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Characterizing high temperature crack growth behaviour under mixed environmental, creep and fatigue conditions

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ABSTRACT

Components in high temperature plant could undergo failure due to combinations of fatigue, creep or oxidation/corrosion depending on the loading, temperature and environmental conditions. A novel and robust approach for a progressive failure modelling is presented in this paper which for the first time attempts to combine these failure mechanisms as time or cycle dependent processes. In this study, a combined multiaxial inter/transgranular crack growth model at the meso-scale level was proposed to conveniently deal with the various failure scenarios that may exist in plant components. The simulated crack under the combinations of time dependent creep and oxidation mainly propagated along grain boundaries initiating from the notch surface, exhibiting an irregular shapes with crack branching. Whereas under fatigue/oxidation condition, the crack grew in a transgranular manner. Furthermore, the role of creep, fatigue and oxidation on the failure life was dependent on the applied duration period at peak loads. Cracks were prone to nucleate in transgranular and then propagate in intergranular. There existed competitions between creep, fatigue and oxidation damage. Finally, the failure modes due to different damage mechanisms and loading conditions in the cases of creep-fatigue-oxidation were proposed. The calculated failure modes corresponded with those observed in engineering alloys.

1. Introduction

For the engineering components operating at high temperatures, it is possible that multiaxial creep, fatigue, oxidation or a combination of these mechanism could be reasons to premature failures. To understand the crack growth behaviour and failure life under creep or fatigue or oxidation conditions, many researches have been performed. However, modelling a combination of these mechanisms, which may contribute to premature failure, has received less attention [1,2]. The role of creep or oxidation or fatigue damage significantly change when the materials and loading conditions vary. Therefore, various failure behaviours are observed, i.e. the creep-ductile steels in power plants components suffer the creep-fatigue [3–6], the creep-brittle high strength alloys in aerospace applications suffer the oxidation fatigue [7,8] and the materials under complex loading conditions are subjected to the creep-fatigue-oxidation [1,2,9]. In addition, even though many mechanical tests have been conducted, there is scarce literature pertaining to the crack growth behaviour, trans/inter-granular failure mechanisms and their correlation with the interaction among creep, fatigue and oxidation.

Creep-fatigue-oxidation is a much more complex phenomenon. Particularly, the modelling of this combination is difficult to perform at the fundamental level. Creep damage is usually associated with the formation of micro voids at grain boundaries or grain boundaries intersections [10,11]. In addition, high temperature components often operate under highly oxidizing or carburizing or corrosion conditions. The damage under these conditions is similar to that caused by the environmental creep deformation and is also time dependent. There are three categories of damage rate dependencies in the oxidation processes: linear relationship between damage rates and service time [12–14]; logarithmic and parabolic relationship [15–19] describing the reduced damage rates with the increased time. In contrast, the fatigue damage usually happens in the start-up and shut-down of thermal systems and the gradients in the temperature at elevated temperatures and is cycle dependent. However, the damage trend is significantly complicated when the components operate under combined high temperature, oxidation environment and cyclic or static loading conditions. The combination could stimulate the damage accumulation. It has been revealed that J [20] revealed that the damage accumulation could be accelerated for repeated buckling of oxide under compressive loading and brittle cracking under tensile loading. The load bearing section could be reduced owing to the oxidation spallation; as a result, the subjected stress increased and subsequently the remained creep life was

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greatly reduced. Osgerby and Dyson [21] and Andrieu et al. [11] revealed that the degradation of the creep resistance in heat resistant steels was related to the carbon dioxides development at grain boundaries. Other creep-fatigue-oxidation interaction consequences such as embrittlement or dynamic embrittlement were also observed in Nickel alloys under high temperatures [22]. The oxidation damage was serviced as the nucleation of the cracks in creep or fatigue and then affected the damage and failure modes.

The failure modes under complex environments have been studied and considered in the engineering standards, i.e., evaluating the remaining life under creep-fatigue interaction. However, owing to the difficulties in testing and modelling crack initiation and crack growth under the creep-fatigue-oxidation interactions, the conclusive results were limited. For simulating the intergranular or transgranular crack growth modes caused by the various operational conditions, the classical numerical simulation procedures using a finite element fine mesh distribution could not be used as no differences in material properties can be shown to exist between grains and grain boundaries. Recently, using a finite element fine mesh distribution consisting of generic grains and independent grain-boundaries structure to represent an idealized microstructure in real materials has shown a significant improvement in developing realistic failure simulations [7,8]. This work revealed that the intergranular crack growth modes under creep-oxidation and creep-fatigue conditions are possible to model and that differences can exist in the failure times. Further novel development of this approach to take into account fatigue damage is therefore beneficial to understanding the crack growth under the interactions of creep, fatigue and oxidation. In this paper, a model using a novel mesh generation scheme which simulates idealized grains and grain boundaries the failure mechanisms can be distinguished by the mode of failure they produce. This model idealised allows for surface depletion and intergranular and transgranular cracking [23]. Elastic/plastic/creep runs using ABAQUS [24] and a user subroutine in which the creep/oxidation/fatigue strain and rate dependent based criteria model is implemented to derive failure times for different conditions.

