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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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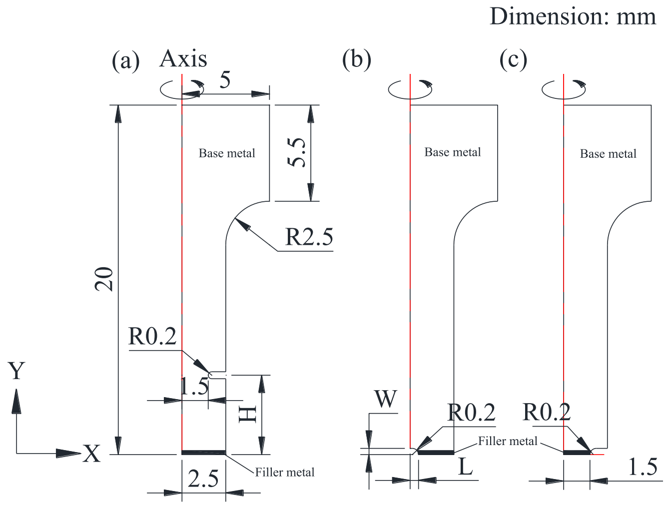

Fig. 1. Geometry of the brazed specimen with (a) base notch, (b) inside notch and (c) surface notch.

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

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

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.

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, 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

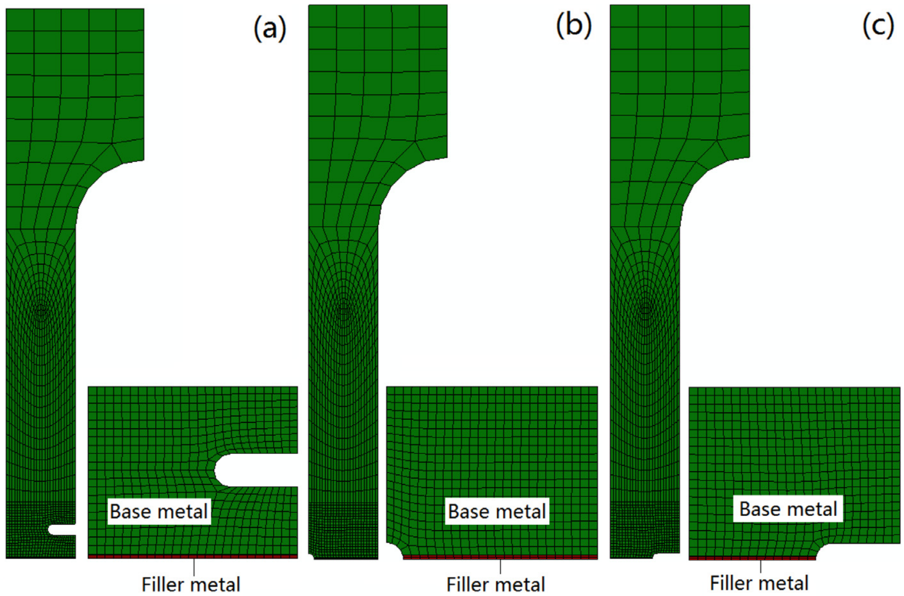

Fig. 2. Finite element meshing of (a) base notch, (b) inside notch and (c) surface notch.

Table 2
Temperature-dependent mechanical properties of Hastelloy C276 and BNi-2.

Temperature (°C)	α is coefficient thermal expansion (10^{-6} mm/mm/°C), E is Young's Modulus (GPa), μ is Poisson's ratio, σ is yield strength (MPa)							
	Hastelloy C276				BNi-2			
	α	E	μ	σ	α	E	μ	σ
20	10.8	206	0.3	388	13.4	205	0.30	300
100	11.3	201	0.29	343	14.1	201	0.30	280
200	12.1	195	0.322	303	15.1	195	0.30	260
300	12.7	190	0.298	278	16.0	190	0.30	240
400	13.1	183	0.256	264	16.8	184	0.30	220
500	13.4	178	0.23	256	17.5	178	0.30	206
600	14.3	163	0.228	241	18.2	172	0.31	193
700	15.2	138	0.227	233	18.6	169	0.32	180
800	16.1	114	0.226	229	19.9	161	0.32	160
1000	17.9	100	0.224	102	25.3	40	0.37	90
1100	18.2	73	0.224	73	35.3	17	0.47	76

state. Therefore, the brazed residual stress is simulated during the cooling from 1050 °C to 20 °C [32]. The total strain can be decomposed into three components as follows:

$$\varepsilon = \varepsilon^{e} + \varepsilon^{p} + \varepsilon^{ts} \tag{6}$$

where ε^{e}, ε^{p} and ε^{ts} stand for the elastic strain, plastic strain and thermal strain, respectively. Elastic strain is modeled using the isotropic Hooke's law with temperature-dependent Young's modulus and Poisson's ratio. The thermal strain is calculated using the temperature-dependent coefficient of thermal expansion (CTE). For the plastic strain, a rate-independent plastic model is employed with Von Mises yield surface, temperature-dependent mechanical properties and isotropic hardening model. Temperature-dependent material properties were shown in Table 2 [26].

3. Results and discussion

3.1. Creep damage distribution for different notch positions

Fig. 3 shows the contours of creep damage for the three models. Obviously, different notch position generates different creep damage distribution. The maximum creep damage 0.99 (i.e. initial creep failure location) locates at notch tip for the inside and surface notch, while it locates at center of filler metal for the base notch. Fig. 4 shows the damage evolution with time. The damage contains three stages: first it increases sharply (first stage) and then increase by a steady rate (steady state); finally, the damage increasing rate increases sharply (tertiary state). The time to reach the maximum creep damage (i.e. creep damage failure time, represented by t_D) for the surface notch, inside notch and base notch are 2059, 319 777 and 11 528 h, respectively. The failure time of the inside notch is biggest, then the base notch and the least is the surface notch, which indicates that the surface notch is the easiest to generate creep failure.

