

HIGH TEMPERATURE CREEP DAMAGE OF FABRICATED STRUCTURES

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ABSTRACT

The need for structural systems to perform reliably at high temperatures continues to increase. Improvements in energy production, pollution control, chemical processes (especially, engine propulsion), efficient micro-process devices, among other applications, are possible with higher temperature operations. Higher temperature operation means that creep damage must be managed over the life of the component. One of the important mechanisms of creep damage development, matter diffusion, is investigated here. In particular, the effect of elastic accommodation on the grain boundary diffusion-controlled void growth is analyzed using an axisymmetric unit cell model. An incremental form of the virtual work principle was used to formulate the boundary value problem involving grain boundary diffusion. The model accounts for material elasticity and void interaction effects. Analyses are performed for initially spherical voids spaced periodically along the grain boundary. The results of the analyses on void growth rates agree well with the Hull-Rimmer [1] model after the initial transient time. During the elastic transient, void growth rates can be several orders of magnitude higher than the steady state growth rate. Though the elastic transient time may occupy a small portion of the total rupture time, in metallic components experiencing cyclic loading conditions with short hold times, elasticity effects may be important.

KEYWORDS

Creep, damage, diffusion, fracture, high temperature, steel.

INTRODUCTION

Failure in metals exposed to high temperature creep conditions predominantly occurs by nucleation and growth of cavities along grain boundaries, thus resulting in intergranular fracture. Nucleation of such cavities is mainly driven by diffusion of atomic flux from the lattice or interfaces into grain boundaries. Further growth of these cavities is aided by diffusion of atomic flux primarily from cavity surface into grain boundaries. The nucleation of these intergranular cavities in many instances occurs during the primary creep stage. In addition to diffusion mechanisms, the creep deformation of the material also contributes to cavity growth. The purpose of this paper is to quantitatively examine the effect of elastic transient on growth of spherical cavities. The growth of the cavities was controlled by grain boundary diffusion as well as material elasticity.

ANALYSIS

Consider a damaged material exposed to high temperature creep conditions in which voids were periodically arranged in parallel sheets. The initial shape of the voids was assumed to be spherical with a radius of 'a'. Interaction effects between voids lying within a sheet, with initial mean center-to-center spacing of 'b', were accounted for by approximating the voided medium as consisting of cylindrical unit cells, each with a void located at its center, as shown in Figure 1. Assuming axisymmetric conditions, only one quarter of the cylindrical unit cell needs to be modeled. The axisymmetric unit cell is shown as hatched region in Figure 1. The far-field stress state was assumed to be uniaxial. The grain material was assumed to be elastically linear and isotropic. Diffusion of matter takes place along the grain boundaries.

