Assessment of High-temperature Component Containing Multiple Flaws

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Abstract—Multiple flaws are often found in many high-temperature components. The interaction of multiple flaws may significantly affect the service life of high-temperature components. Flaws re-characterization rules for multiple flaws have been proposed in ASME and BS7910. However, most rules are formulated according to the elastic fracture parameter. Due to the different failure mechanism among linear-elastic stress conditions, elastic-plastic conditions and high-temperature creep conditions, the interacting behavior of components containing multiple flaws is also different. Therefore, it is important to investigate the interacting behavior of multiple flaws under high-temperature creep conditions. In the current work, the high-temperature creep fracture parameter is calculated for a plate containing multiple flaws by using the finite element analysis (FEA) under the tensile load. Based on these analyses, the new re-characterization rules are proposed to exclude the non-conservativeness caused by the current re-characterization rules in high-temperature creep conditions for heat-resistant steel. The coalescence rule for collinear cracks is \( S \leq 2.5a \), and the parallel cracks can be treated as collinear cracks for all distance \( S \) when the equation \( h \leq a \) is satisfied.

1. INTRODUCTION

The structural integrity of high-temperature components should be evaluated by considering the influence of flaws, which can greatly affect the reliability of these components. A single flaw may be safe, but multiple flaws may significantly decrease the damage tolerance of these components. Structural failure usually occurs as a result of interaction of these flaws.

The interacting behavior of components with multiple flaws under linear-elastic conditions and elastic-plastic conditions has been widely investigated [1-4]. In many fitness-for-service codes, such as ASME [5] and BS7910 [6], multiple discrete flaws are re-characterized and treated as a single flaw.
when some rules are satisfied. However, most re-characterization rules are proposed according to elastic fracture regime and elastic-plastic fracture regime. These re-characterization rules have been pointed out to be non-conservative and so should be revised based on the high-temperature fracture parameter $C^*$ [7].

In this work, the high-temperature fracture parameter $C^*$ of flaws were calculated by using the finite element analysis (FEA). Because the interaction effect of two dissimilar flaws is less than that of two identical flaws, only cases of plates containing two identical flaws are taken into account herein. According to the analysis results, a new flaw re-characterization rule was proposed under high-temperature creep conditions.

2. FRACTURE PARAMETERS AND MATERIAL CONSTANTS

The strain and stress rate of response of materials undergoing high-temperature creep deformation is generally modelled by the following elastic-secondary creep constitutive relation.

$$\dot{\epsilon} = \frac{\sigma}{E + A\sigma^n}$$

(1)

Where $\dot{\epsilon}$ is the uniaxial strain rate, $\sigma$ is the uniaxial stress rate, and $E$ is the Young’s modulus, and $A$ and $n$ are the steady state creep coefficient and exponent, respectively. This constitutive equation has been successfully used for high-temperature creep deformation analysis.

Material used in this study is heat-resistant steel (1Cr10NiMoW2VNbN). High-temperature creep fracture data were obtained from constant load, uniaxial tensile creep tests at 600°C. The experiment results of the high-temperature creep tests are shown in figure 1.

![Figure 1. Uniaxial creep test between the load-line displacement and time under constant stress for heat-resistant steel at 600°C.](image)

The material constants of secondary creep constitutive relation (often known as Norton’s law) from high-temperature creep tests of smooth bar specimens was fitted by the least-squares method. The results fitted could be written as follows:

$$\dot{\epsilon} = A\sigma^n = 1.167 \times 10^{-27} \sigma^{10}$$

(2)

The interaction coefficient $M_{\text{creep}}$ is defined as the ratio of the value calculated of $C^*$ around the crack tips between a plate with two flaws and a plate with a single flaw, subject to the identical remote tension. The equation can be described as follows.

$$M_{\text{creep}} = \frac{C^*_{\text{double}}}{C^*_{\text{single}}}$$

(3)

3.FINITE ELEMENT ANALYSIS

The ABAQUS software [8] is used to analyse the high-temperature creep fracture parameters from small-scale creep to steady-state creep conditions. In order to investigate the effect on the interaction of multiple cracks, two kinds of crack models were used for this analysis, as shown in figure 2. The first one contains two identical through cracks in the same plane. The distance between the cracks was
represented by parameter $S$. The other model contains two identical through cracks in the different plane. The offset distance between crack planes was represented by parameter $2h$. In order to remove the effect of exterior boundary, a sufficiently large plate was considered with height to width ratio $L/2W=1.5$ and $W/a=16$ in the current models. Under plane-strain conditions and identical applied load conditions, all the finite element analysis in the work were carried out.

Because of symmetry for collinear cracks, only a quarter of the finite element model was taken into account. The mesh adopted for this analysis consists of 1168 elements for collinear cracks, and consists of 6504 elements for parallel cracks, as shown in figure 3. To solve problems associated with incompressibility, eight-node reduced integration elements (CPE8R) are adopted for this finite element analysis. Near the crack tip area, extremely refine elements are generated, and degenerate elements are adopted by collapsing three nodes along one side into one initial point, while these nodes are allowed to displace independently under deformation.

