



Modelling damage and creep crack growth in structural ceramics at ultra-high temperatures

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Abstract

A continuum damage model based on multiaxial ductility exhaustion of accumulated creep strains is proposed to predict creep crack growth (CCG) in structural ceramics at ultra-high temperatures where it is known that power law creep operates. The paper focuses on monolithic ZrB₂ ultra-high temperature ceramic (UHTC), for which a reasonable set of material creep data is available. The predominant deformation mechanism shown by ZrB₂ at temperatures greater than 1800 K and at stresses above 200 MPa is power law creep. Using the creep constitutive properties that have been found for this material, the proposed methodology is applied to a representative three-point bend geometry, which is planned to be tested. Relevant Fracture Mechanics parameters such as stress intensity factor, K , and steady state creep parameter, C^* , are evaluated and compared with available models. In this way the essential properties required to develop predictive damage simulations are investigated, underlining the importance of having accurate material test data.

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1. Introduction

Structural applications at ultra-high temperatures require materials with excellent thermo-mechanical and chemical stability. Examples of such applications include rocket nozzles and hypersonic leading edges. Among the most attractive candidate materials are the refractory diborides of zirconium and hafnium; a comprehensive review of their properties can be found in Ref. 1. In addition to their high melting temperature, high strength at high temperatures and excellent thermal shock resistance, nominally pure diborides show good oxidation resistance up to ~1500 K. In order to improve the resistance to oxidation above this temperature several additives have been extensively tested. The addition of silicon carbide as a second phase was found to promote the formation of an outer borosilicate glass layer, which reduces oxygen diffusion to the substrate thus improving oxidation resistance of UHTC diborides up to ~1900 K. Other additives are under study to further improving oxidation resistance of these compounds at higher temperatures. A review covering the oxidation behaviour of ZrB₂ and HfB₂ can be found in Ref. 2.

As these materials are required to operate at extreme temperatures under load, creep is another phenomenon that has to be considered.³ After some early investigations on ZrB₂ reported by Rhodes et al.⁴ back in 1970, the interest in creep has been recently growing.^{5–10} Researchers have focused on ZrB₂, with SiC contents in the range 0–30% in volume. The observed stress exponents suggest diffusion creep as the predominant deformation mechanism, in agreement with the relatively low applied stresses. At higher stresses and temperatures in excess of 1500 K, however, power law creep is expected to become the dominant deformation mechanism.¹¹

The present work aims to propose a continuum model to predict damage and creep crack growth under power law creep conditions. By making use of the available creep properties for monolithic ZrB₂ the methodology is applied to a three-point bend finite element (FE) model. Experiments on a similar geometry are being planned to confirm ZrB₂ creep properties and assess the predictive capability of the proposed methodology.

2. Fracture Mechanics under creep conditions

A creep curve, like the one shown in Fig. 1, can be used to describe creep deformation. It generally consists of three regions, namely the primary, secondary and tertiary creep

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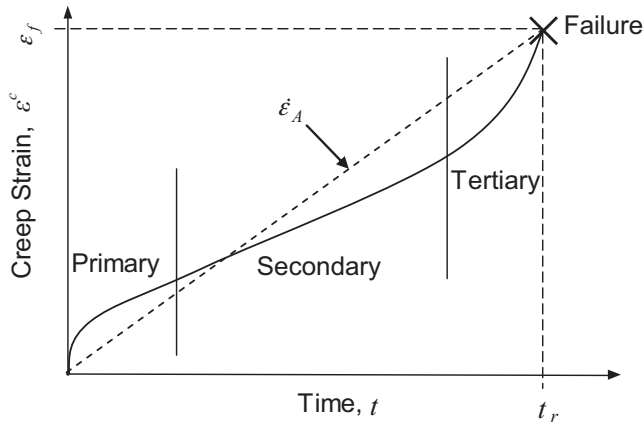


Fig. 1. Schematic for a creep curve showing definition of the average creep strain rate $\dot{\varepsilon}_A$.

regimes. The secondary region is also called steady state region and can be described using Norton's relation:

$$\dot{\varepsilon}_c = A\sigma^n \quad (1)$$

where $\dot{\varepsilon}_c$ is the steady state creep strain rate, σ is the applied stress, A is a temperature-dependent material constant and n is the power law creep stress exponent. Moreover, using an average creep rate the three stages of creep can be accounted in one formulation¹⁴:

$$\dot{\varepsilon}_A = A_A\sigma^{nA} = \frac{\varepsilon_f}{t_r} \quad (2)$$

where ε_f is the uniaxial failure strain and t_r is the rupture time in a uniaxial creep test. This approach is more relevant for ceramic materials as the exact form of the curve is not known.

