Finite element analysis of the creep crack growth of T-type brazed joints

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Abstract. Plate-fin heat exchangers are widely used in the field of nuclear waste heat recovery due to their high heat transfer efficiency and compact structures. The vacuum brazing technology is frequently employed to package these structures. Under high temperature, high pressure and harsh working conditions, cracks caused by creep or creep damage can initiate and growth easily in the brazed joints. they will further bring about the failure of structures. In this work, the creep failure behavior of T-type brazed joints at 650°C was investigated by finite element method. The creep crack initiation and growth of T-brazed joints were analyzed. Combined with actual vacuum brazing process, the effect of brazing metal thickness on the creep crack initiation and growth of the brazed joint were analyzed. Results showed that the edge of the brazing material was most vulnerable to damage. Later on, the central area of the brazing metal was subsequently damaged.An appropriate increase of the brazing metal thickness is thought to be helpful to prolong the creep life of the T-type brazed joints.

Introduction

Plate-fin heat exchangers are often used in the field of nuclear power for waste heat recovery. However, they are not continuous in structure, nor do their mechanical properties match, plate-fin heat exchanger joints are therefore prone to creep cracks and cavities. When a crack reaches its critical size, it often leads to catastrophic consequences[1]. Therefore, it is imperative to study the characteristics of the creep crack growth of brazed joints at elevated temperatures.With the development of computer technology, using finite element method to study the mechanical behavior of brazed joints has gradually drawn the attention of researchers. HAN Fei et al. [2] carried out the simulation to study the residual stress of ceramic metal brazing joints. Tu Shandong et al. [3]used FEM to analyze the creep damage of 304 stainless steel brazed joints in the plate-fin heat exchanger, whose results showed that the brazing area was a weak region in the brazing joint. Chen Jianjun et al. [4] analysed the creep damage of a 304 / BNi2 lap joint, The results also showed that the brazing area was the weakest region of the joint. Jiang Wenchun et al. [5] considered the steady state creep of a brazing filler metal, the effect of brazing metal thickness on the creep of stainless steel plate fin structure was analyzed by using Norton constitutive. However, the aforemensioned studies did not take into account the primary stage of the creep of the brazing filler metal during creep simulations[2-5]. At the primary stage strain of the brazing material account for about 10% of the total creep strain, and the neglect of the primary stage may lead to large error of simulation results. Therefore, it is the key to accurately study the high temperature mechanical properties of brazed joints to consider the primary-stage creep of brazing metals.

Based on a modified stress-based damage model, with the incorporation of the primary stage of the creep of the brazing metal, the creep crack growth in the T-type brazed joint wasconsequently simulated. Both the behavior of the creep crack growth and the effect of the thickness of the brazed joint on the creep performance of the T-brazing joint were studied in detail. This work can be a basis for evaluating the creep life of the brazed joints.

FE model

Creep damage constitutive model.

In this paper, a modifiey L-M model obtained by combining the K-R creep damage model[6]was

employed. The model can be expressed as follows:

$$\dot{\varepsilon}_{ij}^c = \frac{3}{2} B_0 \sigma_{eq}^{n_0-1} S_{ij} t^{m-1} + \frac{3}{2} B \sigma_{eq}^{n-1} S_{ij} \exp[\frac{2(n+1)}{\pi\sqrt{1+(3/n)}}\omega^{3/2}]$$

(1)

$$\dot{\omega} = \frac{A[1-\exp(-q_2)]}{q_2} \sigma_r^p \exp(q_2\omega)$$

(2)

$$\sigma_r = \alpha \cdot \sigma_I + \alpha \cdot \sigma_{eq}$$

(3)

Where B_0, n_0, m are material constants of the primary creep stage of the solder, $\dot{\varepsilon}_{ij}^c$ is the creep strain rate tensor, A、B、n、q_2、p are material constants，σ_{eq} and σ_I are the von Mises stress and Maximum principal stress, respectively. S_{ij} is the deviatoric stress, ω is the damage state variable, σ_r is the equivalent stress, α is the multi-axial stress state parameter. From the formula (1) ,we can see that the model combines the advantages of the K-R model, taking into account the first stage of the creep of the solder.

