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Creep cavity growth models for austenitic stainless steels

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ABSTRACT

Diffusion controlled cavity growth models tend to exaggerate the growth rate. For this reason it is essential to take into account the restrictions caused by creep rate of the surrounding material, so called constrained growth. This has the consequence that the stress that the cavities are exposed to is reduced in comparison to the applied creep stress. Previous constrained growth models have been based on linear viscoplasticity. To avoid this limitation a new model for constrained growth has been formulated. Part of the work is based on a FEM study of expanding cavities in a creeping material. Compared with the previous constrained cavity growth models, the modified one gives lower reduced stresses and thereby lower cavity growth rates. By using recently developed cavity nucleation models, the modified creep cavity growth model can predict the cavity growth behaviour quantitatively for different types of austenitic stainless steels, such as 18Cr10Ni, 17Cr12NiNb and 17Cr12NiTi.

1. Introduction

In order to improve the efficiencies of power plants and reduce CO_2 emission, as well as save costs, the operating temperatures and stresses have been increased in the fossil fired power plants [1]. However, the life of components in the high temperature and stress condition is limited by the properties of materials, especially creep strength and oxidation resistance. Austenitic stainless steels are widely used for high temperature components of power plants. It is important to study the rupture controlling mechanisms in these steels.

Creep cavitation, which causes intergranular fracture of materials, is a vital phenomenon for the design life of the materials. Fracture due to creep cavitation proceeds with the formation, growth and coalescence of creep cavities along grain boundaries. Models about formation of creep cavities have recently been presented by He and Sandström [2,3], where the cavity nucleation is related to Grain boundary sliding (GBS). With the models in [3], a good agreement has been reached with the experimental observations for GBS. Contrary to the situation for cavity nucleation, well established models for creep cavity growth exist [4,5]. Although fundamental models for cavity growth have existed for a long time, they have had limited success in describing observations for austenitic stainless steels. One reason has been lack of models for the formation of creep cavities. Now with the recently developed models for cavity nucleation [2], it is possible to predict the cavity growth behaviour for austenitic stainless steels.

The main aim of this paper is to analyze the current cavity growth models and propose a modified model for constrained creep cavity growth. Combining with the recently developed cavity nucleation models, the modelled creep cavity growth will be compared with experiments. The modified creep cavity growth model will also be compared with previous ones.

2. Cavity nucleation models

In paper [2], a double ledge model has been proposed for cavity nucleation at intersections of subboundaries with grain boundaries due to GBS. In the model, it is assumed that cavities are nucleated when subboundary corners or particles on one side of a sliding grain boundary meet subboundaries on the other side of the sliding grain boundary. The final results for cavity nucleation rate is:

$$\frac{dn}{dt} = \frac{0.9C_s}{d_{sub}}\left(\frac{1}{\lambda^2} + \frac{1}{d_{sub}^2}\right)\dot{\varepsilon}(\sigma_{app}) = B\dot{\varepsilon}(\sigma_{app}) \tag{1}$$

where dn/dt is the cavity nucleation rate, 0.9 is a factor due to the angle between the grain boundary and the sliding direction. C_s is a GBS parameter, d_{sub} is the subgrain size, λ is the particle spacing and $\dot{\varepsilon}_{cr}(\sigma_{appl})$ is the steady state creep strain rate at the applied stress. B is a parameter that relates the cavity nucleation rate to the creep rate.

d_{sub} is the subgrain size that can be related to the applied creep stress σ

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$$d_{sub} = \frac{KGb}{\sigma} \tag{2}$$

where G is the shear modulus, b Burgers' vector and K a constant. For austenitic stainless steels $K \approx 20$. Further details of the derivation of the cavity nucleation rate are given in [2].

C_s is the parameter that relates the GBS displacement velocity υ_{sd} (often called the displacement rate) to the creep strain rate [3].

$$\nu_{sd} = C_s \dot{\varepsilon}(\sigma_{app}) \tag{3}$$

The modelling results of C_s shows a good agreement with the average value of the experimental data for austenitic stainless steels, including the initial stage of GBS, where the GBS velocity is higher. Detailed information for the parameter C_s and GBS can be found in [3].

In double ledge model there is no incubation time involved. The threshold stress for formation of cavities has found to be well below the applied stress in agreement with observations. In addition, Eq. (1) has the same form as the experimental findings namely that the cavity nucleation rate is proportional to the creep rate. The cavity nucleation model can make quantitative predictions for austenitic stainless steels [2]. Now, it will be used for the development of the creep cavity growth models in the following sections.

