Numerical simulation on type IV cracking of ASME P92 steel at high temperature†

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1. Introduction

In order to obtain an improvement in thermal efficiency and a reduction of the CO2 emission in modern ultra-supercritical (USC) fossil-fired power, the operating temperature and pressure have to be increased. ASME P92 steel (9Cr-1.8W-0.5Mo-NbV in wt%) have been used as structural materials for boiler components at 600 °C and 25 MPa due to its good mechanical properties, especially high creep rupture strength [1].

Creep cracking often occurs in the fine-grained heat affected zone (FGHAZ) of welded joints of P92 steel at high temperature and high pressure, known as Type IV cracking [2]. It leads to a short creep life of welded joints compared with that of base metal.

In this paper, a fine element method coupled with continuum damage mechanics is used to investigate the mechanism of Type IV cracking and factors affecting creep strength deterioration in the FGHAZ of ASME P92 steel at 650 °C and 70 MPa.

2. Continuum damage mechanics

In the present study, a modified Karchanov-Rabotnov equation for creep damage is used to calculate the stress and creep damage distribution of a welded creep specimen and the constitutive equation is as follows [3]:

$$\frac{d\varepsilon_{ij}^{c}}{dt} = \frac{3}{2} B\sigma_{e}^{n-1} S_{ij} \left(1-\rho+\rho\left(1-D\right)^{-n}\right) \quad (1)$$

$$\frac{dD}{dt} = g \cdot \frac{A}{\phi+1} \cdot \frac{(\alpha\sigma_{1}+(1-\alpha)\sigma_{e})^{v}}{\left(1-D\right)^{\phi}} \quad (2)$$

$$D_{cr} = 1-(1-g)^{(1/(\phi+1))} \quad (3)$$

3. FEM model

The welded joint of P92 steel analyzed in this paper is kept at 650 °C and 70 MPa.The creep specimen of a welded joint where four different material properties namely BM, CGHAZ, FGHAZ, and WM are taken into account is a round bar. The bar has a cross section of 10 mm and a gauge length of 50 mm with a HAZ width at 2 mm (FGHAZ width 1mm, CGHAZ width 1mm) and groove angle at 22° in the middle of the specimen, loaded at a uniform tensile stress in the z-direction with 70 MPa. Based on the uniaxial creep test, a FEM model, as shown in **Fig. 1**, half of the creep specimen is adopted to investigate the creep damage development and stress distribution in the welded joint during creep.

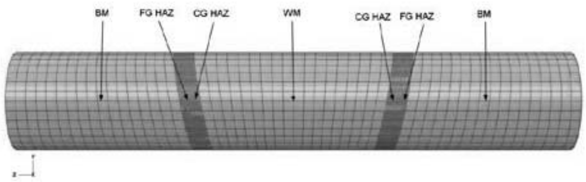

Fig. 1 FEM model of the welded creep specimen

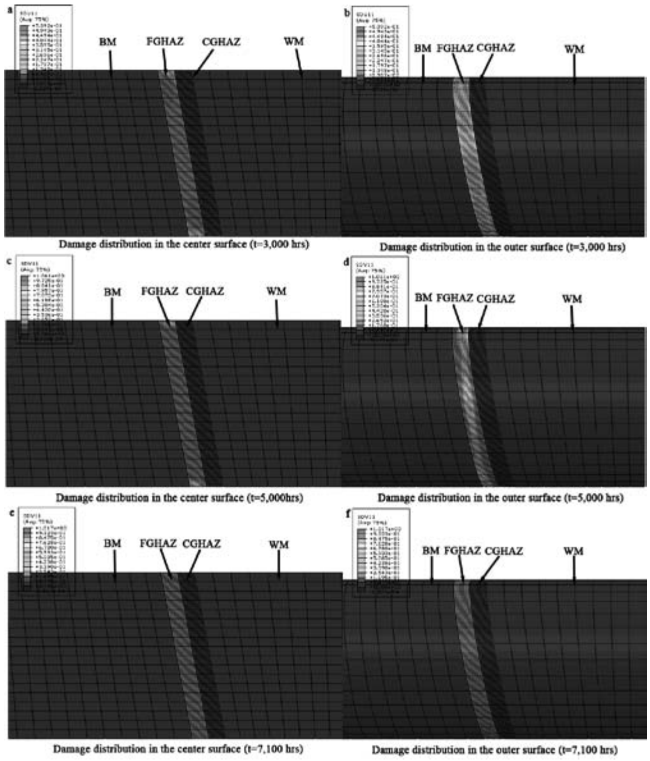

Fig. 2 Contours of creep damage in weld joint with various creep times

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4. Results and discussions

The FEM result demonstrates that the sample fractures in the FGHAZ of welded joint at 7100 h, when the D/Dcr of most elements in the FGHAZ reaches to 100%. It reveals that with increase in creep time, the creep damage of FGHAZ is accumulated faster than that of others zones in welded joint and the first damage elements occur in this zone, as shown in **Fig. 2**. The most elements of FGHAZ reach to the critical damage while the creep damage of other zones in welded joint is still small. Further, the creep damage in the inner part of FGHAZ is accumulated faster that that in the outer part of FGHAZ.

