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Evaluation of multiple cracks interaction effect subjected to biaxial tension under creep regime

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ABSTRACT

Under creep regime, the multiple cracks would remarkably deteriorate the service life of the component with respect to the case of a single crack due to the higher C^* values induced by the interaction and coalescence of the adjacent cracks. In this paper, the creep interaction effect of two identical coplanar surface flaws in a plate subjected to biaxial tension loads were calculated under various crack configurations, creep properties and biaxial stress ratios. The results revealed that the creep interaction level was greatly dependent on crack depth, crack distance, creep exponent and biaxial stress ratio whereas crack shape had little influence. In addition, the creep interaction factor determined by the average C^* values along the crack front could better represent the multiple cracks interaction under biaxial stress state. Finally, an empirical equation for the creep interaction factor was established on the basis of the comprehensive finite element analyses and the size of the equivalent single crack replacing the interacted multiple cracks should be determined by the creep interaction factor.

1. Introduction

In recent years, as the social demands for reducing greening house gas emissions and enhancing the efficiency of energy conversion increase, the higher service temperature coupled with the higher designed stresses have been widely applied in modern high temperature structures [1,2]. This increases the requirements of materials and the risks of structure failure due to the creep deformation occurring at the elevated temperature. During manufacturing process and subsequent service stage, defects which containing flaws, porosities, inclusions, cracks and etc., are always inevitable in these components, especially for the large structures and the welded components [3,4]. Thus, the assessment of components safety should take into account the influence of cracks, which can greatly affect the reliability of these components.

For dealing with postulated cracks in high temperature large structures and components in fossil power generation industry and process industry such as main steam pipes, super heater headers, reheater headers, turbine rotors, pressure vessels and so on, the remained life prediction approach on the basis of the time-dependent fracture mechanics has been developed and applied successfully to many high temperature structural components. The precision of predicted life is dominated by the various aspects, for example better material creep constitutive model, presence of welded joints, complex service conditions and in particular crack geometries [5,6].

The crack geometry mainly refers to the crack size, the crack depth, the crack distance and the number of the crack. Besides a single crack, more than one crack-like defects and flaws always simultaneously present in engineering structures [7–9]. These multiple cracks would interact each other and even coalesce during crack growth process and affect the stress and strain filed along the crack tip. Thus, the presence of multiple cracks would stimulate the creep crack growth rate and shorten the damage tolerance of the flawed engineering structures, which makes the assessment problem of the flawed structures become more complex. Hence, it is very crucial to consider the interacting effect induced by multiple cracks under creep regime.

In the current fitness-for-service (FFS) codes, i.e. BS7910 [10] and R5 [11], ASME BPVC (Boiler and Pressure Vessel Code) Section XI [12], ASME API579 [13] and JSME FFS code [14], the effects of multiple cracks are considered by replacing the multiple cracks with an equivalent single crack when the distance between two adjacent cracks meets a prescribed requirements. However, the studies of the references [15–18] remarked that the criteria for the replacement law extremely underestimated the remained creep life of the structures with flaws in some cases. Firstly, the difference of the crack configurations such as crack shape, crack depth and crack size has not been included in the combination rule. Masayuki Kamaya [8,15] investigated the interaction of two coplanar surface cracks with dissimilar sizes in a plate and revealed that the offset distance and the relative size of the multiple cracks also greatly affected the interaction level. The conservativeness in the prevailed FFS codes increased with the difference in crack size

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enlarging. Secondly, the current equivalent laws were developed on the basis of the comprehensive multiple cracks interaction analysis that were mainly conducted in the linear elastic or the elastic-plastic fracture regimes. However, at high temperature, the stress and strain fields not only depend on the applied stress, but also rely on the creep time. Si and Xuan [16] pioneeringly investigated the creep interaction effect caused by twin surface cracks under uniform tensile stress and proposed a creep interaction factor to represent the interaction level in creep regime. In addition, it was reported that the creep interaction level was obviously higher comparing with that occurring in the elastic or elastic-plastic deformation regimes. Xuan et al. [17,18] proposed a new C^* evaluation method for interacting cracks in plates under uniform tension and established a new combination rule of the interacted multiple cracks in creep process, which could provide more accurate predictions compared with ASME BPVC Section XI [12].

What's more, the biaxial stress states always are found to present in many components and structures. In particular, stress biaxiality caused by biaxial loads has a major influence on the stress concentration state and the fracture resistance, and then affects the crack driving force. Through biaxial tension-compression fatigue tests, Joshi [19] and Tanaka et al. [20] reported that the biaxial stress changed the crack growth behavior and the crack-growth rate was a function of nominal biaxial-stress condition in the crack-tip region. Yasumi and Akira [21] revealed that the crack propagation was greatly dependent on the stress state using the fatigue crack propagation tests under conditions of biaxial and uniaxial loading and found that the crack growth rate would be accelerated when a biaxial load stress ratio was minus while it became slow as the occurring of the plus biaxial load stress ratio. For the aim of characterizing the crack growth behavior, R. Hamam et al. [22] centered on the role of the T-stress on fatigue crack growth under the biaxial remote loading. Zeng and Dai [23] established a simplified analytical model for an inclined surface crack subjected to biaxial stresses and proposed a closed-form solutions to evaluate stress intensity factors under biaxial stress state. Singh ad Gope [24] investigated the effects of biaxial stress factor, position, crack size on stress intensity factors. Madia [25] proposed a reference load instead of the common limit load in terms of stresses with biaxial loads, which not only provided more exact fracture mechanics predictions, but also showed a wider and more general application range than the conventional parameters. Bhagat [26] studied the effect of two inclined cracks (parallel and non-parallel) under biaxial mixed mode condition and analyzed the role of the crack inclination angle on stress intensity factors. Therefore, investigation of the crack growth behavior under biaxial loading plays an important role in the structural integrity of flawed components.