The reason why the creep failure location and time are different for different notch positions is that the stress distribution at notch tip is different. In our previous study [26], we found that the brazed joint with higher stress concentration generates the creep failure easier. The creep axial stresses at notch tip have been proved available to explain the creep damage distribution at notch tip [12]. Here, the creep axial stresses in filler metal were picked out at the time when the damage reaches 0.99. Fig. 5 shows the maximum creep axial stresses in the filler metal for the three models. The maximum creep axial stresses for the surface notch, inside notch and base notch are 128.2, 57.8 and 87.8 MPa, respectively. The differences of maximum creep axial stresses are caused by the difference of creep time and effective sectional area of notch specimen. Fig. 6 shows the contour distribution of creep axial stresses

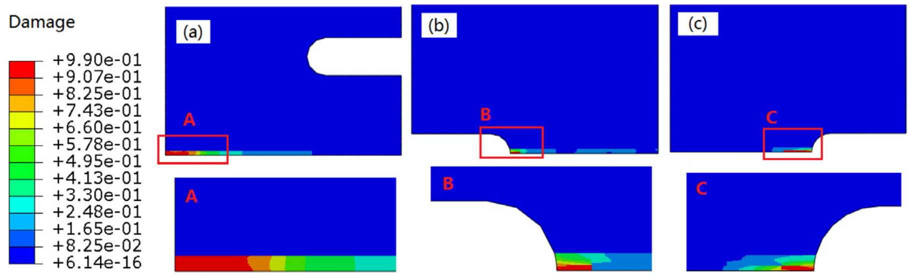

Fig. 3. Contours of creep damage of base notch (a), inside notch (b) and surface notch (c).

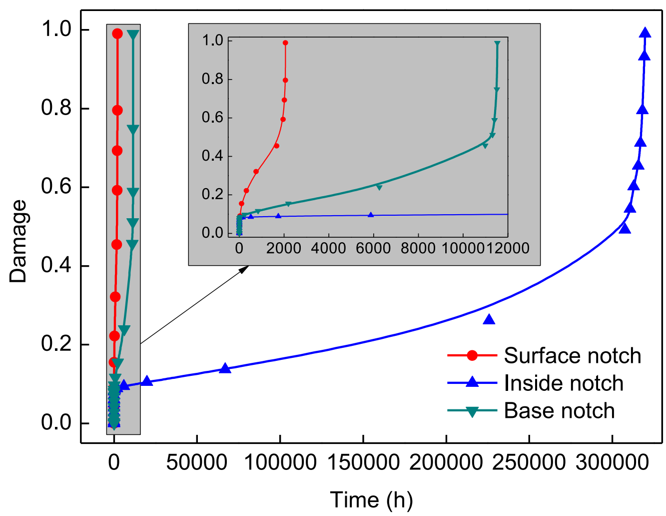

Fig. 4. Damage evolution with time for different notch positions.

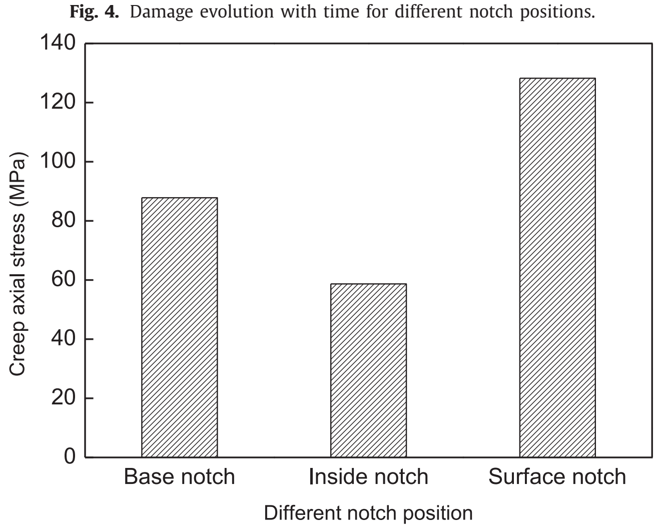

Fig. 5. The maximum creep axial stresses for different notch positions.

for the three models. It can be obviously seen that the creep axial stress in notch tip for the surface notch is largest while for the inside notch is smallest. Before creep, the residual stresses in three models are the same. After a different creep time, the residual stresses in filler metal are relaxed at different extent. According to Fig. 4, the model order in terms of creep time from low to high is surface notch, base notch, inside notch. Because longer creep time can lead to the greater relaxation of residual stress, the model order in terms of creep axial stresses from high to low is surface notch, base notch, inside notch. On the other hand, the notch can reduce the effective section area of the specimen. For the inside notch, the effective section area is bigger than that for base notch and surface notch, resulting in the creep axial stress is smaller than that of other models. Compared to the base notch, the surface notch will generate a bigger concentration stress in notch tip due to the braze residual stress generated in filler metal, so the creep axial stress of surface notch is bigger than that of base notch. Therefore, the creep axial stress for the surface notch is biggest while the creep axial stress for the inside notch is smallest. Because the creep axial stress of surface notch is bigger than that of inside notch and base notch, the creep failure time of surface notch is smaller than other notches. The creep failure time has an inverse relationship with creep axial stress. For the surface notch, the creep axial stress is the maximum which locates at notch tip. So the brazed joint with surface notch is easier to generate creep failure at notch tip.