Model parameters and material parameters.

The model parameters for 316L at 650°C are B=1.133e-20, n=8.3076, A=1.216E-22, and P= 8.5911[7-8]. q_2 in the L-M model is hard to obtain. According to the empirical formula, $q_2=\phi+2$, where ϕ is a constant in the K-R model[9]. ϕ can be obtained by fitting the normalized uniaxial creep strain curve , by doing so, ϕ was identified, namely ϕ=6.075[10], then q_2=8.075. The creep parameters of the Nickel-based brazing metal BNi-2 at 650°C are as follows[7]. Therefore, the material parameters of 316L and BNi2 at 650°C are shown in Table 1. The elastic modulus of 316L and BNi-2 at 650°C is 149GPa and 170GPa, respectively; the yield strength 161MPa and 200MPa respectively[11-12].

Tab.1 Creep parameters of BNi2 and 316L at 650°C

parameters	B_0	n_0	m	A	B	n	p	q	α[13]
BNi2	1.562e-7	1.965	0.29	7.899e-9	8.016e-11	2.92	2.70	3.2307	0.15
316L	-	-	-	1.216e-22	1.133e-20	8.3076	8.591	8.075	0.43

FE model and boundary conditions.

In terms of the actual plate fin structure in Fig. 1a, the finite element model shown in Fig. 1b was established, where the thickness of the brazing seam was 80 μm. The bottom end of the T-brazing joint specimen was defined as encastre, i.e U1=U2=UR3=0, the freedoms of the X direction displacement and rotation were restricted at the top end, i.e U1=UR3=0, the 15MPa load was exerted on the top end of the T-brazed joint in the Y direction. The stress state of the brazed joint was closer to the plane strain state than plane strain state when a brazed joint failed, so in the finite element analysis, the plane strain unit CPE4R was chosen for the brazing filler metal. Considered that the brazing filler metal area was invariably the weakest region of a brazing joint, smaller element size was used when the brazing filler metal area was meshed, as shown in Fig2, where the red area indicated the brazing area.
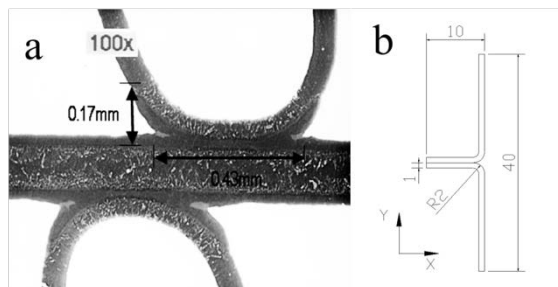

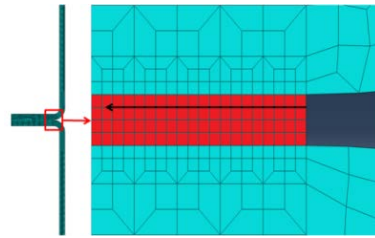Fig.1(a)Plate-fin structure (b)Geometrical dimensions of T-type brazing joint

Fig.2 Meshing result of T-type brazing joint and stress analysis path1

Results and analysis

Figure 3 showed the damage contours at different times in the vincinity of the brazing area. It can be seen from the figure that the edge region of the brazing filler metal was initially damaged, which means that the creep crack propagated in the edge area at the beginning, and then it penetrated into the central area of the solder. It is when the element damage in the edge area and the central region reaches 0.99 that the failure of the brazing filler metal occours.
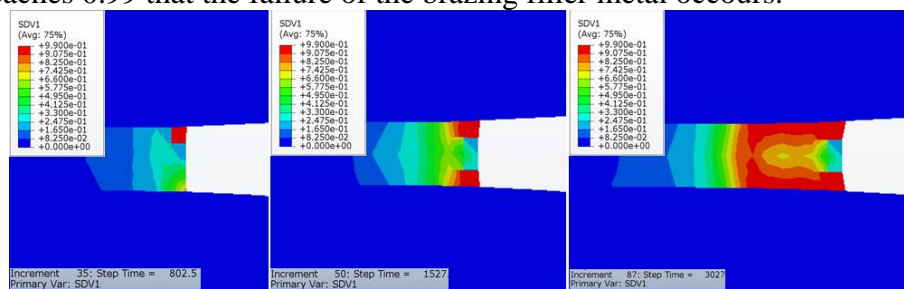

