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The effect of discontinuous cracks on elastic and inelastic responses of fracture toughness and creep crack growth tests

Nak-Hyun Kim[a*], Gyeong-Hoi Koo [a], Yun-Jae Kim [b], Catrin M. Davies [c]
[a]*Korea Atomic Energy Research Institute, Daedeok-Daero, Yuseong-Gu, Daejeon, Korea*
[b] *Korea University, Department of Mechanical Engineering, Anam-Dong, Sungbuk-Ku, Seoul, Korea*
[b] *Imperial College London, Department of Mechanical Engineering, London SW7 2AZ, UK*
[*]*Corresponding author: nhk@kaeri.re.kr*

1. Introduction

Creep crack growth may occur in a discontinuous manner in relatively long-term, low-stress creep crack growth (CCG) tests [1]. When the applied (reference) stress is below yield, it has been observed that branching and discontinuous cracking may occur. Some examples of such discontinuous cracking are shown in Fig. 1. Figure 1 shows cracking in a relatively long term CCG on 316H stainless steel tested at 550℃. As test results are often interpreted using potential difference, elastic and elastic-plastic responses of a material, an error in potential difference and compliance measurements which may occur due to the crack discontinuity will result in estimating inaccurate crack lengths in the test specimen. Therefore, it is important to investigate the effects of discontinuous cracks on potential difference, elastic and elastic-plastic responses. In paper, potential difference, elastic and elastic-plastic responses are investigated for a C(T) specimen with discontinuous cracks using finite element analyses.

2. Geometry and FE analyses

2.1 Geometry

As schematically shown in Fig. 2, plane sided (i.e. not side grooved) C(T) specimens with a (a) single continuous crack and (b) two in-line discontinuous cracks were considered to investigate the effects of crack discontinuity on potential difference, elastic and inelastic responses. For all cases, the specimen width, W, was 50 mm. For single crack cases, the crack length, a, was varied from a = 25 mm to a = 31 mm. For discontinuous crack cases, the length of the main crack, a_1, was fixed to a_1 = 25 mm, whereas for the disjointed sub-crack, a_2, two different lengths of a_2 = 4 mm and 6 mm were considered. The distance between the main crack and the sub-crack, d, was varied from d = 0.5 mm to d = 7 mm.

2.2 Finite Element Analyses

Elastic and elastic-plastic numerical simulations were performed using the finite element software package ABAQUS v.6.11 [2]. Two-dimensional (2D) plane strain conditions were assumed in all simulations. Figure 3 illustrate a typical FE mesh for elastic and elastic-plastic analysis with discontinuous cracks. For both single and discontinuous crack cases, the crack-tips were designed with crack-tip elements (i.e. multiple nodes), and a ring of wedge-shaped elements was used at the crack-tip region for contour integral calculations. Eight-noded quadratic, plane strain elements with reduced integration points (CPE8R) were used and the small strain assumption was employed in the elastic and elastic-plastic analyses. Eight-noded biquadratic elements (DC2D8E) were used for potential difference analysis.

For the elastic FE analyses, the material was assumed to be isotropic with a Young's modulus and Poisson's ratio of E = 200GPa and = 0.3, respectively. For the limit load analyses, the material was assumed to be elastic, perfectly-plastic with the limiting yield strength of y = 200MPa. For the elastic-plastic analyses, the material was assumed to follow the Ramberg-Osgood model given by

$$\frac{\varepsilon}{\left(\sigma_y / E\right)} = \frac{\sigma}{\sigma_y} + \left(\frac{\sigma}{\sigma_y}\right)^n \qquad (1)$$

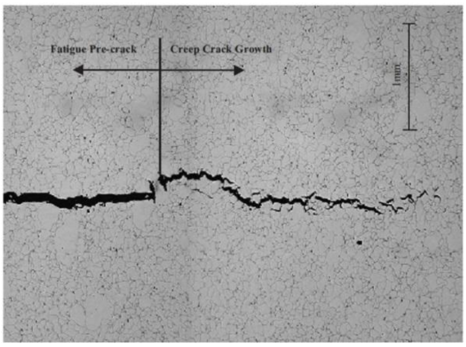

Fig. 1. Discontinuous cracks in creep crack growth tests on C(T) specimens of 316H at 550℃ for long term test.

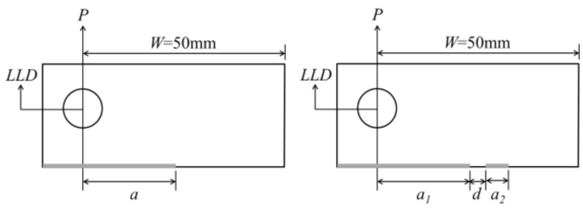

Fig. 2. Schematic illustration of a C(T) specimen containing (a) a single crack and (b) discontinuous crack.

