation of boron nitride (BN) and to maximize the grain boundary strengthening effect of boron. MARBN12 steel contains higher nitrogen than MARBN10 steel. These steels were normalized at 1100 ˚C for 1 h and tempered at 800 ˚C for 1 h.

Four kinds of dissimilar welds between high B-9Cr steels (MARBN10 and MARBN12) and Ni base alloys for A-USC boilers (Alloy 617 and Alloy 263) were prepared by gas tungsten arc (GTA) welding using the filler wire of Inconel 82 as shown in Fig. 1. The groove configuration of these welds was U with 20 ˚ of groove angle. After welding, all the weld joints were given post weld heat treatment (PWHT) at 740 ˚C for 4 h. Weld defects were not detected in the radiographic examination and magnetic particle testing. The distribution of micro Vickers hardness of the MARBN10 steel-Alloy 263 weld after PWHT and before creep condition is shown in Fig. 2.

Creep tests of the base metals were conducted using round bar-type specimens 6 mm in diameter and 30 mm in gauge length. Creep tests of the dissimilar weld joints were conducted at 650 ˚C using the smooth plate-type specimens 17.5 × 5 mm in section and 100 mm in gauge length as shown in Fig. 3.

Table 1. Chemical compositions of the present high B-9Cr steels (wt. %)

| | C | Si | Mn | P | S | Cr | W | Mo | Co | Ni | V | Nb | N | O | B | Sol.Al |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MARBN10 | 0.078 | 0.29 | 0.54 | 0.003 | 0.001 | 9.11 | 3.13 | <0.01 | 3.03 | <0.01 | 0.21 | 0.052 | 0.0030 | 0.003 | 0.010 | 0.001 |
| MARBN12 | 0.081 | 0.30 | 0.53 | 0.001 | 0.001 | 9.09 | 2.62 | <0.01 | 3.02 | <0.01 | 0.21 | 0.052 | 0.0072 | 0.003 | 0.011 | 0.001 |

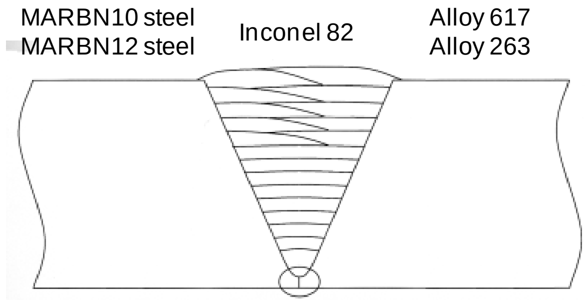


Figure 1. Dissimilar welds used in the present study

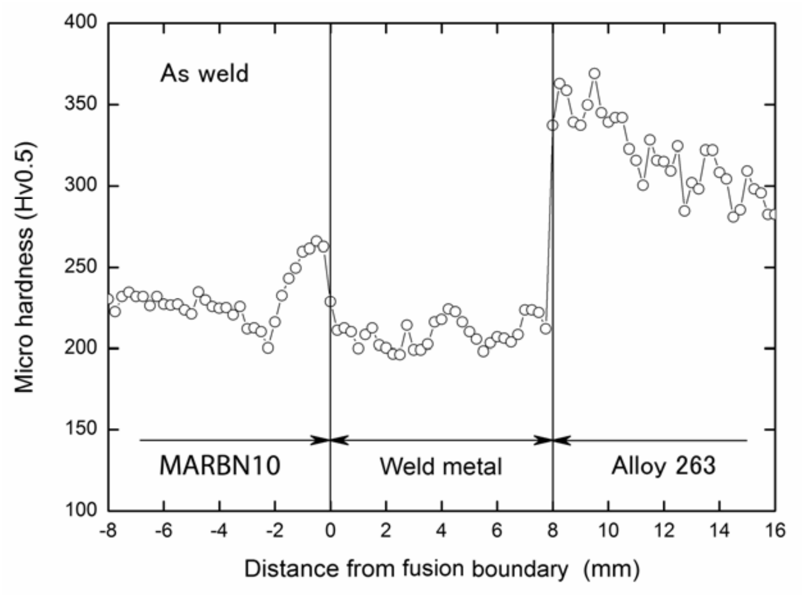


Figure 2. Hardness distribution in the present dissimilar weld joint (MARBN10 steel-Alloy 263 weld) after PWHT and before creep

