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Mismatch effect in creep properties on creep crack growth behavior in welded joints

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The finite element method based on ductility exhaustion model was used to systematically investigate the mismatch effect in creep properties on creep crack growth (CCG) behavior in welded joints. The crack-tip damage, stress states, CCG paths, CCG rate and rupture life were calculated for different configurations of creep properties between weldment constituents under the same load level, and the creep life assessment and design for welded joints were discussed. The results show that when the zone containing the crack is softer than at least one of the other two surrounding materials or both, the creep crack propagates straight along the initial crack plane. Otherwise, it will form a second crack in the soft material near interface. These simulation results were confirmed by the experimental observations in the literature, and the mechanism was analyzed. The harder surrounding materials can lead to higher CCG rate and shorter rupture life due to the higher constraint given from them. The early initiation and propagation of the second cracks increase CCG rate and reduce rupture life, and the incubation time of the second cracks in soft materials near interfaces should be accurately determined in the creep life assessment and design for the welded joints. A proper mismatch design with harder material containing crack and softer surrounding material can improve CCG properties of welded joints (decreasing CCG rate and prolong rupture life).

1. Introduction

Most problems of crack initiation and propagation in high temperature components are likely to originate from welded joints [1], which is caused by the multi stress and strain fields appearing ahead of crack-tip or near the interface of weldment constituents due to the mismatch in creep deformation properties among base metal (BM), weld metal (WM) and heat affected zone (HAZ) [2,3]. The original cracks may exist anywhere in welded joint randomly, and mainly classified into four types. The type I crack is confined in WM, the type II crack occurring in WM may grow into BM, the type III crack occurs in coarse grained HAZ and the type IV crack propagates in the critical zone of HAZ adjacent to BM/HAZ interface [4].

Experiences showed that both the deformation properties of materials containing crack and surrounding materials influence the creep crack growth (CCG) behavior in welded joints [5–7]. Such as, the type IV crack is the most severe form of cracks due to the high creep strain of type IV region where the crack is propagating and the high constraint given from hard BM of surrounding materials [4]. Sugiura et al. [1,3] and Yatomi et al. [8] found that the crack located in the middle of HAZ region can deviate from the original crack plane to the type IV crack region with minimum hardness for the P92 welded joint, and the acceleration of CCG occurred as soon as the crack started to initiate near the HAZ/BM interface. Dogan [9] observed that the crack located in the middle of WM with high creep strength formed a second crack in the type IV crack region with lower creep strength in addition to the extending of CCG straight along the initial crack-tip in P91 welded joint, and the same phenomenon was also found in P122 steel welded joint with the pre-crack located in BM [10]. Hyde et al. [11] found that the cracks laid in the type IV region still stayed in this region, and the CCG rate was about four times higher than the corresponding BM for a given value of C^*. All the above results show that the material constraint caused by the mismatch effect in creep properties of weldment constituents plays an important role on the CCG behavior in welded joints. For accurate creep life assessment and safety design of the welded joints, it needs to investigate and understand this material constraint effect on the CCG behavior and properties.

Recently, there are some investigations on the creep crack-tip constraint effect caused by specimen geometry, crack size and loading configuration for homogenous materials [12–16] and welded joints [17,18]. However, only a few mechanical analyses

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for the material constraint effect on CCG behavior due to the mismatch in creep properties between different materials in welded joints could be found in the literature. Lee et al. [19] and Han et al. [20,21] defined a mismatch factor about creep constant and exponent of Norton's law between different materials in weldment to quantify the mismatch effect in creep properties on the distribution of steady-state stress. Tu et al. [22,23] and Xuan et al. [24] studied the influence of material mismatch on the evaluation of the time-dependent fracture mechanics parameters $C(t)$ and C^*. There are also some numerical investigations on the mismatch effect on C^* and CCG rate in welded joints [5–7]. But the actual CCG path generally could not be realized and it was assumed that all the cracks propagated straight. In real CCG process in welded joints, the crack path may change from the initial crack plane to another place [1,3,8–10], and the stress state ahead of crack tip and near the interface between different materials may change with crack growth. Therefore, the mismatch effects in creep properties on crack-tip stress state, creep damage accumulation, real crack path and CCG properties of welded joints need to be systematically investigated and understood. But it is difficult to do the experimental studies due to the difficulty of systematic change and control in creep properties of weldment constituents. The numerical method based on creep damage model may provide suitable tool for these investigations.

In this paper, the finite element method (FEM) based on ductility exhaustion model was used to investigate the mismatch effect in creep properties between weldment constituents on CCG behavior in compact tension (CT) specimens of welded joints. A brief introduction to the subject is given in this section. Section 2 describes the geometry of specimen, configurations of creep properties between weldment constituents, damage model and the calculation of CCG rate. The numerical results and discussions including mismatch effects on CCG path, CCG rate, rupture life, integrity assessment and design of welded joints are given in Section 3. Section 4 is the conclusion.