3. Results

3.1 Elastic compliance

The elastic compliance, *C*, can be determined from knowledge of *a*/*W* using the following equation [3]:

$$C = \frac{1}{EB}\left(\frac{W+a}{W-a}\right)^2 \times \left[\begin{array}{l} 2.1630 + 12.219\left(\frac{a}{W}\right) - 20.065\left(\frac{a}{W}\right)^2 - \\ 0.9925\left(\frac{a}{W}\right)^3 + 20.609\left(\frac{a}{W}\right)^4 - 9.9314\left(\frac{a}{W}\right)^5 \end{array}\right] \quad (2)$$

where *B* is the specimen thickness. The crack length, *a*, can be determined from knowledge of compliance using the following equation [3]:

$$\frac{a}{W} = \left[\begin{array}{l} 1.000196 - 4.06319u + 11.242u^2 - \\ 106.043u^3 + 464.335u^4 - 650.677u^5 \end{array}\right]$$
$$u = \frac{1}{[BEC]^{1/2} + 1} \quad (3)$$

For the single crack cases (d = 0 mm) considered in these simulations, the elastic compliances predicted by FE analyses are in good agreement with those obtained from Eq. (2) (shown as dashed lines), as shown in Fig. 4. It can be seen in Fig. 4 that the values of a_{eq} are close to the main crack length a_1 = 25 mm for all discontinuous crack cases considered. These results suggest that the elastic compliance of a C(T) specimen with discontinuous cracks is determined mainly by the main crack and thus it would be difficult to detect the presence of the sub-cracks and their effective lengths using the elastic compliance.

3.2 Plastic Load-Line Displacement

Figure 5 shows the load-plastic load line displacement curves from elastic-plastic FE analyses. The plastic load line displacements from FE results are calculated from

$$\Delta_p = \Delta_t - \Delta_e \quad (4)$$

where Δ_t, Δ_p and Δ_e are total, plastic and elastic parts of the load line displacement (LLD), respectively. In Fig.5, FE results for single cracks of a = 25 mm, 25.50 mm and 29 mm are compared with those for the discontinuous cracks with a_1 = 25 mm, d = 1 mm and a_2 = 4 mm. Note that the crack length of a = 25.50 mm is the equivalent crack length of the C(T) specimen with the discontinuous cracks. The FE load-plastic load line displacement result for the discontinuous cracks is much more compliant than that for the single crack of the

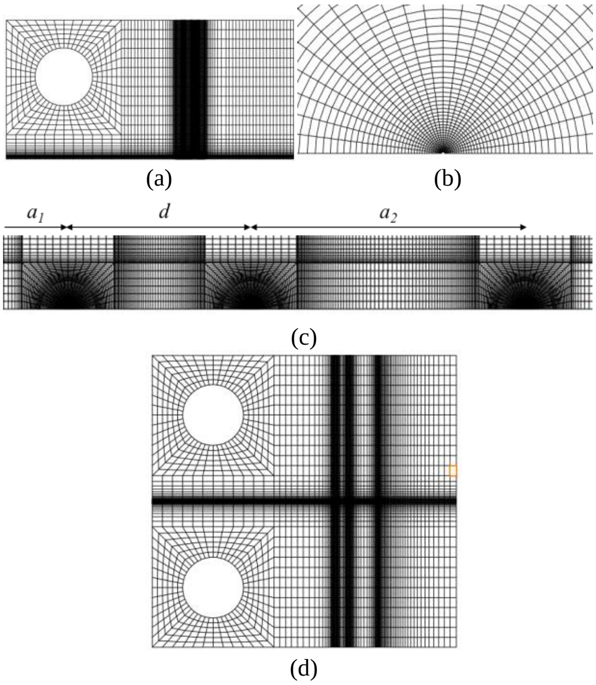

Fig. 3. Typical FE mesh of C(T) specimen with a discontinuous crack: (a) whole mesh for elastic and elastic-plastic analysis, (b) individual crack-tip mesh, (c) position of three crack tips, and (d) whole mesh for potential difference analysis.