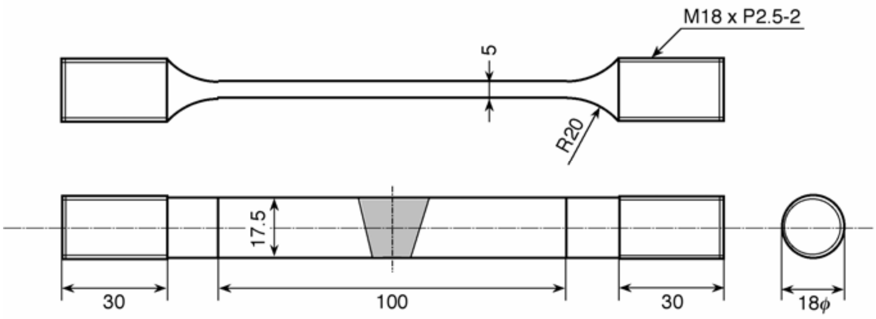


Figure 3. Creep test specimen for the dissimilar welds

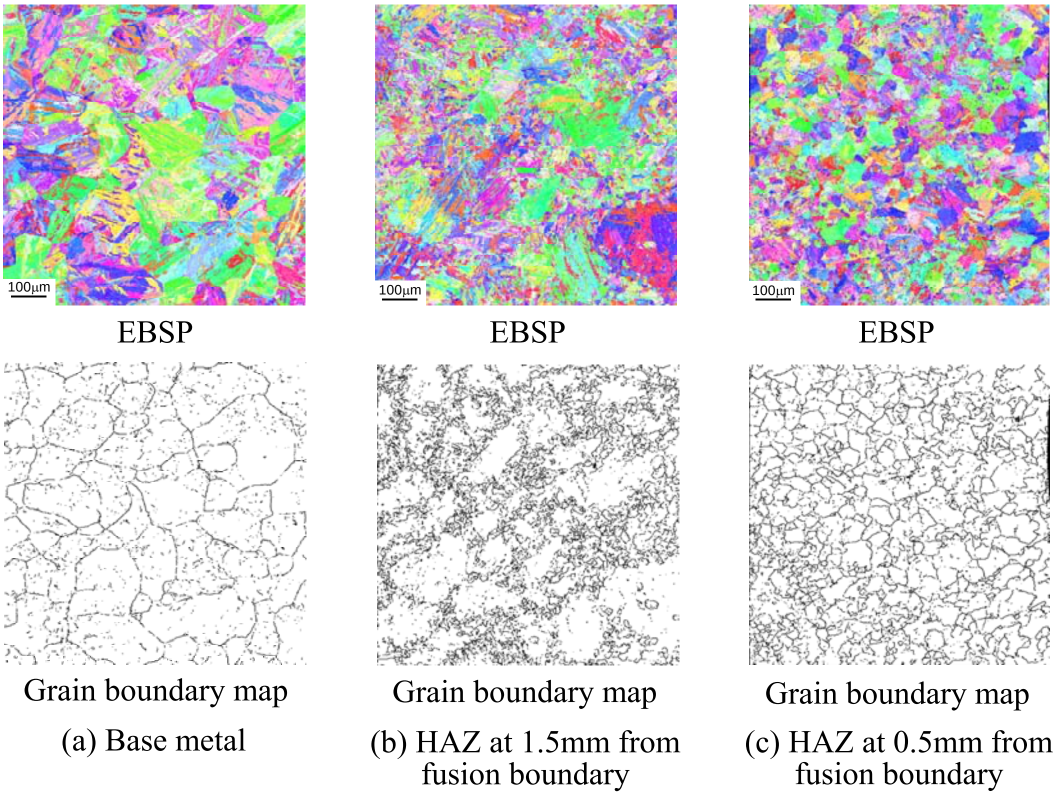


Figure 4. EBSP images and grain boundary mapping (15-48˚) for the base metal and HAZ of the high B-9Cr steel in the MARBN10 steel-Alloy 263 weld joint