3.2. Effects of the location of base notch

In order to investigate the effects of the base notch location on creep damage, keeping other parameters the same, five different brazed joints with different base notch distances (H = 1, 2, 3, 4 and 5 mm) were studied. The external load is 120 MPa. Fig. 7 shows the creep damage contours for different base notch distances. The maximum creep damages in the five models reach 0.99, but their positions are different. As the notch distance is smaller than 3 mm, the maximum creep damage locates at the center of filler metal. As the notch distance is bigger than 3 mm, the maximum creep damage locates at notch tip. As the notch moves gradually away from filler metal, the creep damage in filler metal becomes smaller and

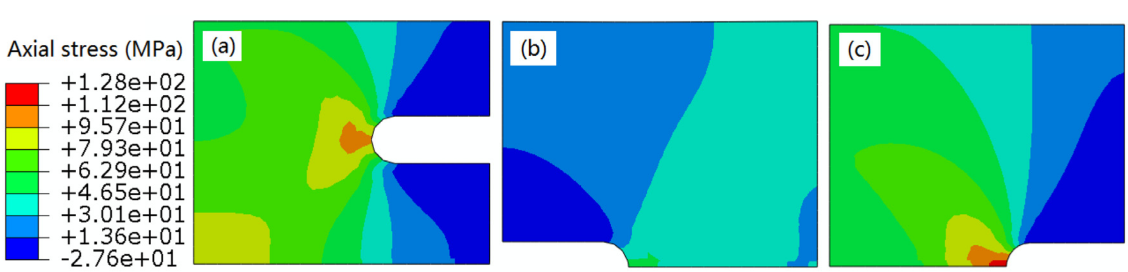

Fig. 6. The contour of creep axial stresses for base notch (a), inside notch (b) and surface notch (c).

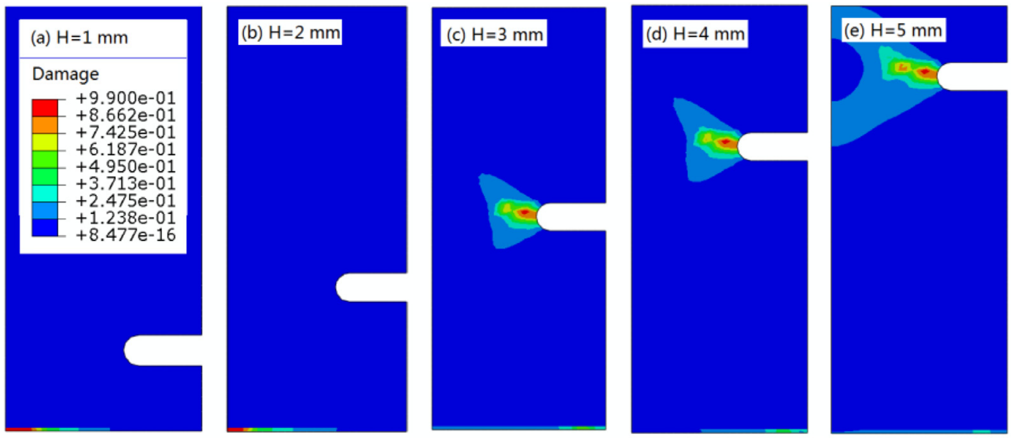

Fig. 7. Contours of creep damage for base notch with different notch distances.

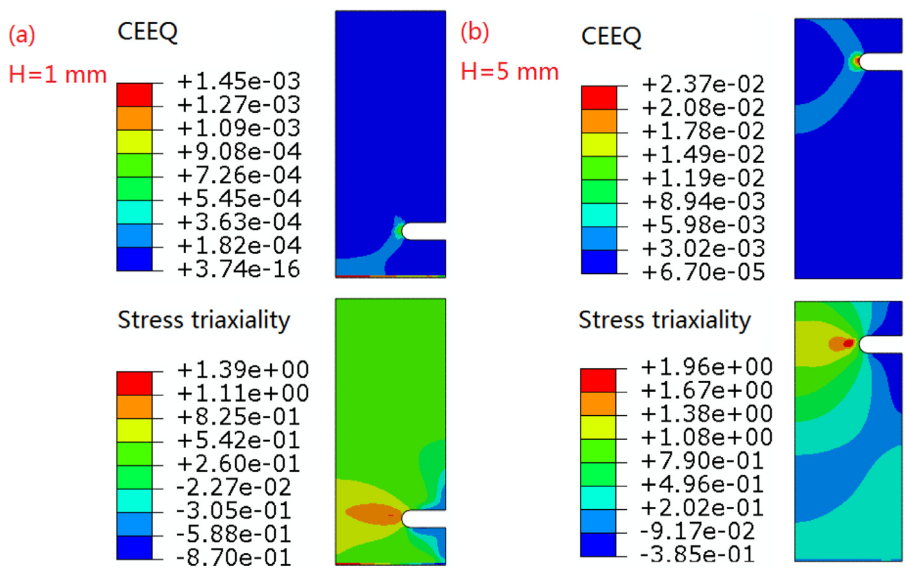

Fig. 8. Contours of CEEQ, stress triaxiality and micro-crack damage parameter for base notch with H = 1 (a) and 5 mm (b).

smaller. As the notch distance increases from 1 to 5 mm, the maximum creep damage in the filler metal decreases from 0.99 to 0.37. It indicates that the notch far away from filler metal is beneficial to reduce the creep damage of the filler metal.

