CHARACTERIZATION OF CREEP BEHAVIOR OF CRACK IN NON-HOMOGENEOUS MATERIALS

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ABSTRACT

A C^* integral estimation method is proposed for a crack located in the base or matrix material with mismatched mechanical properties from the other material. The method involves the definition of an equivalent stress-creep strain rate (ESCSR) relationship based on the mechanical properties of both the base and inclusion (welding) materials and the geometries of material system. The value of creep fracture mechanics parameter C^* is then estimated using the proposed ESCSR in conjunction with the reference stress (RS) method. Nonlinear finite element analysis of the models with various degrees of mismatch in creep behavior and different dimensions of inclusions or welding seam has been performed. Good agreement between the ESCSR method and the FE results provides confidence in the use of the proposed method in practice. It is found that the inclusion particles should be more “hard” than the matrix material in order to toughen the composite. However, there is a saturated point of creep property ratio of inclusions to matrix beyond which the creep property of the composite could hardly be improved.

1. INTRODUCTION

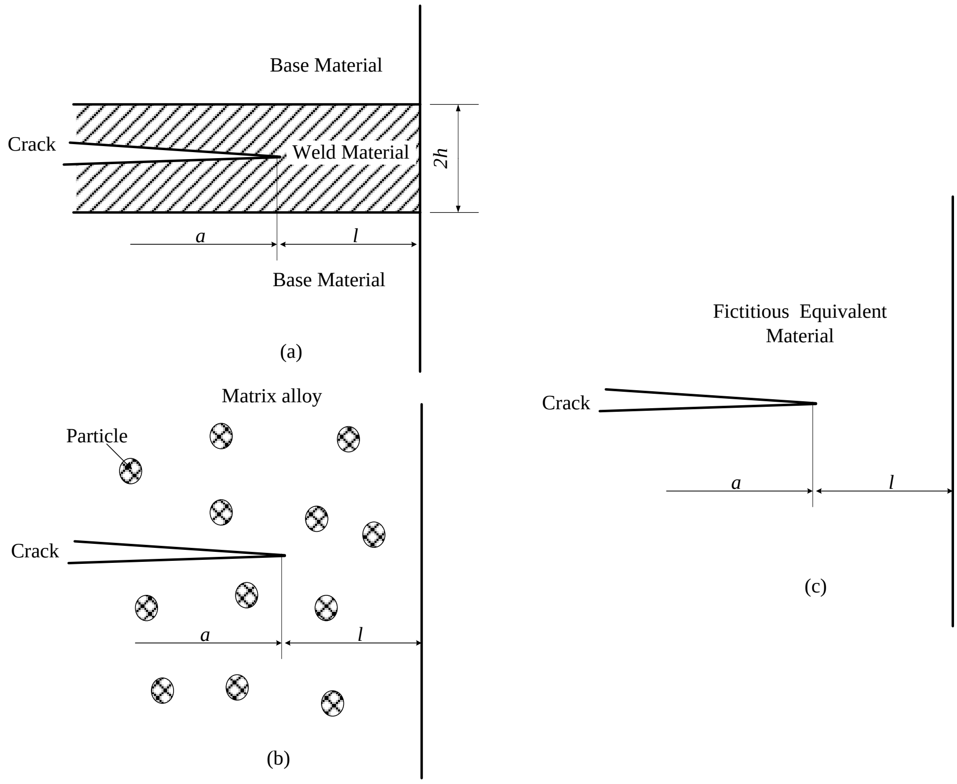
Composite materials have found more and more applications in high temperature engineering. Welded joints, on the other hand, makes possible the practical use of new materials. They are basically composed of two or more materials components. The non-homogeneity of the material system complicates the cracking behavior, particularly at high temperature. Many failure examples indicated that the material boundaries of composites or joints are the weakest links in the structures. The cracks are generally initiated in or in the vicinity of material boundaries. It is thus of importance to understand the cracking behavior in the non- homogeneous materials. In the last decade, research efforts have been taken to study the creep fracture of bi-material or composites containing interfacial defects [1 - 3]. There is the need to further identify time dependent fracture parameters that control creep crack growth (CCG). Large errors could result [4] if the homogeneous material fracture parameters were used for analyzing the behavior of cracks in bi-material. A modification of the conventional fracture parameters should be required [5]. From the design point of view, the optimized material composition can be helpful to improved the physical properties of the material system [6]. This should also be applied to the improvement of creep crack resistance of non-homogeneous materials.