## 3. Results and discussion

### 3.1. Microstructures of HAZ in the dissimilar welds

Figure 4 shows the EBSP (electron backscattered pattern) images and grain boundary maps of the base metal and HAZ of the high B-9Cr steel in the dissimilar welds between MARBN10 steel and Alloy 263. In the grain boundary map, grain boundaries with misorientation from 15 ˚ to 48 ˚ were drawn and their length was measured. We have reported that the fine-grained structures were not formed in HAZ of weld joints for the 9Cr-3W-3Co-VNb steel with boron and low nitrogen [1, 2]. The base metal of the present steel shows the tempered martensitic structures having the grain boundary length of 2.07 cm and KAM of 1.83 (Fig. 4(a)). The micro Vickers hardness of the present base metal was 220-235 as shown in Fig. 2. In the conventional high Cr steels, fine-grained HAZ structures 5 μm in the average grain size were observed in the area at about 1.5 mm from the fusion boundary. In the present high B-9Cr steels, however, the fine-grained structures were not formed at a distance of 1.5 mm from the fusion boundary. In this region, the grain size of the base metal was retained and small grains formed only on the prior-austenite grain boundaries (Fig. 4(b)). The grain boundary length was 5.99 cm, KAM was 1.94, and hardness was 243 for the microstructure of Fig. 4(b). At a distance of 0.5 mm from the fusion boundary, recrystallization occurred; however their grain size was more than 10 μm (Fig. 4(c)). The grain boundary length was 4.94 cm, KAM was 2.22, and hardness was 266 for the microstructure of Fig. 4(c). The KAM corresponds well to the hardness.

In the conventional high Cr steel welds, Type-IV creep damages form in the fine-grained HAZ with average grain size of about 5 μm; consequently creep strength of welds decreases than base metal [4, 5]. These results mentioned above in Fig. 4 confirm that the HAZ microstructures of high B-9Cr steel are considerably different from those of the conventional high Cr ferritic steels, and soluble free boron is essential for suppression of grain refinement during weld thermal cycle. We consider that the free boron decreases the grain boundary energies, and suppresses the nucleation of $\gamma$ phase from grain boundaries by diffusional transformation, and causes the martensitic reverse transformation. The similar phenomena of the martensitic reverse transformation that the original grain size and crystal orientation was retained after heating up to $A_{C3}$ transformation temperature were also reported in the maraging steels [6] and 12Cr turbine rotor steels containing boron [7].

### 3.2. Creep strength of dissimilar weld joints

Figure 5 shows the relations between stress and creep rupture time of the base metal of high B-9Cr steels and four kinds of the present dissimilar weld joints at 650 ˚C. Open symbols show the rupture times of the base metal and dissimilar weld joints for the MARBN10 steel, and solid symbols show those for the MARBN12 steel. The creep strength of base metal of the high B-9Cr steels was higher than that of the conventional 9Cr steel (Gr.92 steel) due to the grain boundary strengthening effect of boron. The creep strength of base metal of MARBN12 steel with 0.007 % N was higher than that of MARBN10 steel with 0.003 % N.

The creep rupture tests of the dissimilar weld joints were conducted at 650 ˚C for 160, 140, 120 and 100 MPa. The dissimilar welds using the high B-9Cr steel show 5-10 times longer creep rupture times than the Gr.92 steel weld at 100 MPa. The differences of the creep strength between dissimilar welds and base metals are small up to 20000h at 650 ˚C, and we are now investigating the creep strength at lower stress conditions; 90 and 80 MPa.

The dissimilar welds fractured in the base metal of high B-9Cr steel for the short term test conditions and in the fusion boundary between high B-9Cr steel and Ni base filler wire (Inconel 82) for the long term test conditions. The failure in the fusion boundary was observed at the stresses lower than 120 MPa for the MARBN10 steel welds and lower than 140 MPa for the MARBN12 steel welds. All the present dissimilar weld joints using high B-9Cr steels did not show the Type-IV failure in HAZ and consequently the creep rupture lives were much longer than those of the conventional 9Cr steel welds that showed the Type-IV failure at the present creep test conditions. This means that the microstructures and creep strength of HAZ was considerably improved in the high B-9Cr steel, which contains 0.01 % boron and low nitrogen (<0.01 %), due to the effect of soluble boron.