Fig.3 Creep damage contours of brazing seam at different time

Figure 4 showed the changes of the von Mises stress and damage over time for the first and second elements of the upper edge of the brazing seam. It could be seen from the figure that at the outset of creep, the stress for the first two elements were 200MPa and 150MPa respectively, and then the stresses were rapidly relaxed. The stress of the first two elements plummeted to about 100MPa and 70MPa respectively. Then the stress relaxation slowed down and the creep damage begin to accelerate, but the damage rate of the first element was obviously much higher than that of the second one. In 800 hours or so, the damage of the first element reached 0.99，that was when the stress became 0, causing the first element to fail.Then the second element stress increased obviously, which in turn caused the creep damage rate to increase obviously, and when the secend element failed, the creep crack has already propagated for one element. When the creep time approached about 1500h, the damage of the second element reached 0.99, and then the stress was reduced to 0. The creep crack finished its secend element growth.
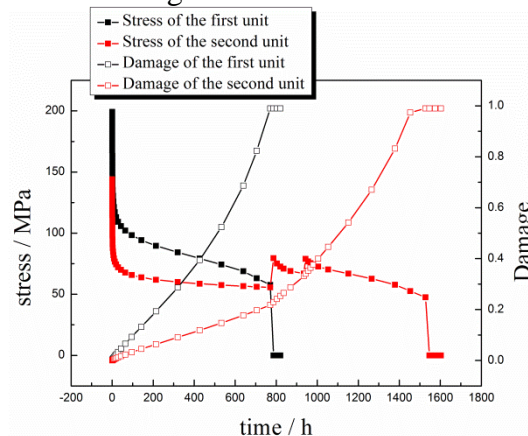

Fig.4 Stress and damage curves

Under different load conditions, the creep crack initiation times of the brazing joint were different, in general the initiation time t_i is the time when creep crack propagate for 0.2mm. Figure 5 showed the effect of stress on crack initiation times under different loads. It can be seen that there

is an approxime linear relationship between the creep initiation times and stress in the double logarithmic coordinates, and it can be expressed as power law formula ($t_i = A_i\sigma^{-n_i}$). Though fitting the data in the graph, it was obtained that the constant A_i=1.70616×10^{50}，and n_i=10.49675. In the actual application process, the formula can be used to predict the initiation time of a brazing joint, and then by controlling loading level to prevent the brazing joint from the premature of creep crack initiation .
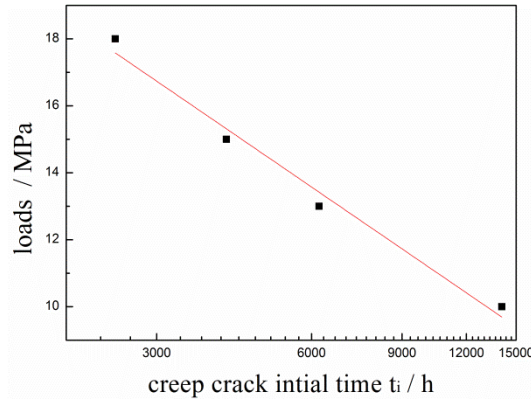

Fig.5 Crack initial time at different load levels

The thickness of the brazing filler metal is a vital process parameter in the brazed joint. The difference in thickness can exert a great impact on the stress generation and redistribution in the creep process of the brazed joint, which will further affect the initiation and growth of the creep crack. The thickness of brazing filler metal of 60, 80, 100, 120 and 140 μm were selected to study the effect of brazing filler metal on the creep crack initiation and growth of T-brazing joints.