Fig. 8 shows the contours of equivalent creep strain (CEEQ) and stress triaxility with H = 1 and 5 mm. The maximum CEEQ and stress triaxility with H = 1 mm were 0.00145 and 1.39, respectively, which all locate at the center of filler metal. However, as H is 5 mm, the maximum CEEQ (0.0237) locates at notch tip, while the maximum stress triaxility (1.96) locates at about 0.3 mm away from notch tip. The notch distance has a great influence on the distribution of CEEQ and stress triaxility. Bigger H will lead to the maximum CEEQ and stress triaxility moving from filler metal to base metal. According to Eqs.(4–5), the creep damage is determined by CEEQ and stress triaxility. The maximum creep damage was generated in the area with the maximum CEEQ and stress triaxility. Therefore, the maximum creep damage locates at the center of filler metal for smaller H, while it is at notch tip for bigger H, as shown in Fig. 7a and e, respectively.

Fig. 9 shows the damage evolution with time for base notch with different H. The creep failure time increases as H increases. The failure time increases from 264 to 3577 h as H increases from 1 to 3 mm. However, the creep failure time increases only by 27 h as H increase from 3 to 5 mm. The creep damage evolution curve

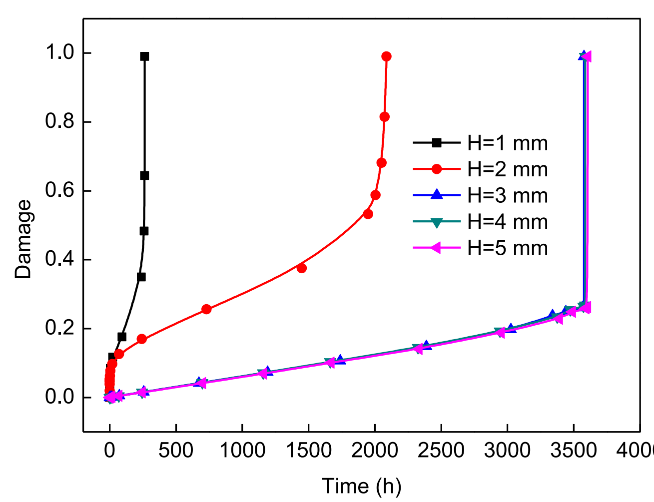

Fig. 9. Damage evolution with time for base notch with different notch distances.

and creep failure time are almost the same as H is bigger than 3 mm. Fig. 10 presents the variation of creep failure time and maximum creep axial stresses with different H. The failure time has

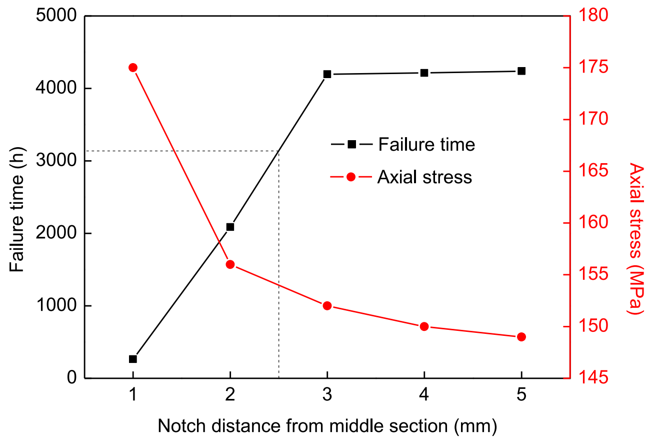

Fig. 10. The creep failure time and maximum creep axial stresses for base notch with different notch distances.

an inverse relationship with the creep axial stress. As H increases from 1 to 5 mm, the maximum creep axial stresses decreases from 175 to 149 MPa while the creep failure time increases from 264 to 3604 h. The larger creep axial stress concentrating at notch tip results in larger creep strain rate. For H=1 mm, the creep axial stress is the maximum resulting in the smallest failure time. Therefore, the creep damage failure is easier to generate for smaller H due to the larger creep axial stress. The base notch position has a great effect on the creep damage of brazed joint. Comparing to smaller H, the brazed joint with bigger H is not easy to generate creep failure. The further base notch distance is helpful to reduce creep damage in filler metal and enhance creep life of brazed joint.

Based on the above analysis, there may be a critical H between 2 and 3 mm, which determines the failure location changing from the center of filler metal to notch tip. Thus, we performed creep damage analysis on another four models with H = 2.2, 2.4, 2.6 and 2.8 mm respectively, and their results are shown in Fig. 11. As H increases from 2.2 to 2.8 mm, the creep failure location moves from filler metal to base metal and the failure time increases from 2858 to 4180 h. Especially for H = 2.4 mm, the maximum damage locates at the center of filler metal and the damage value at the notch tip has been 0.82. However, for H = 2.6 mm, the maximum damage all locates around the notch tip. It illustrates that the creep failure location moves gradually from filler metal to base metal as H increases from 2.4 to 2.6 mm. Therefore, we can assume that the critical distance is around 2.5 mm, which determines the failure location shifting from filler metal to base metal. Because the round bar radius is also equal to 2.5 mm, the critical distance is equal to the radius of round bar. The bar radius have a crucial influence on creep failure location of bar specimen with base notch. If H is smaller than the bar radius, the maximum damage generates in the center of filler metal; otherwise, the maximum damage generates at notch tip. The base notch with distance below the bar radius is easier to generate creep failure.