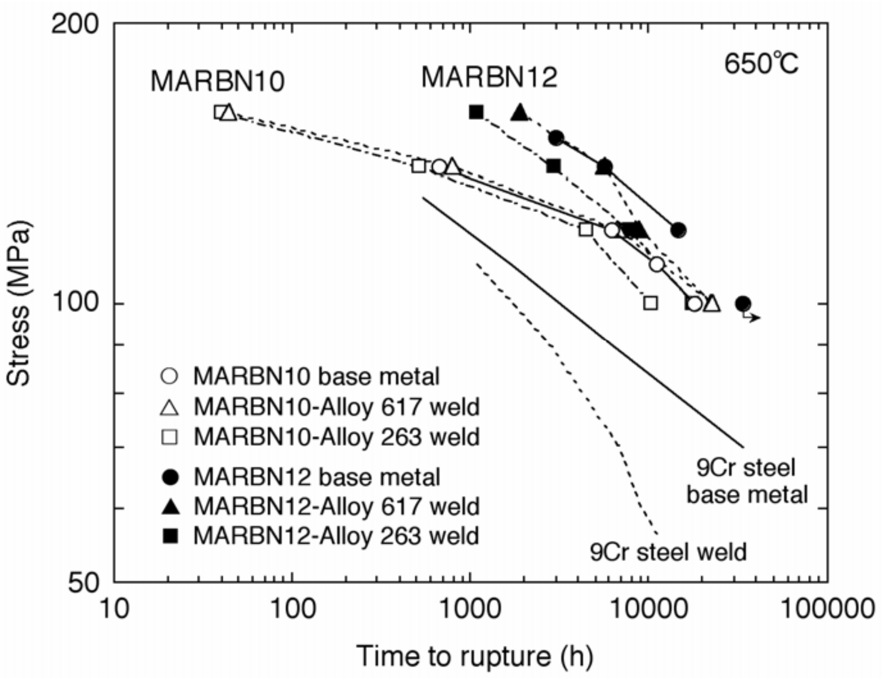


Figure 5. Creep rupture times of the base metals of the high B-9Cr steels and the dissimilar weld joints between high B-9Cr steels and Ni base alloys for A-USC boiler at 650 ˚C

(a) MARBN10 steel-Alloy 617 weld joint, 650 ˚C, 100MPa, 22766h

(b) MARBN12 steel-Alloy 617 weld joint, 650 ˚C, 100MPa, 22518h

Figure 6. Dissimilar weld joint specimens creep ruptured at 650 ˚C and 100MPa for 22000h

We have investigated the microstructures and creep damages in the crept welds. Figure 6 shows the dissimilar weld joint specimens creep ruptured at long-term test condition. It was observed that a creep crack initiated in the fusion boundary at the lower surface of U-groove and then propagated toward to the HAZ of the high B-9Cr steel.

Figure 7 shows microstructures and creep damages observed in the HAZ of the dissimilar welds between MARBN12 steel and Alloy 617 ruptured at 650 ˚C and 140 MPa for 5619h. In the HAZ at 1.5 mm from the fusion boundary, small amounts of creep voids were observed as shown in Fig. 7. This area corresponds to Fig. 4(b) where the grain size of the base metal was retained and small grains formed only on the prior-austenite grain boundaries. Creep voids in the HAZ of high B-9Cr steel were observed on the prior-austenite grain boundaries with large grain size. It is considered that the void coalescence and crack formation, which causes Type-IV failure, is suppressed and consequently the life of weld is improved in these HAZ microstructures of high B-9Cr steel compared with the fine-grained HAZ microstructures of conventional high Cr steels.