2. Finite element models and numerical procedures

2.1. Finite element models

In order to investigate the mismatch effect in creep properties on CCG behavior in detail, the CT specimen of welded joint was used for the FE analyses with ABAQUS code [25], which consists of three materials, i.e. BM, WM and HAZ. The geometry and dimensions of the specimen are corresponding to those of the experiments in Ref. [3], as shown in Fig. 1. The width W of the CT specimen is 50.8 mm and the initial crack length a_0 is 26.4 mm (a_0/W = 0.52). The width of the WM and HAZ is 20 mm and 2.4 mm, respectively. A sharp crack tip with 0.009° angle was used to represent the fatigue pre-crack and located in the middle of HAZ. The load was applied on the centre of the upper hole using a reference point which was tied to the internal hole surface that represents the bolt in the experiments. The centre of the upper hole was constrained in X-direction, and the centre of the lower hole was constrained in X and Y-directions. The four-node plane strain element (CPE4) was used for all FE models. The mesh dependency investigations in the CCG simulations have been carried out by Yatomi et al. [26] and Oh et al. [27] for the mesh size from 50 μm to 250 μm. The results show that the creep crack initiation time decreases with decreasing mesh size due to the increased crack-tip stress and strain, and the CCG rate was not sensitive to mesh size. So, the fine meshes with size of 50 μm × 50 μm were used ahead of crack tip and near the interfaces of HAZ/WM and HAZ/BM. The whole and local meshes for the CT specimen are shown in Fig. 2, which includes 20,891 elements and 21,063 nodes.

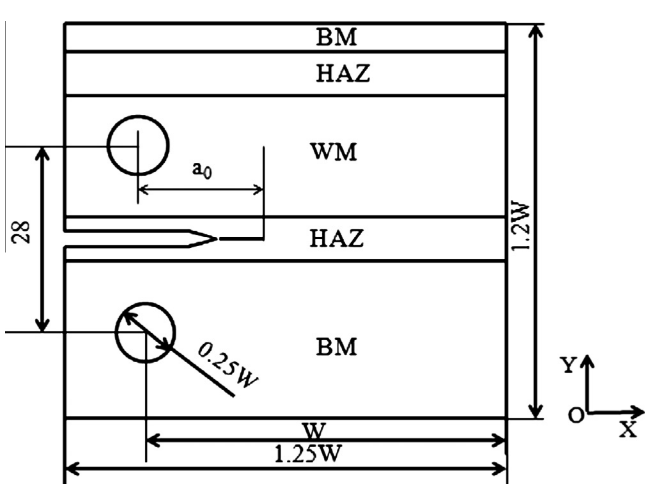

Fig. 1. The geometry and dimensions of the CT specimen of welded joint [3].

2.2. Materials and configurations of mismatch in creep properties

The ASME Grade P92 steel was chosen for BM. The elastic–plastic-creep material model was used in FE calculations. The elastic modulus E and yield stress σ_y of the BM at 650 °C is 85GPa and 126 MPa, respectively [28]. The characteristic of work hardening for plastic deformation is taken from Ref. [1], and is approximated by Eq. (1):

$$\sigma = c(a + \varepsilon_p)^{\alpha} \tag{1}$$

where c, a and α are constants (c = 162, $a = 0.32 \times 10^{-2}$, α = 0.105), and ε_p is true plastic strain. To investigate the mismatch effect in creep properties on creep crack growth behavior in welded joints and facilitate explanation of results, the elastic modulus and plastic deformation characteristics for WM and HAZ are assumed to be the same as those of BM. For the sake of simplicity and changing creep properties easily, the Norton's law was taken as creep constitutive equation for the three materials as follows:

$$\dot{\varepsilon}_b = A_b \sigma^{n_b}, \quad \dot{\varepsilon}_W = A_W \sigma^{n_W}, \quad \dot{\varepsilon}_{HAZ} = A_{HAZ} \sigma^{n_{HAZ}} \tag{2}$$

where A_b, A_w and A_{HAZ} are creep constant, and n_b, n_w and n_{HAZ} are creep stress exponent for BM, WM and HAZ, respectively. The Norton's parameters (A_b = 3.77E−19 MPa^{-n} h^{-1}, n_b = 6.71) for the ASME Grade P92 BM at 650 °C were used, and they were taken from Ref. [28]. To examine the mismatch effect in creep properties among WM, HAZ and BM on creep crack growth behavior in welded joints, different configurations of mismatch in creep strain rates of WM, HAZ and BM should be designed. For WM and HAZ, the material properties were given that the minimum creep strain rate was higher or lower than that of BM by varying the constant A and keeping the exponent $n_W = n_{HAZ} = n_b$ = 6.71. The mismatch factors of MF_W and MF_{HAZ} shown in Eq. (3) were given to represent the mismatch effect in creep properties relative to BM for WM and HAZ, respectively. Thus, three cases of MF > 1, MF = 1 and MF < 1 refer to creep soft material, creep match and creep hard material, respectively. This type of design of configurations of mismatch in creep properties was widely used in the literature [5–7,19–21].

$$MF_W = \frac{A_W}{A_b}, \quad MF_{HAZ} = \frac{A_{HAZ}}{A_b} \tag{3}$$

For investigating the mismatch effect in creep properties on CCG behavior, the MF_W and MF_{HAZ} are assumed as 10, 0.1 and 1, respectively, which means that the minimum creep strain rate is 10 times larger or smaller and the same relative to BM both for