Although the welded joint is loaded by a uniform tensile stress during creep, there are gradients in the creep strength of the micro zones in welded joint, which leads to stress redistribution during creep, as shown in **Fig. 3**. Numerical simulations reveal that the equivalent stress varies with increase in creep time. At a creep time of 0 h there is no significant difference in equivalent stresses in the WM, CGHAZ, FGHAZ, and BM, but after a long creep time the difference is remarkable. The equivalent stress is low in the FGHAZ but high in the CGHAZ region adjacent to the FGHAZ and for the FGHAZ/BM interface, equivalent stress is low in the FGHAZ but high in the BM region adjacent to the FGHAZ. The reason is that the constraints of the CGHAZ and BM on the FGHAZ lead to the stress concentration.

Figure 4 and **Figure 5** show the distribution of stress triaxiality and maximum principle stress, respectively. The stress triaxiality and maximum principle stress are high in the FGHAZ while they are low in the CGHAZ. For the WM/CGHAZ interface, the stress triaxiality and maximum principle stress increase in both of the CGHAZ and the WM as the creep time increases. For the CGHAZ/FGHAZ, the stress triaxiality and maximum principle stress increase in the FGHAZ but decreases in the CGHAZ. For the FGHAZ/BM interface, the stress triaxiality and maximum principle stress increase in the FGHAZ, but decreases in the BM.

For the CGHAZ/FGHAZ interface or the FGHAZ/BM, the stress triaxiality and maximum principle stress in FGHAZ are high and the creep damage is high. The high creep damage also occurs in the FGHAZ for the CGHAZ/FGHAZ interface or the FGHAZ/BM interface, where the maximum principle stress and stress triaxiality are high. It implies that the high maximum principle stress and high stress triaxiality play an important role on the accumulation of creep damage. They may accelerate the growth and coalescence of creep voids and the subsequent micro crack formation during creep. The creep damage expands from the center of the FGHAZ to the outer surface and the elements reaching to the critical damage also firstly occur in the center of FGHAZ. Because the stress triaxiality and maximum principle stress of the center surface are much higher than those of the outer surface.

Since the FGHAZ is the key factor to the occurrence of Type IV cracking in welded joint of ASME P92 steel, it is necessary to investigate the effect of HAZ width and the effect of groove angle on the creep damage development.

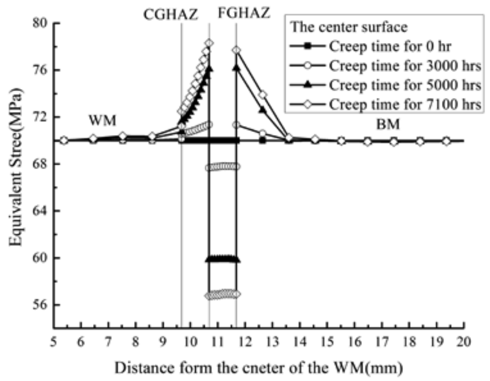

Fig. 3 Equivalent stress distribution with various creep times

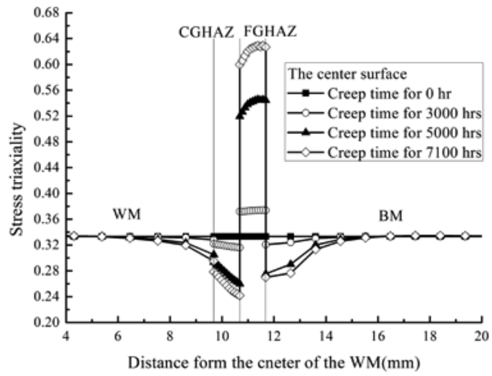

Fig. 4 Stress triaxiality distribution with various creep times

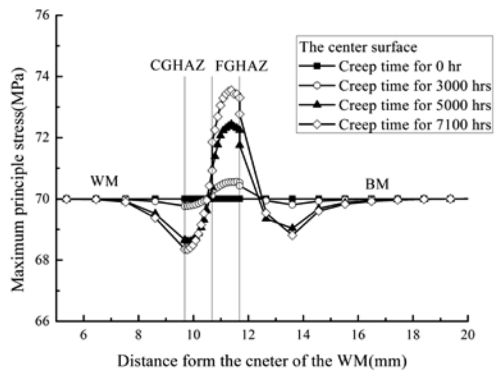

Fig. 5 Maximum principle stress distribution with various creep times

FEM models with different HAZ widths and various groove angles are calculated. The results reveal that a small groove angle and a narrow HAZ width can reduce the stress triaxiality and maximum principle stress in the FGHAZ of welded joint of P92 steel, which can suppress the accumulation of creep damage and the development of equivalent creep strain in FGHAZ; as a result Type IV cracking can be suppressed in welded joint of P92 steel.

It is considered that the narrow-gap welding technique which can produce a small groove angle and a narrow HAZ should be applied on the welding specification of ASME P92 steel to decrease the accumulation of creep damage in the FGHAZ and to suppress Type IV cracking.

5. Conclusions

(1) The creep damage in FGHAZ is severe and the failure life of FGHAZ is 7100 h. The stress triaxiality and maximum principle stress located at the FGHAZ are higher than that of other zones in the welded joint during creep. It implies that they can accelerate the creep strain development and creep damage accumulation; as a result Type IV cracking is likely to occur in this zone.

(2) A small groove angle and a narrow HAZ width of the welded joint are calculated to decrease the maximum principle stress and stress triaxiality in the FGHAZ, which leads to a decline in the accumulation of creep damage and can suppress Type IV cracking in ASME P92 steel.

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