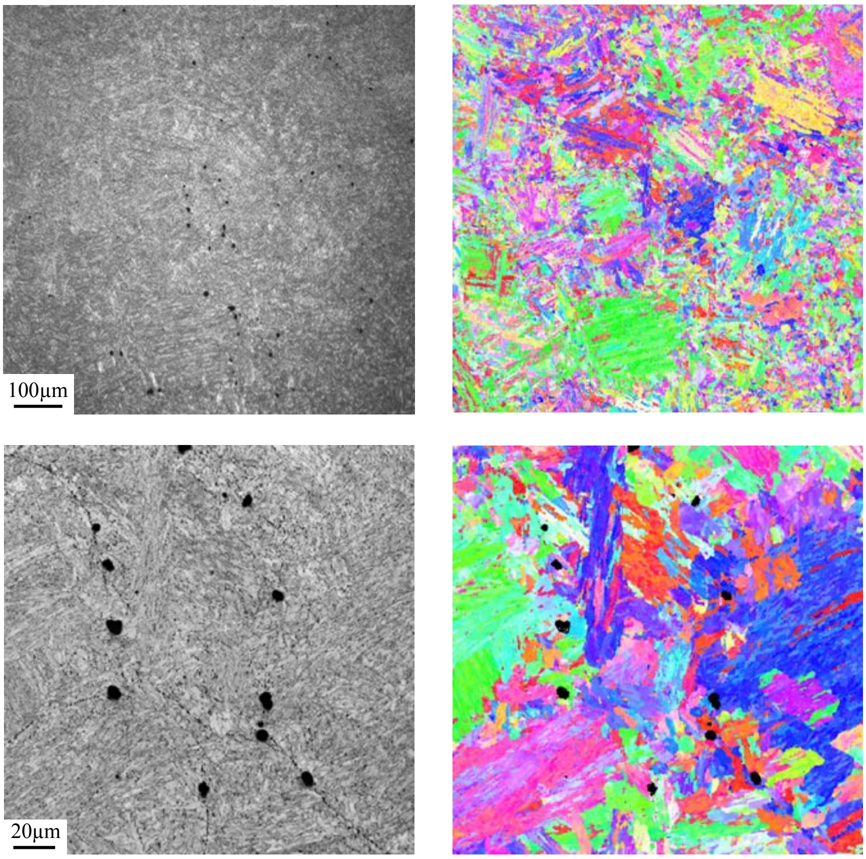


Figure 7. Microstructure and creep damage in the HAZ of the MARBN12 steel-Alloy 617 weld joint creep ruptured at 650 ˚C and 140 MPa for 5619 h

## 4. Conclusions

In the present paper, creep tests of the dissimilar welds between high B-9Cr steels and Ni base alloys, which are planning to be used in the 700 ˚C class pulverized coal power system (A-USC), were conducted. The results can be summarized as follows:

(1) For the high B-9Cr steels, fine-grained microstructures as shown in the conventional high Cr steels did not form in the HAZ. Free soluble boron is considered to decrease the grain boundary energy and change the mechanisms of the α-γ transformation during the weld thermal cycle.

(2) The creep rupture lives of the present dissimilar welds between high B-9Cr steels and Ni base alloys were 5-10 times longer than those of the conventional 9Cr steel welds at 650˚C.

(3) The failure locations of the dissimilar weld joints were base metal or fusion boundary. Small amounts of creep voids were observed in the HAZ with large grain size; however Type-IV failure did not occur for about 20000 h at 650˚C.

## References

[1] M. Tabuchi, M. Kondo, H. Hongo, T. Watanabe, F. Yin, F. Abe, Improvement of creep properties of high Cr steel weldment by boron addition. Journal of the Society of Materials Science Japan, 54 (2005) 162-167.

[2] S.K. Albert, M. Kondo, M. Tabuchi, F. Yin, K. Sawada, F. Abe, Improving the creep properties of 9Cr-3W-3Co-NbV steels and their weld joints by the addition of boron. Metallurgical and Materials Transactions A, 36A (2005) 333-343.

[3] M. Fukuda, Advanced USC power generation technology. Journal of the Japan Society of Mechanical Engineers, 114 (2011) 244-247.

[4] H. Hongo, M. Tabuchi, T. Watanabe, Type IV creep damage behavior in Gr.91 steel welded joints. Metallurgical and Materials Transactions A, 43A (2012) 1163-1173.

[5] M. Tabuchi, H. Hongo, Evaluation of long-term creep damage in high Cr ferritic steel welds. Materials at High Temperatures, 28 (2011) 172-180.

[6] T. Maki, H. Morimoto, I. Tamura, Recrystallization of the austenite transformed reversely and structure of martensite in 18Ni maraging steel. Tetsu-To-Hagane, 65 (1979) 1598-1606.

[7] T. Azuma, K. Miki, Y. Tanaka, T. Ishiguro, Effect of B on the behavior of austenite formation and recrystallization in high Cr ferritic heat resistant steel. Tetsu-To-Hagane, 86 (2000) 667-673.