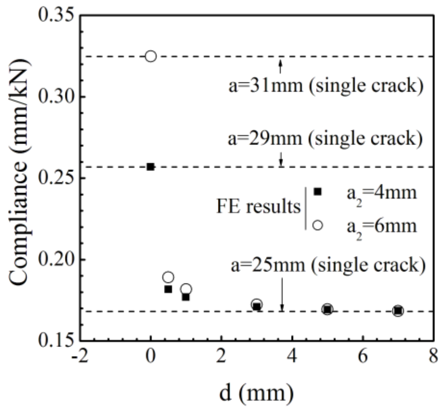

Fig. 4. Elastic compliances in a C(T) specimen containing single and discontinuous cracks (dashed lines are from Eqn. (2)).

equivalent crack length. In fact, it is in between those of the single crack of a = 25 mm and a = 29 mm. This suggests that the plastic responses for discontinuous cracks are affected by the sub-cracks, which is in contrast to the elastic response where the presence of the sub-crack has minimal effect on the elastic compliance.

3.3 Potential difference

The crack length, a, can be determined from knowledge of potential difference using the following equation [4]:

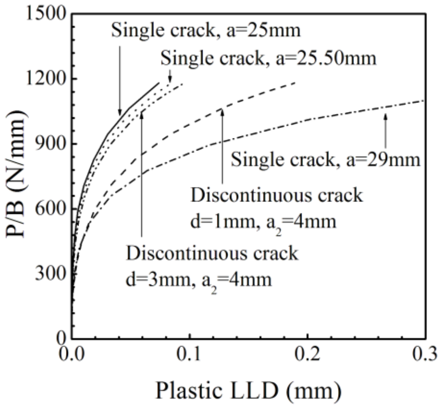

Fig. 5. FEA results for load-plastic load line displacement (LLD) curves.

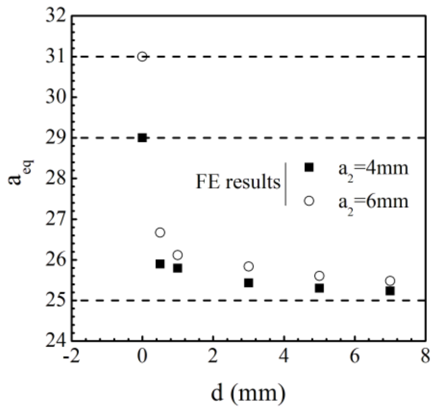

Fig. 6. Equivalent crack length in a C(T) specimen containing single and discontinuous cracks based on potential difference (dashed lines are from Eqn. (5)).

$$\frac{a}{W}=\frac{2}{\pi}\left[\begin{array}{l}\cosh\left(\pi Y_0/2W\right)/\cosh \\ \left[\dfrac{V}{V_0}\cosh^{-1}\left\{\dfrac{\cosh\left(\pi Y_0/2W\right)}{\cos\left(\pi a_0/2W\right)}\right\}\right]\end{array}\right] \qquad (5)$$

where a_0 is reference crack size with respect to the reference voltage, V_0; Y_0 denotes half distance between the output voltage leads; and V is output voltage. For the single crack cases (d = 0 mm) considered in these simulations, the crack length predicted by FE analyses are in good agreement with those obtained from Eq. (5) (shown as dashed lines), as shown in Fig. 6.

The FE results of potential difference for discontinuous cracks are also shown in Fig. 6. For discontinuous cracks, the equivalent crack length (corresponding to a single crack), a_{eq}, can be found by comparing FE results with Eq. (5). The values of a_{eq} are close to the main crack length a_1 = 25 mm for all discontinuous crack cases considered. Even for the cases that d = 0.5 mm, a_{eq} = 25.90 mm for a_2 = 4mm and a_{eq} = 26.67 mm for a_2 = 6 mm. These results suggest that the potential difference of a C(T) specimen with discontinuous cracks is determined mainly by the main crack and thus it would be difficult to detect the presence of the sub-cracks and their effective lengths using the potential difference.

4. Conclusions

This paper investigates the potential difference, elastic and elastic-plastic responses of a C(T) specimen in the presence of two-dimensional discontinuous cracks using FE analyses. Discontinuous cracks were modelled as two cracks, a main and a sub-crack. The distance between two cracks is systematically varied. For elastic responses, elastic compliance for discontinuous cracks is calculated and compared with those for a single crack. For elastic-plastic responses, plastic load line displacement has been compared with those for a single crack. For potential difference, equivalent crack length for discontinuous cracks are calculated and compared with those for a single crack.

Overall the FE results show that equivalent crack length from elastic compliance values and potential differences for discontinuous cracks are close to the single main crack length regardless of distance between the cracks and thus the presence of the sub-crack has minimal effect on the elastic compliance and potential difference. In contrast, it is found plastic load line displacement values for discontinuous cracks are more sensitive to the sub-cracks present ahead of the main crack tip.

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