3.3. Effects of inside notch dimension

Due to the manufacture effects, some defects maybe exist inside the brazed joints [27]. Different inside notch dimension may have different effects on creep damage. Fig. 12 shows the creep damage contours of inside notch with different notch lengths (L = 0.2, 0.5, 0.8, 1.0 mm) and widths (W = 0.2, 0.5, 0.8, 1.0 mm). A external load 150 MPa is applied. It shows that the notch length has no effects on creep failure location which all locates at notch tip, while different notch widths generate different creep damage distributions. The maximum creep damage locates at notch tip for the width 0.2 mm. As the notch width increases to 0.5 mm, the maximum creep damage locates at about 0.5 mm away from notch tip. For the width are 0.8 and 1.0 mm, the maximum creep damage position moves to 2.0 mm away from notch tip.

Fig. 13 shows the damage evolution curve with time for the inside notch with different notch lengths and widths. The failure is easily generated for longer inside notch. As the notch length increases from 0.2 to 1.0 mm, the failure time decreases from 19 527 to 129 h. The creep failure time decreases as notch length increases, while it increases as notch width increases. As the notch width increases from 0.2 to 1.0 mm, the failure time increases from 19 527 to 54 944 h. The damage evolution curve and creep failure time for the inside notch with width 0.8 and 1.0 mm are almost the same. It indicates that there is a critical peak width to determinate the smallest failure time.

Fig. 14 shows that the variation of maximum creep axial stresses at notch tip for inside notch with different notch lengths and widths. The maximum creep axial stresses increases from 75.8 to 100 MPa as the notch length increases from 0.2 to 1.0 mm. The creep axial stress is the main reason to induce creep damage. Therefore, the creep damage failure occurs quickly for longer inside notch. Opposite to the effects of notch length, the maximum creep axial stresses decreases from 75.8 to 72.5 MPa as the notch width increases from 0.2 to 1.0 mm. Therefore, in the case of same notch length, the smaller notch width is easier to generate failure. Because the creep axial stresses for the notch width 0.8 and 1.0 mm are the same, the creep failure time is also almost the same. Therefore, the critical peak width is 0.8 mm, which is four times as the notch length (0.2 mm). If the notch width is bigger than the critical width, the effects of notch width will not change.

3.4. Discussion

Based on above analysis, we can see that the notch location and dimension have a great influence on the creep damage distribution of brazed joints. For the brazed joints, the notch will bring a multiaxial stress state around the notch tip, which will result in a different creep rupture life. The multiaxial stress state is a function of the notch geometry and material property [33]. Creep life at multiaxial state stress is generally defined by the representative stress (σ_{rep}) [34]. The representative stress is defined as the stress applied in the uniaxial plain bar specimen which has the same life as the notched bar specimen. The material is found to show a notch weakening effect if σ_{rep} is higher than net applied stress, whereas notch strengthening effect if σ_{rep} is lesser than net applied stress [34]. This representative stress under multiaxial state of stress is generally defined by combination of the maximum principal stress and the Von Mises stress which proposed by Hayhurst based on the plasticity controlled creep cavity growth mechanism [35]:

$$\sigma_{rep} = \alpha\sigma_1 + (1-\alpha)\sigma_{eq} \tag{7}$$

where α, σ_1 and σ_{eq} are material constants, first principal stress and Von Mises equivalent stress, respectively.

The von Mises stress mainly governs the plastic deformation and creep cavity nucleation, while the hydrostatic stress and maximum principal stress mainly controls the continuum intergranular cavity growth [35]. As the increase of Von Mises stress, the ability of deforming plastically decreased leads to the reduction of creep rupture ductility. Goyal et al. [9] and Lan et al. [36] concluded that the creep life decreases with the increases of notch acuity ratio because of the reduction of creep rupture ductility. Fig. 15 shows the maximum principal and Von Mises stress along the normalized distance from notch tip with different notch position. Both the maximum principal and Von Mises stress decrease gradually away from notch tip. Both the maximum principal stress and Von Mises stress of surface notch are bigger than those of base notch

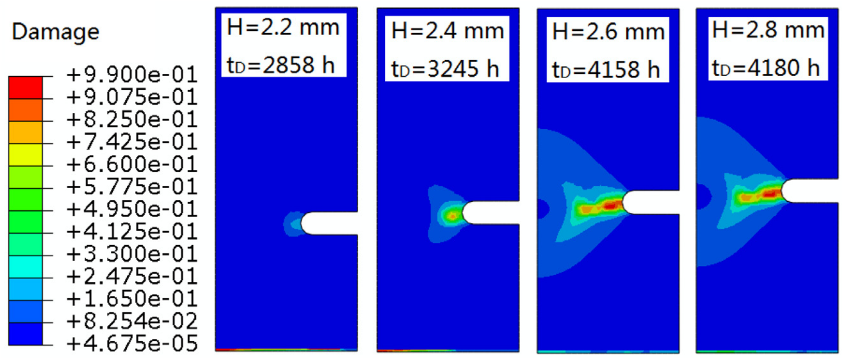

Fig. 11. Contours of creep damage for base notch with different notch distances.

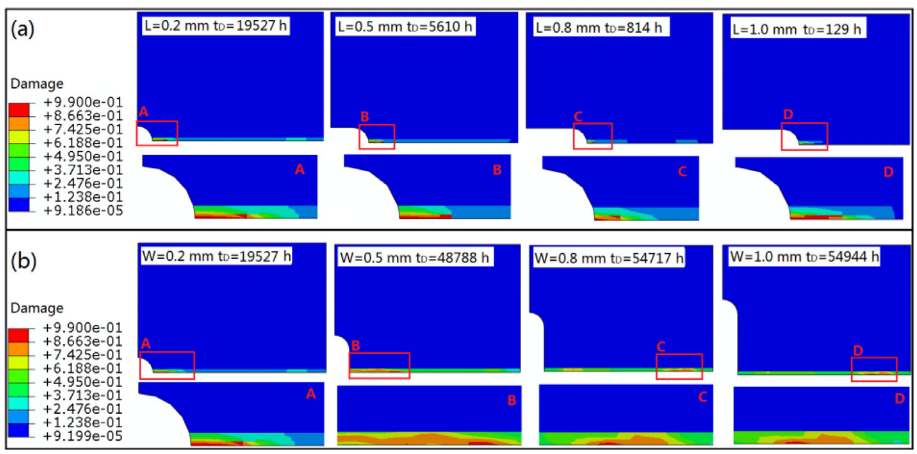

Fig. 12. Contours of creep damage for inside notch with different notch lengths (a) and widths (b).

