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Research paper

Effect of notch position on creep damage for brazed joint

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ABSTRACT

In this paper, we investigated the effect of notch position on creep damage for Hastelloy C276-BNi2 brazed joint. Three different types of notches locate in edge of base metal (base notch), edge of filler metal (surface notch) and center of filler metal (inside notch) were compared, and the influence of notch geometric parameters on creep damage was also investigated. The results show that the different notch position and dimension generate different creep damage distributions and have a great influence on creep life. The creep failure is the easiest to occur in surface notch, then the base notch, and the last is inside notch. The brazed joint with higher maximum principal stress and von Mises stress generates creep failure easier. For the base notch, the failure time increases with the increase of base notch distance and the creep failure location moves gradually from the center of filler metal to notch tip. The notch locating away from filler metal is beneficial to reduce the creep damage in filler metal and enhance the creep life. For the inside notch, the failure time decreases with notch length increases and the maximum creep damage locates at notch tip. With the increase of inside notch width, the failure time increases first and then keep steadiness, and the failure location moves away from notch tip. The effects of notch position and dimension should be fully considered in creep failure analyses and life assessments of brazed joints.

1. Introduction

Plate fin heat exchangers (PFHEs) are currently developed as compact heat exchanger in high temperature gas reactor (HTGR) [1,2]. At high temperature, the time dependent creep deformation may occur in plate-fin structure. The plate-fin structure is a porous structure with a number of brazed joints [3], and always has geometrical discontinuities like fillets or defects working as notches [4]. Theses notches change the uniaxial stress to multiaxial stress state, leading to the initiation and propagation of creep cracks from these notches [5,6]. For creep damage assessment under multiaxial stress, notched specimens were often employed [7]. Therefore, a study of the notch effect on creep damage taking account of multiaxial stresses is essential for the quality assurance of the brazing joints [8].

To date, the creep damage of the notched specimen has been extensively studied. Goyal et al. [9–11] studied the effect of multiaxial stress on creep rupture behaviors and found that there is a notch strengthening effect under multiaxial stress state because of the reduction of von Mises stress. Jiang et al. [12,13] investigated the effects of notch shape on creep damage development under constant loading, and found that the development of creep damage is clearly affected by applied stress, material parameter and notch shapes. Zhang et al. [14] studied the influence of the notch location on the fatigue behavior in welded high-strength low-alloy and shows that the U-notch in weld metal and parent metal will bring to ductile fracture and brittle fracture, respectively. Turski et al. [15], Zhao et al. [16] and Chen et al. [17] employed in-plane pre-compression method to introduce the residual stress fields into notched specimens and concluded that the residual tensile stress promotes creep damage and crack initiation ahead of notch tips. Yu et al. [18] presented a study of the creep damage development in heat affected zone (HAZ) induced by void growth by a new constitutive model and proved that this model could be used to account for the microstructural changes during the process of creep rupture. Ganesan et al. [19] carried out a creep test on smooth and notched sample of 316LN Stainless steel and found that the ratio of rupture life of smooth to notched specimens decreased with the increase of the nitrogen content.

The present work about creep behavior of notched specimen was mostly paid on the homogenous material or macro-welded

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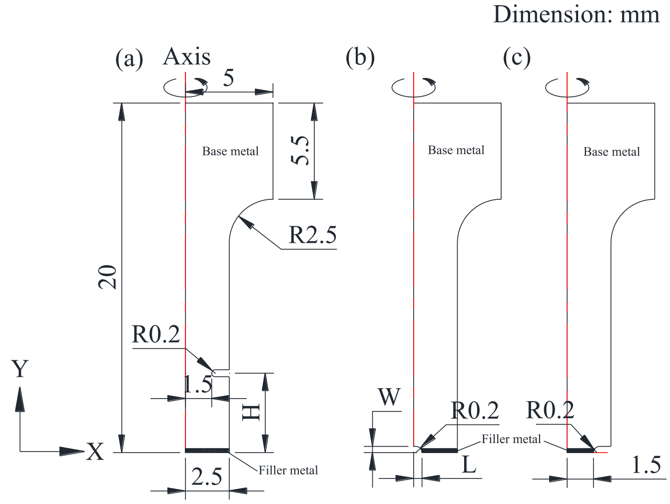

Fig. 1. Geometry of the brazed specimen with (a) base notch, (b) inside notch and (c) surface notch.

joints, and very little attention has been paid on the brazed joints. Yang et al. [20,21] found that the brazed joints exhibited a lower creep life compared with base metal and fractured in the brazing seam. Leinenbach et al. [22–24] introduced some typical defects with different sizes and geometries in the brazing zone to study the effect of brazing defects on the structural integrity, and deduced that the stress concentrations at brazing defects must be taken into account for calculating the strength of defect containing brazed component. Recently, we presented a study on the creep damage and creep crack initiation in P92-BNi2 brazed compact tension joint specimen, and found that the creep crack initiation (CCI) is a function of residual stress, load level, joint thickness and notch radius [25]. In our previous study [26], we have investigated the effect of surface notch in filler metal on creep damage, and discussed the effects of notch type, radius and angle on creep damage distribution and failure time. We found that different notch types bring different stress state, and generate different creep damage. But it only paid attention to the notches at the surface of filler metal. However, the defects also generate inside the filler metal or at the base metal, liking a notch located in base or filler metals [27]. It is still unclear how they influence the creep damage. The strain-based continuum damage mechanics approach (ductility exhaustion model) is an available method to predict the creep damage of components at high temperature [28]. Therefore in this paper, we studied the creep damage of notch locates inside the filler metal and at base metal by a strain-based continuum damage mechanics method.