Based on the creep properties of the material, the stress and strain rate fields in a cracked component can be evaluated as a function of the C^* creep parameter using the Hutchinson–Rice–Rosengren (HRR) equations^{15–17}:

$$\sigma_{ij} = \sigma_0 \left(\frac{C^*}{\dot{\varepsilon}_0 \sigma_0 I_n r} \right)^{1/(n+1)} \tilde{\sigma}_{ij}(\theta, n) \quad (3)$$

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}_0 \left(\frac{C^*}{\dot{\varepsilon}_0 \sigma_0 I_n r} \right)^{n/(n+1)} \tilde{\varepsilon}_{ij}(\theta, n) \quad (4)$$

where r is the radial distance from the crack tip, θ is the crack tip angle, I_n , $\tilde{\sigma}_{ij}$ and $\tilde{\varepsilon}_{ij}$ are non-dimensional functions of n and C^* is the steady state creep Fracture Mechanics parameter.

Further, C^* can be obtained experimentally from the displacement rate measured at the loading pin, also called load-line displacement rate (LLD) and denoted with $\dot{\Delta}$, using the equation¹⁸:

$$C^* = \frac{P\dot{\Delta}}{B_n b} F \quad (5)$$

where P is the applied load, b is the remaining ligament ahead of the crack, B_n is the net thickness and F is a factor which depends on crack length, sample geometry and creep stress exponent, n .

When creep displacement rate is not available, such as in components, C^* can be estimated from other methods. One way

makes use of the built-in feature provided by several commercial FE codes to calculate the $C(t)$ -Integral, which is a path and time dependent parameter similar to the J -Integral used in Non-linear Elastic Fracture Mechanics. Once steady state creep condition is established in the component, $C(t)$ becomes path independent and is denoted by C^* .

Another way of calculating C^* uses the reference stress approach, according to Eq. (6)^{12,19,20}:

$$C^* = \sigma_{ref} \dot{\varepsilon}_{ref}^C \left(\frac{K}{\sigma_{ref}} \right)^2 \quad (6)$$

where $\dot{\varepsilon}_{ref}^C$ is the reference creep strain rate corresponding to the reference stress, σ_{ref} . The reference stress is defined as

$$\sigma_{ref} = \sigma_Y \frac{P}{P_{LC}} \quad (7)$$

where P is the applied load, σ_Y is the material yield stress and P_{LC} is the corresponding collapse load of the cracked component.

Once steady state creep stress and damage distribution are present ahead of the crack tip,¹⁸ creep crack growth can be described by a law of the form:

$$\dot{a} = DC^{*\phi} \quad (8)$$

where D and ϕ are temperature dependent material constants, which can be based on an experimental crack growth law or can be estimated from uniaxial creep and rupture data using a model of the cracking process.¹⁴

Alternatively, when there is insufficient data to evaluate D and ϕ and experiments have not been performed, a remaining ductility exhaustion model, NSW, can be used^{14,21} to predict crack growth rate under plane stress/plane strain conditions. The form of the model suggests an inverse relationship between cracking rate and failure strain. An approximate form of the NSW model which is valid for plane stress and plane strain conditions, respectively, is given as

$$\dot{a} = \frac{3C^{*0.85}}{\varepsilon_f} \quad (9)$$

$$\dot{a} = \frac{90C^{*0.85}}{\varepsilon_f} \quad (10)$$

where C^* has units MJ/m² h to give \dot{a} in mm/h and $\phi = n/(n+1)$ in Eq. (8). The failure strain is taken as the uniaxial failure strain for plane stress and as $\varepsilon_f/30$ for plane strain. It is conceivable for brittle materials such as ceramics, where the failure strains are low, that steady state cracking under plane strain conditions would not exist and that fast fracture would control the failure process.

3. Material data

According to the deformation mechanism map for ZrB₂ proposed by Wang et al.,¹¹ power law creep is the expected predominant deformation mechanism at temperatures above 1500 K and high stresses. Making use of the creep properties listed in

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