and inside notch. So the nuclear and growth rate of creep cavities for the surface notch are bigger than those of the base notch and inside notch. Because that the creep crack is mainly caused by the creep cavities, nucleation, growth and mirco-crack interaction [37]. First, the creep cavitation proceeds with the nucleation of creep cavities at grain boundary. Then, the creep cavities grow gradually with time, resulting in many discrete cracks at grain boundary. As this discrete crack grows gradually, it leads to the final fracture of brazed structure. Hence, the creep life of the surface notch is smaller than the others, as shown in Fig. 4.

In this paper, we also concluded that the brazed joints with different base notch location and inside notch dimension show different creep failure behavior. This is a result of different stress concentration and triaxiality generated at notch tip. Wang et al. [38] also pointed that the initial crack positions have a great influence on creep failure behavior of welded joints due to the different creep strain and stress triaxiality distribution, which is consistent with our results. For the base notch, the creep failure life increases with notch distance increases. If the notch distance is smaller than the bar radius, the creep life has a proportional relationship with notch distance. The maximum creep damage locates at the center of filler metal because the maximum CEEQ and stress triaxiality also locate at center of filler metal. Fig. 16 shows the maximum principal and Von Mises stress at notch tip for base notch with different notch distance. It shows that the base notch distance has a great effect on stress distribution of notch tip. With the increase of notch distance, the maximum principal and Von Mises stress all decrease firstly and then remain stable. According to the multiaxial creep rupture theory described above, the rate of creep cavities nucleation and growth for shorter notch distance are bigger than that of longer notch distance. As shown in Fig. 16, the critical base notch distance is 2.5 mm. As the notch distance is larger than 2.5 mm, the maximum principal and Von Mises stress will not decrease but remains stable. Once the notch distance exceeds the radius of bar specimen, the base notch distance has no obvious influence on creep life because of the steady stress distribution at notch tip. The brazed component containing the notch near to filler metal is easy to generate creep failure comparing with the faraway notches. We should avoid the notch generated in filler metal or near the filler metal because smaller notch distance will increase the creep damage of filler metal and reduce the creep life.

Compared with base notch, the inside notch is not easy to generate creep failure. But some avoids existed inside of brazed structure may bring a different rupture mechanism. Leinenbach et al. [23] point that defects generated during brazing such as pores or incomplete gap filling may arise and act as stress concentrations, leading to crack growth and spontaneous failure. The creep life increases with notch width increases while it decreases with notch length increases. The effects of notch length are larger than the notch width because the notch length will directly influence the reduction of plasticized load area. Fig. 17 shows the effects of notch length and width on maximum principal and Von Mises stress in notch tip. The Von Mises and maximum principal stresses increase as notch length increases, which results in a decrease of creep life, as shown in Fig. 16a. However, the Von Mises and maximum principal stresses all decrease firstly and then keep stable as notch width increases, as shown in Fig. 16b. As the notch width increases to 0.8 mm, the nucleation and growth of creep cavities controlled by Von Mises stress and maximum principal stress keeps stable, which leads to the unchangeable creep life.

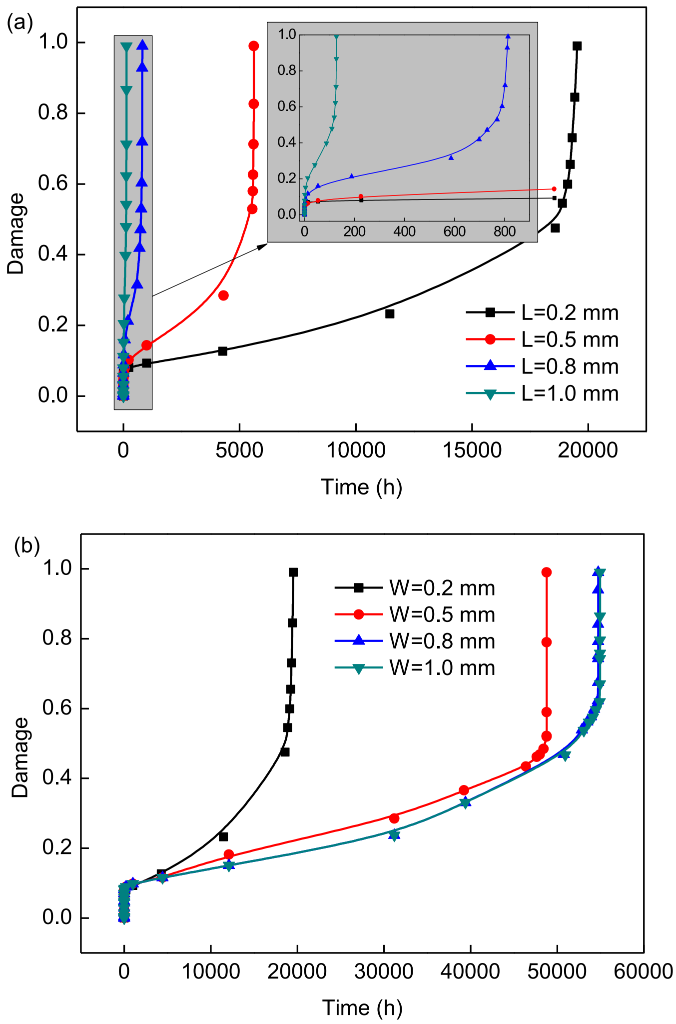

Fig. 13. Damage evolution with time for inside notch with different notch lengths (a) and widths (b).