3. Cavity growth models

3.1. Unconstrained cavity growth model

Expressions for growth of creep cavities based on diffusion control are well established. A diffusion based model was first proposed by Hull and Rimmer [6] and improved by subsequent workers [7–9]. The common expression for the diffusion controlled cavity growth model can be expressed as [7–10]:

$$\frac{dR}{dt} = 2D_0 K_f (\sigma - \sigma_0) \frac{1}{R^2} \tag{4}$$

where dR/dt is the cavity radius growth rate, R the cavity radius in the grain boundary plane, σ is the applied stress, σ_0 is the sintering stress $2\gamma_{surf}\sin(\Theta)/R$, where γ_{surf} is the surface energy per unit area and Θ the cavity tip angle. D_0 is a grain boundary diffusion parameter, $D_0 = \delta D_{GB} \Omega / k_B T$, where δ is the boundary width, D_{GB} the grain boundary self-diffusion coefficient, Ω the atomic volume, k_B Boltzmann's constant and T the absolute temperature. K_f is a factor introduced by Beere and Speight [11], which is a function of the cavitated area fraction f_a.

$$K_f = \frac{1}{-2\log f_a - (1 - f_a)(3 - f_a)} \tag{5}$$

where $f_a = (2R/L)^2$ is the area fraction of the cavitated grain boundaries. The cavity spacing L can be obtained from the number of cavities per unit grain boundary area n_{cav}:

$$L = 1/\sqrt{n_{cav}} \tag{6}$$

The number of cavities n_{cav} can be derived with the help of the cavity nucleation model, Eq. (1).

Plastic deformation also gives a contribution to the cavity growth [8,9]. A number of models have been presented. The one given by Davanas and Solomon can be expressed as [9]:

$$\frac{dR}{dt} = \frac{\sin^2\theta}{\theta - \sin\theta\cos\theta} \frac{R}{3} \dot{\varepsilon}(\sigma_{app}) \tag{7}$$

where $\dot{\varepsilon}(\sigma_{app})$ is the creep rate at the applied stress and Θ the cavity tip angle.

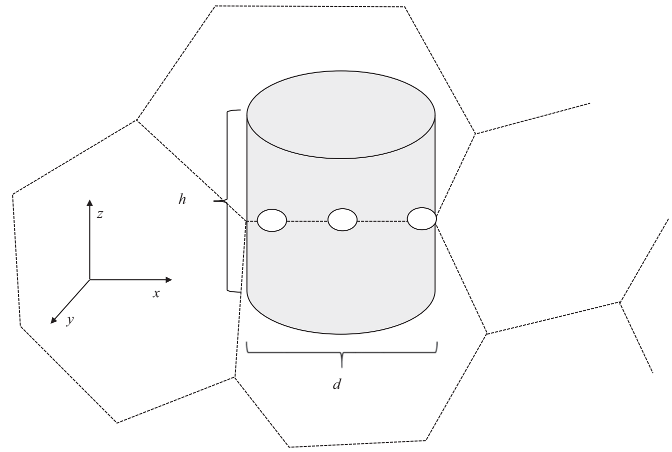

Fig. 1. Schematic illustration of grain boundary cavities and the pillar design.

3.2. Constrained cavity growth

In the models described above, the assumption is that the stress acting over the grain facet is the applied stress. It is diffusion controlled cavity growth driven by the applied stress independent of the creep deformation. It was early on realized that the diffusion growth models gave much larger growth rates than observed experimentally in many cases. However, it was suggested that the cavities should not be able to grow faster than the creep deformation would allow. Thus, the expansion of the cavities must be compatible with the deformation rate of the surrounding material. This concept was first introduced by Dyson [12] and it is referred to as constrained cavity growth.

Rice modelled constrained cavity growth by considering the opening rate of an elastic crack in the cavitated grain boundary. By equating the opening rate of the cavitated boundary to the average opening rate of the grain facet, he derived a reduced stress that would drive the cavity growth [13].

$$\sigma_{red} = \sigma_0 + \frac{1}{\frac{1}{\sigma_{app}} + \frac{32 D_0 K_f}{L^2 d \beta \dot{\varepsilon}(\sigma_{app})}} \tag{8}$$

where β is a material constant ($\beta = 1.8$ for homogeneous materials), d the grain diameter. The cavity spacing L can be obtained from Eq. (6). By replacing the applied stress with the reduced stress, the constrained cavity growth rate could be obtained.

$$\frac{dR}{dt} = 2D_0 K_f (\sigma_{red} - \sigma_0) \frac{1}{R^2} \tag{9}$$

Comparing with the diffusion controlled cavity growth model, Eq. (4), it can be seen that the only difference is that the applied stress is replaced with the reduced stress. The reduced stress, Eq. (8) is a function of the applied stress and the creep rate, which indicates that it is influenced by the creep rate of the surroundings.

3.3. Modified cavity growth model

Eq. (8) was derived from an elastic analysis of an opening crack that was transferred to linear viscoplasticity. However, it is not necessary to make these approximations about linearity, which will now be demonstrated. Consider a grain structure with a pillar of material with a height of h and a cross section corresponding to a grain boundary facet with a width d. A schematic illustration of the grain boundary cavities and the pillar design is shown in Fig. 1. The creep deformation of this pillar in the axial (z) direction can be