For the aim of revealing the effect of the multiple cracks interaction on the structural integrity and the crack growth behavior, extensive studies have been conducted. However, the results for multiple cracks with biaxial stress state are still very limited, particularly in creep regime. The flaws in practical thin-walled structures and components such as pressure vessels and pipelines always are subjected to biaxial stresses, which leads to that the components are apt to fail at finite creep strain [27]. Li et al. [28] revealed that the effect of the biaxial stress could even change the creep mechanism and on the basis of the Eshelby equivalent theory, Li et al. [29] evaluated the interaction force during creep deformation. A good understanding of the multiple cracks interaction behavior with biaxial stress state in creep regime will provide a more accurate prediction and benefits to the safety assessment of the engineering high temperature components.

Hence, in the present paper, two coplanar surface cracks with the same size in a finite thickness plate subjected to remote biaxial loads are considered. The effects of the multiple crack interaction are evaluated using the high temperature fracture mechanics through comprehensive 3D finite element (FE) analysis. What's more, the specimens with a wide range of crack depths, crack shapes, crack distances and stress biaxiality ratios are conducted. Finally, a new re-

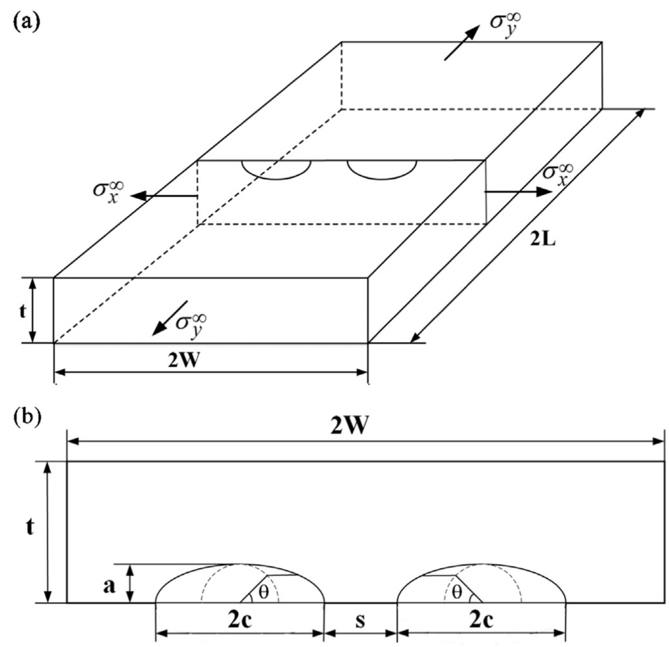

Fig. 1. Illustration of two identical semi-elliptical surface crack in a plate under biaxial stress.

characterization law of the interacted multiple cracks is proposed on the basis of the interaction analysis.

2. Finite element analysis

2.1. Finite element model

FE analysis has been conducted to evaluate the distribution of the high temperature fracture mechanics parameter for twin coplanar surface cracks with a semi-elliptical shape in a finite thickness plate subjected to biaxial loads. A schematic diagram of a 3D geometry with cracks and load conditions is shown in Fig. 1, where c is the half of the crack length, a is the crack depth and s is the distance between the adjacent cracks, θ is related to the locations of the front on the semi-elliptical crack surface, L and H is the half width and the half length of the plate, respectively and t is the thickness of the plate. For delimitating the influence of the specimen width and length on the calculated results, the length and width of the employed plate is assumed to be large in comparison to the thickness of the plate [30]. In addition, a remote biaxial tension load condition is applied to the plate, which is depicted in Fig. 1. The stress biaxiality λ is described by a biaxiality factor:

$$\lambda = \frac{\sigma_x^\infty}{\sigma_y^\infty} \tag{1}$$

where σ_y^∞ represents the remote uniform stress perpendicular to the crack and σ_x^∞ is the remote uniform stress parallel to the crack. In this paper, only positive λ values are employed, ranging from 0 to 1. It can be noted that $\lambda=1$ means that two equal remote uniform stresses are applied to the plate while $\lambda=0$ represents that a uniaxial remote stress is applied to the plate.

The interaction effect induced by multiple cracks with different crack shapes, crack depths, crack distances and biaxial stresses are taken into accounts. Thus, various crack shape ratios ($a/c=0.2,0.4,0.6,0.8,1$), crack depth ratios ($a/t=0.2,0.4,0.6,0.8$), crack distance ratios ($s/c=0.5,1,2,3$) and stress biaxiality ($r=0,0.25,0.5,0.75,1.0$) are employed. For all the cases, c is fixed and the size of the plate such as L and W also is fixed. As a result, the t and the c are varied according to the designed ratios of a/t and a/c. Both the