The objective of the present paper is to provide some basic understanding concerning the creep crack behavior of non-homogeneous materials which include welded joints and particle reinforced composites. Mechanical modeling technique for the non-homogeneous material is developed. A simplified equivalent material model is firstly proposed. Finite element methods are used to verify the model and represent the random distribution of the second phase. The applicability of the contour integral and the strain energy density factor for the characterization of the creep crack behavior is discussed.

2. MODELLING TECHNIQUES

2.1 Equivalent material model

To evaluate the creep crack behavior in non-homogeneous materials, the concept of the equivalent homogeneous materials is introduced, which has the same geometrical dimensions as the original one but without any mismatch or reinforcements and thus it has different material properties. In the present work, two typical non-homogeneous materials, i.e, the mismatched bi-material weld and particle-reinforced metal-matrix composite as depicted in Fig. 1 (a) and (b), are investigated. The corresponding equivalent material model is shown in Fig. 1(c).



(a) Cracked mismatched bi-material weld; (b) Particle-reinforced metal matrix composite;
(c) Equivalent material model

Fig.1. Equivalent material model for cracked mismatched bi-material weld and particle-reinforced metal matrix composite

For a crack located in a weld with a mismatch in creep properties from the surrounding base metal, it is usually simplified as an idealized bi-material ‘sandwich’ structure without HAZ and residual stress, as shown in Fig. 1(a). Both base metal and weld metal under study are assumed to obey the elastic-power creep law with the same value of elastic modulus. Under the condition of long term creep state, the total strain in both metals is dominated by creep component and the plastic strain component is often negligible. The inelastic strain in both materials is then expressed as

$$\varepsilon_{\text{ine}} = \dot{\varepsilon}^c t = B_b \sigma_b^{\,n_b} t \tag{1}$$

$$\varepsilon_{\text{ine}} = \dot{\varepsilon}^c t = B_w \sigma_w^{\,n_w} t \tag{2}$$

where B_{b}, n_{b} and B_{w}, n_{w} are respectively the material constants for base metal and weld metal; t denotes the service time; Dots designate derivatives with time.

Accordingly, the constitutive equation of the corresponding equivalent homogeneous material with the same configuration as shown in Fig. 1(c) is [7]

$$\sigma_{eq} = \left(\frac{\dot{\varepsilon}^c}{B_b}\right)^{\frac{1}{n_b}} \left(\frac{M - F_{\mathrm{Lmis}} / F_{\mathrm{Lb}}}{M - 1}\right) + \left(\frac{\dot{\varepsilon}^c}{B_w}\right)^{\frac{1}{n_w}} \left(\frac{F_{\mathrm{Lmis}} / F_{\mathrm{Lb}} - 1}{M - 1}\right) \tag{3}$$

where F_{Lmis} represents the limit load for the mismatched weld; F_{Lb} is the limit load of the cracked homogeneous structure for base metal corresponds to the 0.2% proof stress ratio; M denotes the mismatch ratio and can be calculated by the following formulation for high temperature application

$$M = \left(\varepsilon_{\mathrm{ine}} / t\right)^{\frac{n_b - n_w}{n_b n_w}} (B_w)^{-\frac{1}{n_w}} (B_b)^{\frac{1}{n_b}} \tag{4}$$

Equation (4) indicates that the mismatch ratio M is a time dependent function at high temperature. For base metal and weld metal with the same value of creep exponent, $n_b = n_w$, M then reduces to a function of material constants which is independent of service time t.