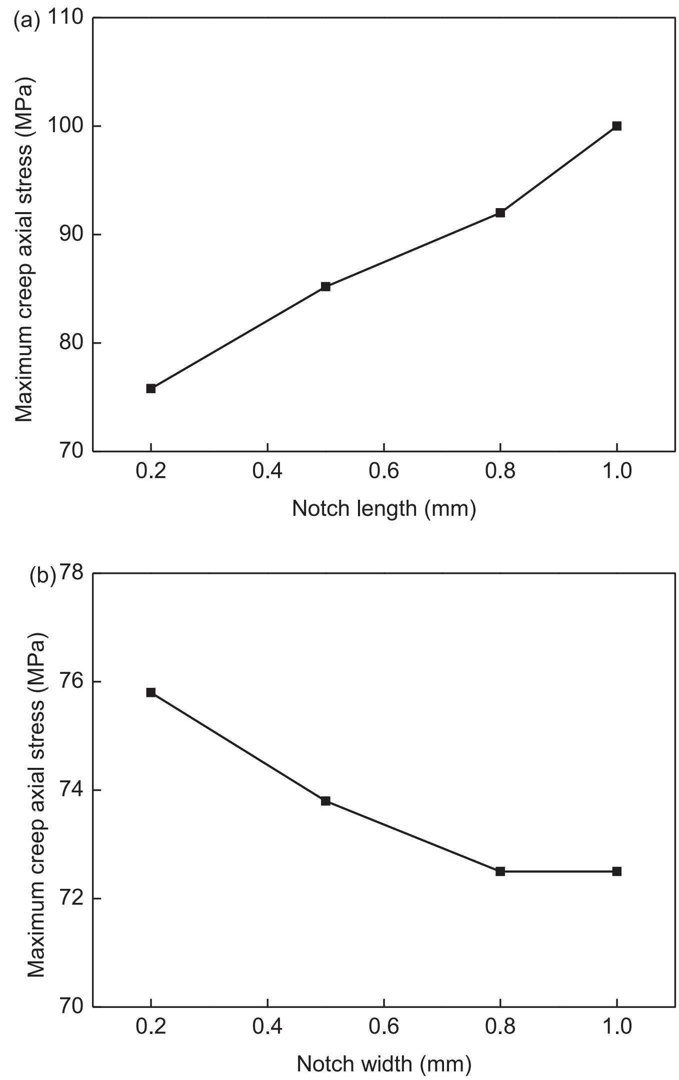

Fig. 14. The maximum creep axial stresses for inside notch with different notch lengths (a) and widths (b).

Overall, the notch position and dimension have a great influence on the creep damage distribution of brazed joint. During brazing, some brazing defects may generate in the filler metal or base metal, inside or surface, etc. This geometrical discontinuities or flaws like fillets often work as notches. So we should build a more precious and comprehensive assessment standard according to different notch type, position and dimension to evaluate the brazed structure containing defects. For example, if the creep life of brazed components is predicted only based on surface notch or base notch, the result is conservative. If the creep life is predicted only based on inside notch, the predicted result is overestimated. Moreover, different notch dimensions have different creep damage distributions. Therefore, the prediction of creep failure life should be based on different notch type, position and dimension. In creep failure analyses and life assessments of brazed joints, the effects of defect position and dimension should be fully considered.

4. Conclusions

This paper studies the effects of notch position on creep damage of brazed joint by continuum creep damage theory and ductility exhaustion damage model. The effects of notch dimension were also investigated. The main results obtained are as follows:

(1) Different notch position generates different creep damage distribution and creep failure time. The creep failure most likely happens for a surface notch, and the next is base notch. The inside notch is not easy to generate creep failure.

(2) The base notch location has a great influence on the creep damage distribution. If the base notch distance is smaller than the specimen radius, the maximum creep damage locates at the center of filler metal and the failure time increases as the notch distance increases. Otherwise, the maximum creep damage locates at the notch tip and the failure time almost keeps the same. The base notch with distance below the specimen radius is easier to generate creep failure. The notches locating in base metal and far away from filler metal are helpful to decrease the creep damage in filler metal and improve the creep life of brazed joint.

(3) The inside notch dimension has a great influence on creep damage. With the increase of inside notch length, the failure time decreases gradually and the maximum creep damage locates at the notch tip. However, with the increase of inside notch width, the failure time increases and the creep failure location moves away from notch tip gradually. As the notch width reaches four times as the notch length, the failure time and location keep the same.