2. Finite element analysis

2.1. Model description

This paper studies three different notches locating at surface of base metal (i.e. base notch), inside of filler metal (i.e. inside notch) and surface of filler metal (i.e. surface notch), respectively, as shown in Fig. 1. The notch radius for the three notches is the same, 0.2 mm. The distance of base notch from filler metal center H (Fig. 1) is 1 mm. The length L and width W of inside notch are 1.0 mm and 0.2 mm, respectively. Two Hastelloy C-276 plates were brazed together by a nickel-based filler metal BNi-2: the assembly is heated to 600 °C at 10 °C/min and hold about 60 min, then it is heated to the brazing temperature 1050 °C and hold 25 min; at last, the assembly is cooled to the ambient temperature. The filler metal thickness is 100 μm. The specimen is a round bar. Due to the structural symmetry, only a half of model is built to save the computation time, and the half model was established by two-dimensional axisymmetric model. The finite element meshing is shown in Fig. 2. The meshing is fine around the notch tip and then becomes coarse far away. The element type is four-node axisymmetric quadrilateral element CAX4. A load of 90 MPa is applied. The isotropic hardening law was assumed in the analysis. All the nodes on the axisymmetric section were applied the symmetric boundary conditions in X-direction, and all the nodes on the bottom section were constrained in Y-direction.

Table 1
Creep constants at 600 °C.

Material	B/MPa^{-n}h^{-1}	n	ε_f
Hastelloy C276	1.29×10^{-18}	5.83	0.08
BNi-2	8.75×10^{-40}	14.75	0.0027

2.2. Creep damage analysis

A continuum creep damage model proposed by Wen and Tu [29] is used, which reasonably reflects the effect of multi-creep axial stress on creep:

$$\dot{\varepsilon}_{ij}^{c} = \frac{3}{2} B \sigma_{eq}^{n-1} S_{ij} \left[1 + \beta \left(\frac{\sigma_1}{\sigma_{eq}} \right)^2 \right]^{\frac{n+1}{2}} \tag{1}$$

$$\beta = \frac{2\rho}{n+1} + \frac{(2n+3)\rho^2}{n(n+1)^2} + \frac{(n+3)\rho^3}{9n(n+1)^3} + \frac{(n+3)\rho^4}{108n(n+1)^4} \tag{2}$$

$$\rho = \frac{2(n+1)}{\pi\sqrt{1+3/n}}\omega^{3/2} \tag{3}$$

where β is a stress-dependent function reflecting the material behavior, ρ is the micro-crack damage parameter, $\dot{\varepsilon}_{\mathrm{ij}}^{c}$ is the rate of creep strain tensor, σ_1 is maximum principle stress, ω denotes the damage state parameter, σ_{eq} is the Von Mises equivalent stress, $\mathrm{S_{ij}}$ is the deviatoric stress, B and n are material constants for creep.

The creep damage accumulation and CCI ahead of a notch is expressed by the ductility exhaustion approach [30]:

$$\omega = \int_0^t \dot{\omega} dt = \int_0^t \frac{\dot{\varepsilon}_e}{\varepsilon_f^*} dt \tag{4}$$

where ω is the damage varies from 0~0.99, and the crack initiation occurs as damage is 0.99. ε_{e} is the equivalent creep strain, and ε_f^* is the multi-axial creep failure strain described by Cocks and Ashby [31]:

$$\frac{\varepsilon_f^*}{\varepsilon_f} = \sinh\left[\frac{2}{3}\left(\frac{n-0.5}{n+0.5}\right)\right] \Big/ \sinh\left[2\left(\frac{n-0.5}{n+0.5}\right)\frac{\sigma_m}{\sigma_{eq}}\right] \tag{5}$$

where σ_m is the hydrostatic stress, and ε_f is the uniaxial creep failure strain.

The continuum creep damage model has been incorporated into ABAQUS by a user subroutine CREEP compiled by FORTRAN language. In order to obtain the variables σ_1 and σ_m at each time increment, the USDFLD subroutine has also been embedded into the ABAQUS, and the creep damage is updated at the end of the each increment. The creep constants required in the calculation were shown in Table 1 [26].

2.3. Residual stress analysis

Large brazed residual stresses will be generated due to the mismatching of materials and have a great effect on creep damage [25]. At high temperature brazing, the assembly is at stress-free