Based on the analysis path shown in Figure 2. Figure 6 showed the distribution of the von Mises stress on path 1 at different times. It can be seen from the figure that when the creep time nears 0h, the stress on the path 1 tends to decrease with the increase of the thickness of the solder layer, and the stress value decreases with the thickness of the solder in a certain area of the crack tip ;When the creep time is 2123h, the stress is relaxed and the stress decreases with the increase of the thickness. When the creep time is 7000h, the stress value of the crack tip is almost the same when the solder thickness is 60 and 80μm, the stress values of thickness 60,80μm are significantly higher than those of 100, 120 and 140 μm.It can be seen that the stress in the brazing filler metal decreases with the increase of the thickness. So a proper increase in thickness may be helpfuo to improve the creep performance of the brazed joint.
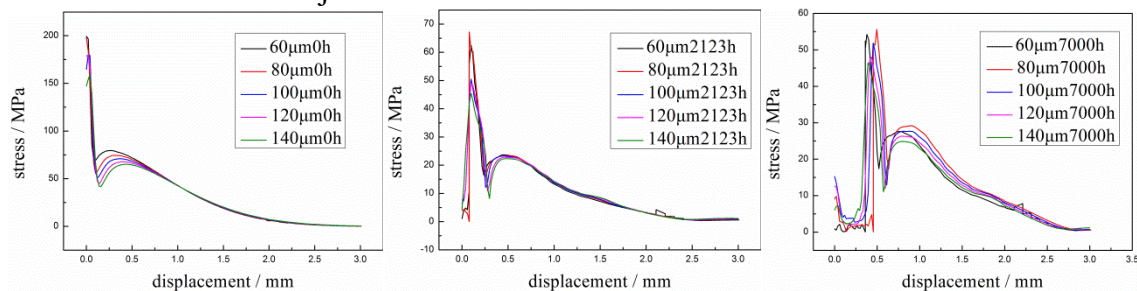

Fig.6 Varitaion of the von mises stress with the time along the path1

Figure 7 showed the variation of creep crack propagation over time at five different solder thicknesses. It can be seen from the figure that the creep crack initiation time of the solder 40μm thick is 4098h while the creep crack initiation time of 140μm is about 4743h, which prolongs the initiation time by 15.7 percent. At the same time with the increasing thickness, the creep crack growte rate is gradually reduced. Therefore, the increase of the thickness of the solder is indeed helpful to prolong the initiation time of the brazed joint and reduce the creep crack growth rate.
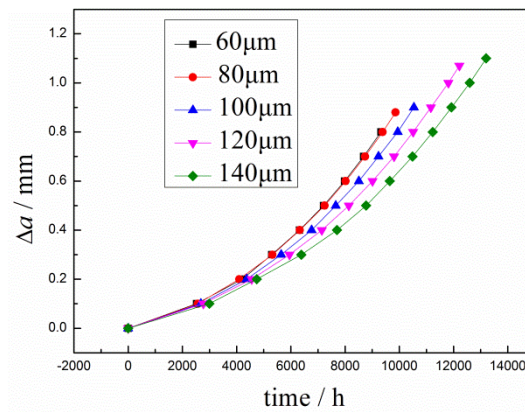
Fig.7 Effect of the brazing filler metal thickness on the creep crack growth

Conclusion

1)In the creep crack initiation stage, due to the creep deformation of the brazing filler metal, the edge of the brazing seam is damaged at first, and later on the central area of the brazing filler metal is damaged. When the damage parameter reaches 0.99, the creep crack starts to propagate.

2)The creep crack initiation time and stress satisfies the power law relationship, i.e, $t_i = A_i\sigma^{-n_i}$. At 650°C, the constant A_i=1.70616×10^{50}，n_i=10.49675. The formula can be used to predict the initiation time of the brazed joint, and then by controlling loading level to prevent creep initiation of the joint prematurely.

3)With the increase of the thickness of the solder, the von Mises stress at the crack tip decreases, the creep crack initiation time increases and the crack growth rate decreases. Therefore, a appropriate increase in the thickness of solder is helpful to improve the creep life of the T-type brazed joint.

Acknowledgments

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