For a crack located in a particle reinforced metal matrix composite, as shown in Fig. 1(b), the proposed equivalent homogenous material model with same geometrical dimensions and equivalent mechanical properties is applicable. Both reinforced particle and metal matrix under study are assumed to obey the elastic-power creep law with same Poisson’s ratio and different elastic modulus and creep properties. It is assumed the particles remain elasticity during the creep crack extending. According to the rule of mixture, the equivalent stress-creep strain rate relationship of the equivalent material model can be expressed by

$$\sigma_{eq} = \left[(1 - \varphi_p) + \varphi_p \frac{E_p}{E_m} \left(\frac{q - E_m}{q - E_p}\right) \right] \left(\frac{\dot{\varepsilon}^c}{B_m}\right)^{\frac{1}{n_m}} \tag{5}$$

where E_p and E_m denote the elastic modulus of particle and matrix, respectively; φ_p is the volume fraction of reinforced particle; B_m and n_m are the stress coefficient and stress exponent of metal matrix in power creep law; q is the distributive coefficient of stress-strain in composite and is defined by

$$q = \frac{\sigma_m - \sigma_p}{\varepsilon_m - \varepsilon_p} \tag{6}$$

In Eq (6), σ_p, ε_p, σ_m, ε_m denote the true stress and strain of particle and matrix, respectively.

The elastic modulus of the equivalent material model can be calculated by

$$E_{eq} = \frac{(1 - \varphi_p) E_m [(q - E_p)/(q - E_m)] + \varphi_p E_p}{(1 - \varphi_p)[(q - E_p)/(q - E_m)] + \varphi_p} \tag{7}$$

Now that the actual creep resistance in the weldment and composite is reflected by the equivalent stress creep strain rate (ESCSR) of a fictitious material (Fig. 1(c)), it is reasonable to assume that C^* can be estimated from previously developed methods for homogeneous materials but using the equivalent stress-creep strain rate relationship developed above.

Following Ainsworth [8], the steady state C^* integral for creep can be estimated on the basis of the reference stress (RS) approach

$$C^* = \sigma_{ref} \dot{\varepsilon}^c_{ref} (K / \sigma_{ref})^2 \tag{8}$$

where $\dot{\varepsilon}^c_{ref}$ is the creep strain rate at $\sigma = \sigma_{ref}$, determined from creep-deformation data for a material of interest, and K is the elastic stress intensity factor. The reference stress σ_{ref} is defined by

$$\sigma_{ref} = F\sigma_{0.2}^{T} / F_{\mathrm{L}}(\sigma_{0.2}^{T}, a) \quad (9)$$

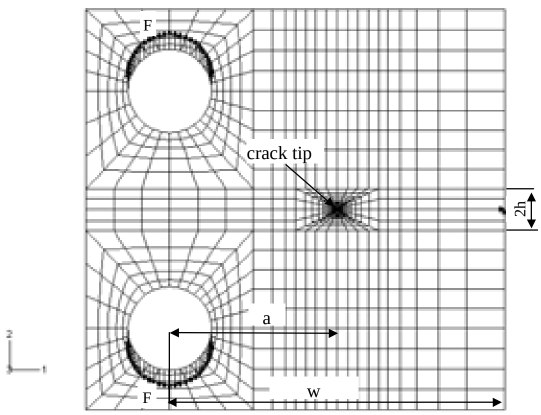
where F represents the magnitude of the applied load and F_L is the corresponding magnitude at plastic collapse for the proof stress $\sigma_{0.2}^{T}$ corresponding to 0.2% inelastic strain and crack size a. As F_L depends linearly on the proof stress $\sigma_{0.2}^{T}$, σ_{ref} does not depends on $\sigma_{0.2}^{T}$, and thus the choice of $\sigma_{0.2}^{T}$ does not affect C^* results.