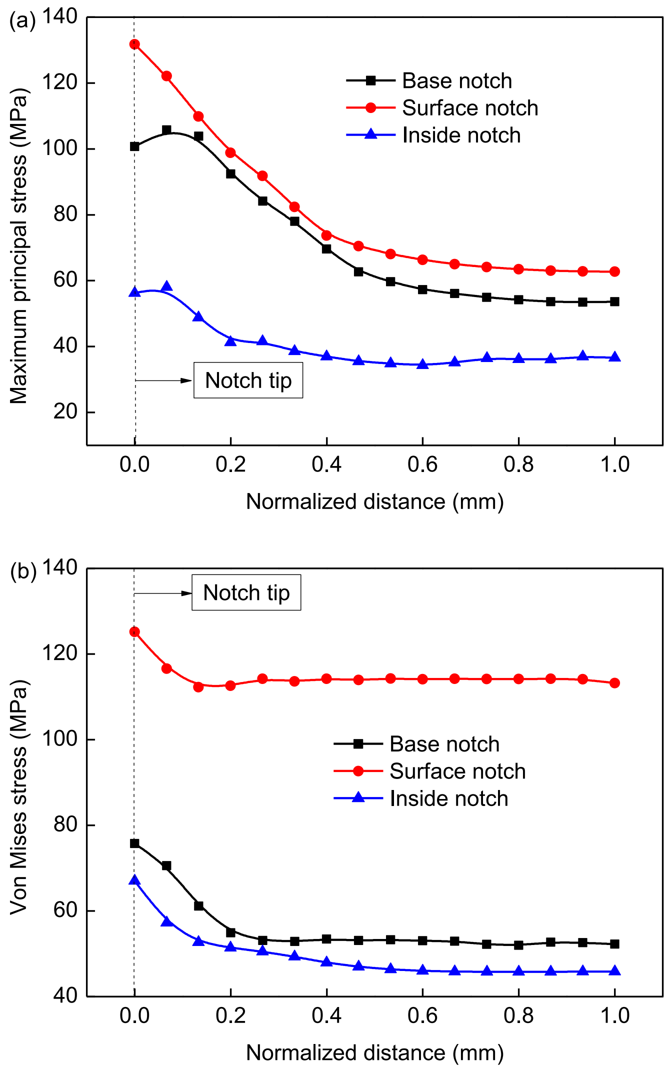

Fig. 15. The maximum principal stress (a) and Von Mises stress (b) along the normalized distance from notch tip for different notch positions.

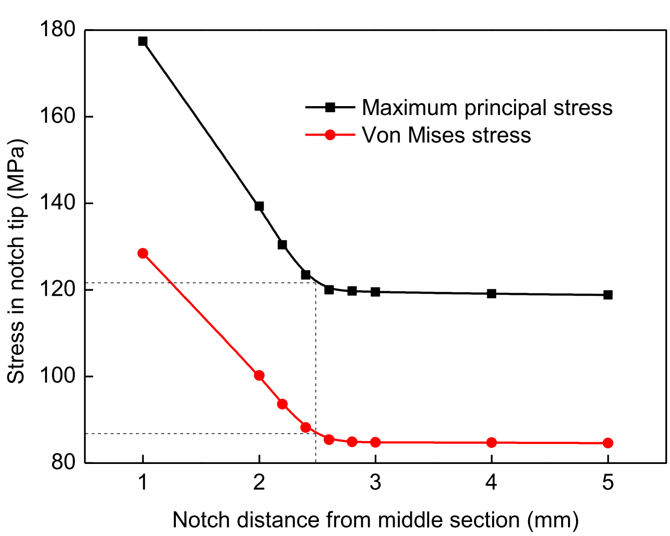

Fig. 16. The maximum principal and Von Mises stress in notch tip for base notch with different notch distances.

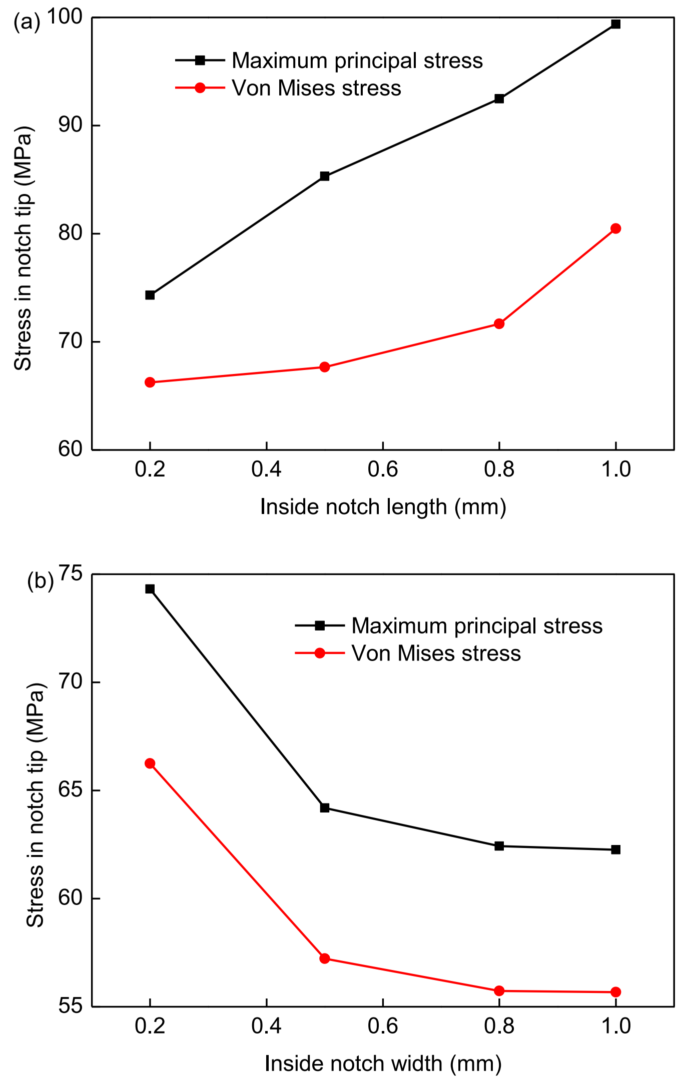

Fig. 17. Effects of notch length (a) and width (b) on maximum principal and Von Mises stress in notch tip.

Acknowledgments

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