In this study, to understand the crack growth manner and the variation of the failure life for materials subjected to the combination of creep, oxidation and fatigue, a continuum damage model is proposed to consider the effect of creep, fatigue and oxidation on the damage accumulation. The meso modelling approach coupled with the finite element (FE) method is performed to allow the crack to propagate along grain boundaries or within grains to demonstrate the real crack growth behaviour in materials. Furthermore, the crack growth mechanism under different conditions are analysed.

2. Continuum damage modelling of creep and environmental cracking in alloys

Creep and fatigue can be described independently with the creep and fatigue damage as a function of the applied load, operating time and cycles number respectively:

$$D^c = f(\sigma, t) \tag{1}$$

$$D^f = f(\sigma, N) \tag{2}$$

The oxidation/corrosion damage is dependent on time and is correlated with the distance in materials. The distance x_i from the surface where the diffusion or environmental damage can take place, which is determined by:

$$D^e = f(x_i, t) \tag{3}$$

The creep and oxidation failure mechanisms are usually intergranular. They operate independently. For one thing, the creep deformation requires an applied load. For another, although the external load and the applied stress assist in the damage process of the stress corrosion cracking (SCC), the environmental attach (such as oxidation) does not rely on the applied load. In contrast, the fatigue is cycle dependent and transgranular in nature. As a simple assumption, a linear accumulation of these mechanisms will give:

$$D^t = D^c + D^f + D^e \tag{4}$$

This allows a simple approach to predict the failure under environmental creep and creep/fatigue conditions to be developed. The creep damage is modelled based on the NSW multiaxial ductility model [25,26]. The approach for modelling the fatigue damage in the low cycle fatigue has been proposed. In addition, Biglari and Nikbin [12,13] proposed a method for evaluating the time dependent surface damage and well demonstrated the intergranular cracking due to oxidation, where the oxidation damage was calculated according to a critical local damage rate criteria and a hardness distribution profile. By combining these mechanism into one modelling process allows a realistic approach to multiaxial failure predictions. The methods are described briefly in the next sections.

2.1. Fracture and damage mechanics under creep

The creep damage increment is assumed to correlate with the local crack tip deformation and the multi-axial failure strain [27–29]. This rule has been used to represent the damage accumulation and crack extension under creep deformations. Based on the NSW model [26,27] considering the effect of the stress state at the crack tip, therefore, the increment of the damage under the multi-axial creep condition can be determined by the ratios of the increment of the equivalent creep strain and the multiaxial creep ductility. This is defined as follows:

$$\Delta D^c = \frac{\Delta\bar{\varepsilon}^{cr}}{\varepsilon_f^*} \tag{5}$$

The multiaxial creep ductility, εf^*, can be obtained from a number of available void growth models as reported in [30,31]. These model are dependent on the creep hardening parameter n. For most engineering materials, the value of the creep hardening parameter n in Norton's law lies within 5–10. In these cases, the creep index n in the full Cocks and Ashby equation [31] can be assumed to be a constant, allowing an approximation of the model to be written as:

$$\frac{\varepsilon_f^*}{\varepsilon_f} = \sinh(0.5)/\sinh(2h) \tag{6}$$

The values of $\varepsilon_f^*/\varepsilon_f$ is between 1 and 30 [27], in the extreme ranging between plane stress to plane strain conditions for creep brittle to creep ductile alloys.

The effect of the stress state on the creep deformation and damage accumulation processes are considered in this model. The creep strain rate is governed by the equivalent stress and void growth and initiation mechanisms. Hence, the creep damage initiation criterion employed in this study assumes that the critical equivalent creep strain $\varepsilon_f(h,\dot{\bar{\varepsilon}}^{cr})$ is a function of stress triaxiality $h = \sigma_m/\sigma_e$ and equivalent creep strain rate $\dot{\bar{\varepsilon}}^{cr}$ giving creep damage as:

$$D^c = \int \frac{d\bar{\varepsilon}^{cr}}{\varepsilon_f(h,\ \bar{\varepsilon}^{cr})} dt \tag{7}$$

where D^c denotes the creep damage accumulation. The damage is calculated using the elastic-plastic-creep analysis and then the crack initiation and crack propagation induced by the multiaxial creep conditions could be obtained. Substantial work has been conducted using this method to predict the damage accumulation and crack growth behaviour [13,26,27] and therefore the details of the method will not be expanded in this paper.

2.2. Damage accumulation under low cycle fatigue

Low cycle fatigue behaviour at elevated temperature is of