2.2 Finite element model

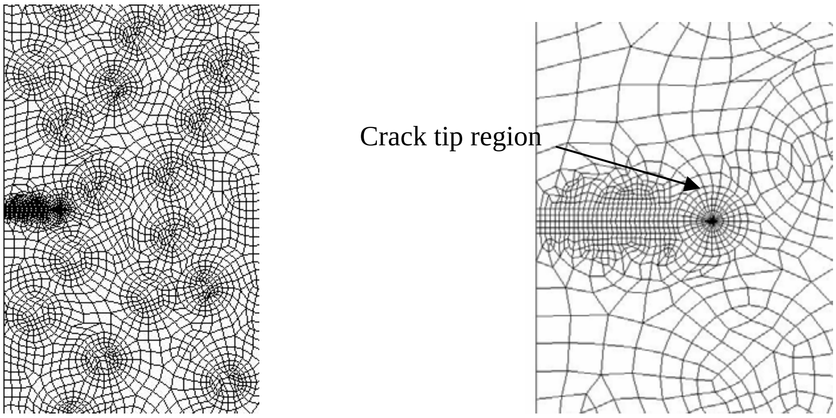
To investigate the creep behaviour of crack in non-homogeneous material, two cases are studied. The first is a crack located in a weld with a mismatch in creep properties from the surrounding base metal. The other is a crack located in particle randomly dispersed composite. The ABAQUS finite element code is used for analyzing the creep deformation and the fracture parameters from small-scale creep to steady state creep conditions. 8-node bi-quadratic reduced integration elements (ABAUQS element type CPE8R) were used (ABAQUS User's Manual, 1996). The specimen geometries to be examined are shown in Fig. 2.

For the welded CT specimen, the overall specimen width is 30 mm and height is 28.8 mm with a thickness of 13 mm, W= 24 mm and crack length of a =12 mm to make a/W= 0.5, and the width of welding seam 2h =2, 3, 4 mm, respectively. The static loads applied to the nodes at the upper half of the pin hole are taken as F=3000, 3920, 5000, 6000, 7000, 7500N, respectively. The node at the specimen end with the arrow heads is fixed as a boundary condition.

In the elastic-creep FE analysis, a mechanical load was firstly applied to the FE model using an elastic calculation at time t =0. The mechanical load was then held constant and subsequent time-dependent creep calculations were performed. For power-law creep, ABAQUS provides an in-built routine to calculate the C(t) integral which is again denoted as C^* under the steady state condition with time exceeding the redistribution time, t_{red}, (Kim, Kim JS and Huh et al, 2002). Total 48 cases were analyzed and C^* integral values were calculated on five contours surrounding the crack tip and average values are shown in Fig.5. The C^* values calculated at any contour differ by less than 5% from the average values.



(a) Finite element model for welded CT specimen a/W=0.5, 918 elements, 2941 nodes.
Note: the region marked 2h is the weld and the rest is base metal



(b) Finite element model for particle reinforced metal matrix SENT (single edge notched tension) specimen (3585 elements and 3973 nodes)

Fig. 2 Finite element mesh for typical non-homogeneous material specimen

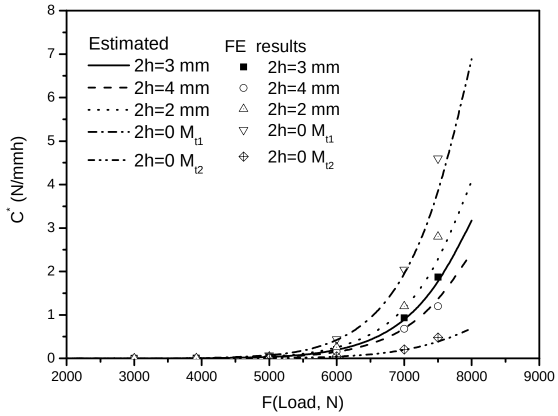
3. INFLUENCE OF MATERIAL MISMATCH ON CREEP CRACK BEHAVIOR

Four materials, denoted Mt1 to Mt4 in Table 1, with different creep coefficients and creep exponents have been chosen to address the influence of material mismatch on creep crack and examine the C^* estimation approach. The data of Mt1 and Mt4 are respectively those of 1Cr0.5Mo and 1.25Cr0.5Mo from the work of Yoon and Kim [9]. The other two materials are idealized to produce a range of stress-creep strain response.

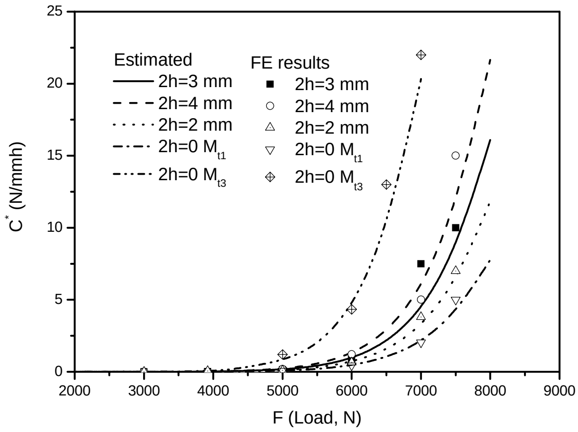
Table 1 Mechanical property utilized in C^* calculation