![Figure 2. Two mechanical models: collinear cracks, parallel cracks.](image)

![Figure 3. Element mesh of collinear cracks and parallel cracks for FEA.](image)

Around crack tip, at least six $C^*$-integral contour integrations could be performed in the FE analysis. In general, the value of $C^*$-integral from the first contour is inaccurate, so the $C^*$-integral calculated in the current work was the average values of the rest of the five contour integral.

Actually the value calculated of interaction coefficient $M_{\text{Creep}}$ may be more accurate than the value of $C^*$ themselves. This is because the value of $M_{\text{Creep}}$ is the ratio of $C^*_{\text{Double}}$ and $C^*_{\text{Single}}$ calculated by finite element analysis by using similar meshes. Errors generated during calculation of these two parameters
respectively are likely to be counteracted when the value of $C_{\text{Double}}$ is divided by the value of $C_{\text{Single}}$. Thereby, the total error is reduced.

4. RESULTS AND DISCUSSIONS
Because of the different fracture mechanism among linear-elastic stress conditions, elastic-plastic conditions and high-temperature creep conditions, the crack driving force is also different. The crack driving force is generally characterized for component containing flaws by the stress intensity factor ($SIF$) in the linear elastic area, or by the $J$-integral in the elastic-plastic stress area, or by the $C^*$-integral in high-temperature creep area. Therefore, it is not appropriate to develop re-characterization rules of multiple cracks at high-temperature creep regime based on the stress intensity factor ($SIF$) and the $J$-integral.

In order to develop unifying principles, the rule based on increment of the crack growth rate is proposed in this work. Based on engineering experience and the current re-characterization rules, the two interacting cracks would be assumed to be a single crack when the maximum value of crack growth rate is 20 percent greater than the value of crack growth rate of a single crack.

Figure 4. Data graph between the interaction coefficient $M_{\text{Creep}}$ and distance $S$ for collinear cracks at the inner crack tip.

Figure 5. Data graph between the interaction coefficient $M_{\text{Creep}}$ and distance $S$ for different offset distance $h$ at the inner crack tip.

The relationship is shown in figure 4 between the interaction coefficient ($M_{\text{Creep}}$) and relative location for two collinear cracks. The interaction effect reduces as the distance $S$ increases. The interaction effect is negligible when the distance $S$ is far enough. The variations of the interaction coefficient at the inner crack tip are shown in figure 5. The value of interaction coefficient $M_{\text{Creep}}$ tends to reduce as the distance $S$ increases, when the distance $S$ is greater than 0. However, the value of
interaction coefficient is less than 1 when two cracks are overlapped (i.e. $S < 0$), which is caused by the stress shielding effect around cracks. The value of interaction coefficient $M_{\text{Creep}}$ reduces as the offset distance $h$ increases. It should approach unity when the offset distance $h$ is far enough. Namely, the interaction effect between two cracks would not being considered.

Essentially the steady state creep crack growth rate $\dot{a}$ can be correlated satisfactorily based on high-temperature fracture parameter $C^*$ by the relation:

$$\frac{da}{dt} = B(C^*)^q$$  \hspace{1cm} (4)

Where $B$ and $q$ are material constants which can be measured experimentally based on a creep zone model. For 1Cr10NiMoW2VNbN materials, $q$ is usually 0.7.

According to the rule of maximum crack growth rate above-mentioned and equation (4), a new cracks re-characterization rule can be obtained when 30 percent increase in creep fracture parameter $C^*$. This means that, when the interaction coefficient $M_{\text{Creep}}$ of two adjacent cracks is larger than 1.3, they would be re-characterized a big single crack under the creep regime. From the results shown in figure 4, when $M_{\text{Creep}}$ is equal to 1.3, which corresponds to $S/a=2.5$. Then the coalescence rule for collinear cracks is developed which is expressed as follows.

$$S \leq 2.5a$$  \hspace{1cm} (5)

Based on the same analysis, the rule for the offset distance $h$ is proposed for parallel cracks. From the results shown in figure 5, when $M_{\text{Creep}}$ is equal to 1.3, which corresponds to $h/a=1$. Then parallel cracks can be treated as collinear cracks for all distance $S$ when the two cracks are located in the following position.

$$h \leq a$$  \hspace{1cm} (6)

5. Conclusions
The high-temperature creep fracture analysis was conducted to determine cracks interaction effect for collinear cracks and parallel cracks. The interaction coefficient $M_{\text{Creep}}$ was evaluated so as to determine the relationship between the fracture driving force $C^*$ and distance among multiple flaws. Based on the relationship between increment of the crack growth rate and relative position, the re-characterization rules of multiple flaws associated with the distance $S$ and the offset distance $h$ at high-temperature creep conditions were proposed.

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