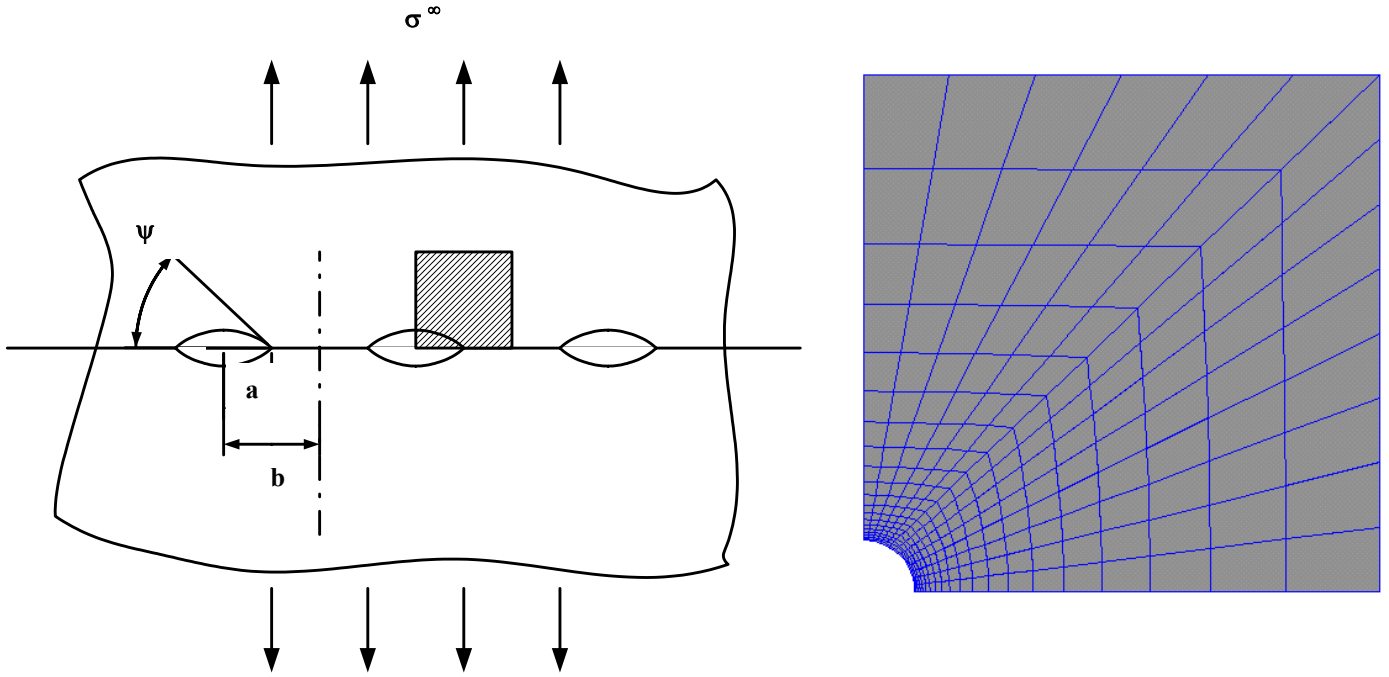


Figure 1. Dimensions and discretization for model.

We consider an incremental form of a functional, F , given by,

$$F = \int_V \sigma : \delta \Delta d \, dV - \int_S T \cdot \delta v + \int_A \frac{1}{2D} \Delta j \cdot \Delta j \, dA + \int_{\Gamma} \sigma_0 m \cdot j \, d\Gamma \quad (1)$$

for all kinematically associated fields, namely, the rate of deformation tensor, d , and the velocity, v , and the volumetric flux, j , crossing unit length in the grain boundary. In Equation (1), σ is the applied stress, T is the applied traction along the boundary S , A denotes the grain boundary area, and Γ denotes the collection of arcs where the grain boundaries meet the void surfaces. The normal stress, σ_0 , on the grain boundary at the void tip, also known as the sintering stress, is given by,

$$\sigma_0 = \gamma_s (\kappa_1 + \kappa_2) \quad (2)$$

where γ_s is the surface energy, and κ_1 and κ_2 are the principal curvatures of the surface of the void. The diffusion parameter, D , used in Equation (1), is related to the grain boundary diffusion coefficient of the material by,

$$D = \frac{\delta_b D_b \exp(-Q_b / RT) \Omega}{kT} \quad (3)$$

where D_b is the grain boundary diffusion coefficient at a given temperature, T , Ω is the atomic volume, δ_b is the thickness of the diffusion layer, Q_b is the activation energy, and R and k are the Gas and Boltzmann's constant. The functional [1] Starts from Needleman and Rice [2], with appropriate modifications to account for material elasticity, etc. It can be easily shown that F as given in equation (1) is not only stationary but also a global minimum for the true field. Exercising the variational principle on F , it can be shown that the full set of field equations for the considered problem will result.

Using the above formulation to develop the finite element equations (as elaborated in [3]), a special user element (UEL) was developed and used with the ABAQUS finite element software [4]. We have examined the transient effect for several metallic materials at a temperature, $T = 0.6 T_m$ in this study. The properties of the materials are given in Table 1. We consider an average void spacing $10 \mu\text{m}$ ($b = 5 \mu\text{m}$). Using this value for b and $a/b = 0.1$, we obtain a characteristic time, τ , also given in Table 1, for the materials considered in this study. The properties listed in Table 1 are obtained from Frost and Ashby [5]. In all the cases examined, the ratio of far-field stress to Young's modulus, σ^∞/E , was 10^{-3} . The characteristic time is defined as:

$$\tau = \frac{(b - a)^3}{ED} \quad (4)$$

TABLE 1.
MATERIAL PROPERTIES OF THE METALLIC MATERIALS USED.