Materials	Stress-strain relationship	Elastic modulus E(MPa)	B (MPa^{-n}h^{-1})	n
Mt1	Elastic-viscosity	175E3	1.83E-24	9.03
Mt2	Elastic-viscosity	175E3	1.83E-25	9.03
Mt3	Elastic-viscosity	175E3	1.83E-23	9.03
Mt4	Elastic-viscosity	175E3	6.36E-23	9.36

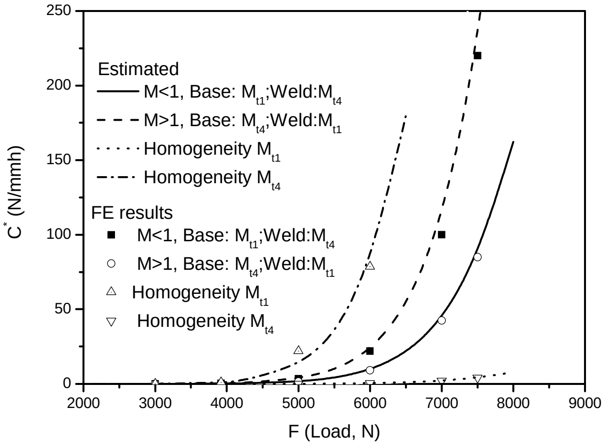
The C^* values estimated by the equivalent material method are depicted in Fig.3 and show good agreement with those calculated by the FEM for situations of both over-matching, Fig.3 (a), and under-matching, Fig. 3 (b). The cases considered cover variation in weld width h. In Fig. 3, all values of C^* of weldements are in between of the results of homogeneous structures made of base metal and weld metal and also affected by geometry of welding seam. For the weldments with smaller h, the value of C^* is closer to of homogeneous specimens for base metal than to of homogeneous specimens for weld metal. With the width h of welding seam increasing, the C^* of weldment is gradually nearing of homogeneous specimens for weld metal.



(a) M>1, Base metal: M_{t1}; Weld metal: M_{t2}



(b) M<1, Base metal: M_{t1}; Weld metal: M_{t3}



(c) 2h =3 mm

Fig 3 (a) Comparison between estimated C^* and that of FEM for overmatched cases; (b) Comparison between estimated C^* and that of FEM for under matched cases; (c) Comparison between estimated C^* and that of FEM for non power law materials of CT specimen with a/W=0.5

The influence of distribution of inclusion particles on the fracture parameters has also been evaluated. It is found that decreasing the minimum creep strain rate of inclusion particles is of help in reducing the crack driving force. This indicates that the inclusion particles should be more "hard" in order to toughen the composite. However, there is a saturated point of creep property ratio of inclusions to matrix beyond which the creep property of the composite could hardly be improved.

4. CONCLUSIONS

Creep behavior of crack in the vicinity of material inhomogeneity is examined by using the steady-state C* path independent integral and Ct for transient conditions. The conditions of material inhomogeneity is relevant to weldments and particle reinforced composites where the properties of base and weld materials, particles and matrix are known to have different creep properties. A C^* integral estimation method is proposed for a crack located in the base or matrix material with a mismatch in mechanical properties from the other material. The method involves the definition of an equivalent stress-creep strain rate (ESCSR) relationship based on the mechanical properties of both the base and inclusion (welding) materials and the geometries of material system. The value of creep fracture mechanics parameter C^* is then estimated using the proposed ESCSR in conjunction with the reference stress (RS) method where the reference stress is defined based on the plastic limit load. Nonlinear finite element analysis of the models with various degrees of mismatch in creep behavior and different dimensions of inclusions or welding seam has been performed. Overall good agreement between the ESCSR method and the FE results provides confidence in the use of the proposed method in practice.

It is found that the inclusion particles should be more "hard" than the matrix material in order to toughen the composite. However, there is a saturated point of creep property ratio of inclusions to matrix beyond which the creep property of the composite could hardly be improved.

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