Material Property	Aluminum	Copper	γ -Iron
Young's Modulus, E (MPa)*	75.30	124.0	205
Poisson's Ratio, ν **	0.34	0.32	0.3
Atomic Volume, Ω (m^3)*	1.66×10^{-29}	1.18×10^{-29}	1.21×10^{-29}
Melting Point, T_m (K)*	933	1356	1810
Grain Boundary (GB) Diffusion Pre-exponential, $\delta_b D_b$ (m^3/s)*	5×10^{-14}	0.5×10^{-14}	7.5×10^{-14}
Activation Energy for GB Diffusion Q_b (kJ/mole)*	84	104	159
Characteristic Time, τ , secs	772	857	327
Grain Boundary Energy, γ_b (J/m^2)**	0.63	0.65	0.78
Surface Energy, γ_s (J/m^2)**	-	1.73	1.95

In Figure 2, the ratio of the void growth rate predicted by FEM and by the Hull-Rimmer model (the Hull-Rimmer classical solution neglect elastic accommodation, i.e., assumes rigid response [1]) is plotted against normalized time. The inset shows the transition from transient to steady state conditions. It can be seen that the transient time is larger for larger a/b values. The variation of the ratio of normal stress and applied stress along the grain boundary ahead of the cavity tip is shown in Figure 3 for a/b of 0.1. In the figure, X denotes the distance from the tip of the cavity along the grain boundary. While in the pure elastic case the peak stresses occur at the cavity tip, matter diffusing into the grain boundary from the cavity surfaces relaxes the stresses at the tip, even during the beginning stages of the transient. Consequently, the peak stress occurs away from the cavity during the transient stage. With increasing time, the peak stress decreases in magnitude and moves away from the cavity tip. As can be seen from the figure, a parabolic profile is

achieved as steady state condition ensues. Vitek [6] obtains a variation similar to the one shown in Figure 3 for the transient stress distribution ahead of crack tip arising due to non-uniform deposition of matter from the tip onto the grain boundary. It is also found (but not shown here) that the peak stress away from the cavity tip is higher for larger a/b ratios. This would imply that the chances for nucleation of new cavities, during transient stages, increase with initial cavity radius-to-spacing ratio.

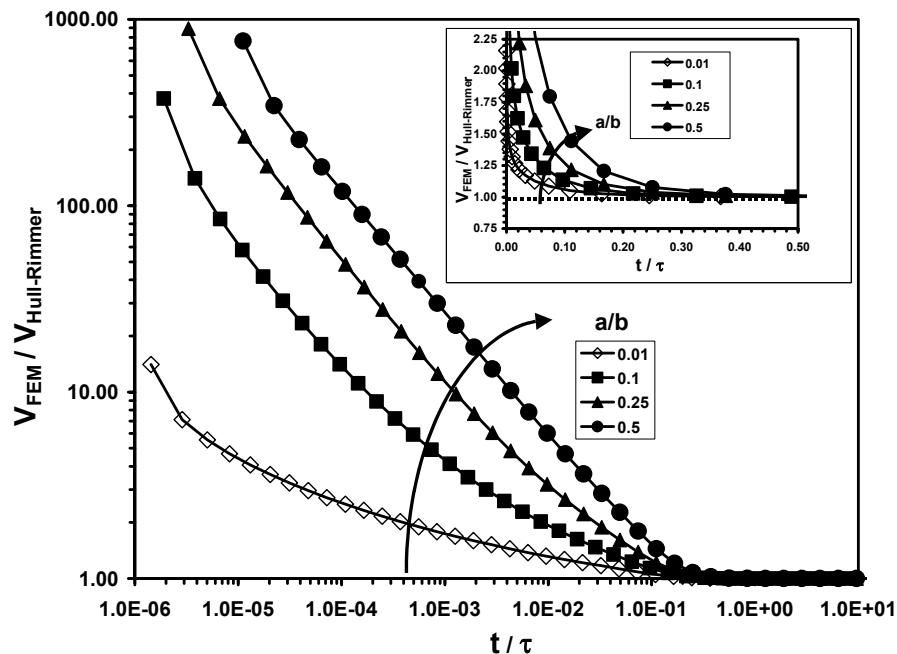


Figure 2. Temporal variation ratio of void growth rate predicted by FEM and by the Hull-Rimmer model for several a/b ratios in γ -Fe. Inset shows the transition from transient to steady state.

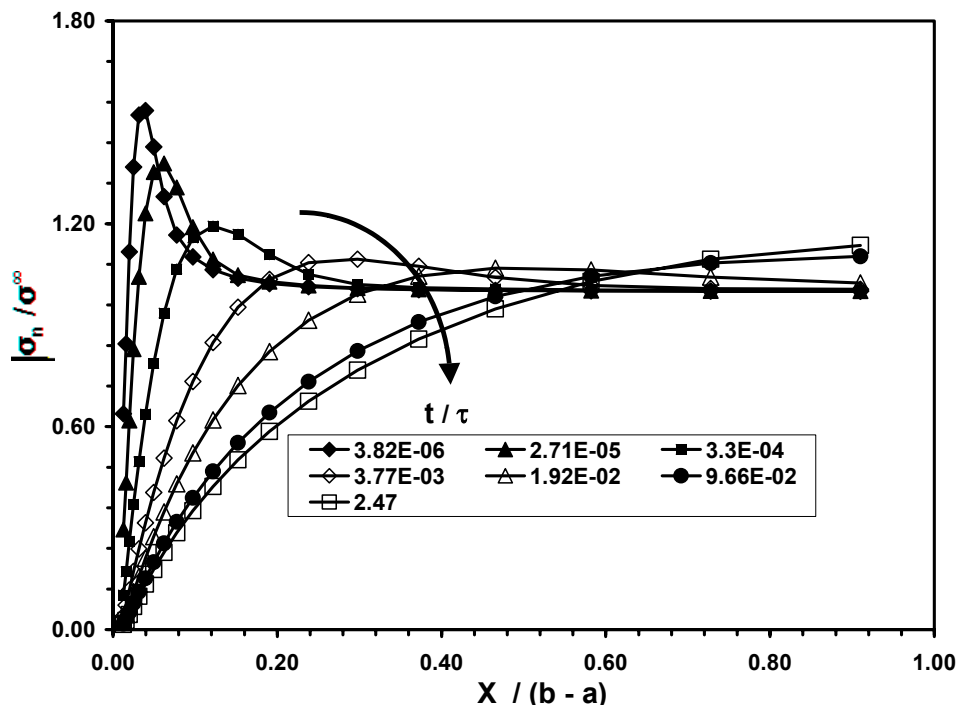


Figure 3. Temporal changes in stress distribution ahead of the cavity tip along the grain boundary in γ -Fe for $a/b = 0.1$.

The temporal variations of void growth rates normalized with the respective rate predicted by Hull-Rimmer model, are shown in Figure 4 for all the three metals. Indeed, all the curves collapse into a single distribution indicating that the choice of time scale is appropriate. It is worth mentioning that Raj [7] was the first to suggest the appropriate time scale as given in equation (4). It is interesting to note that Trinkaus [8] and Shewmon and Anderson [9] note that in the case of an isolated cavity along a grain boundary, the stress and displacement field expand around the cavity in a self-similar manner in proportion to the cavity radius, with $a \propto t^{1/3}$. They obtained this result assuming rigid grains. In our problem, a wedge of material is introduced ahead of the cavity tip during the transient stage, due to material elasticity. In the work of Trinkaus [8] and Shewmon and Anderson [9] a wedge is introduced because the cavity is isolated (well separated and small). In addition, unlike the Hull and Rimmer model they assume that the grain boundary thickening vanishes at some distance away from the cavity. However, their solution is different from the present in that elasticity and void interactions are not taken into account.

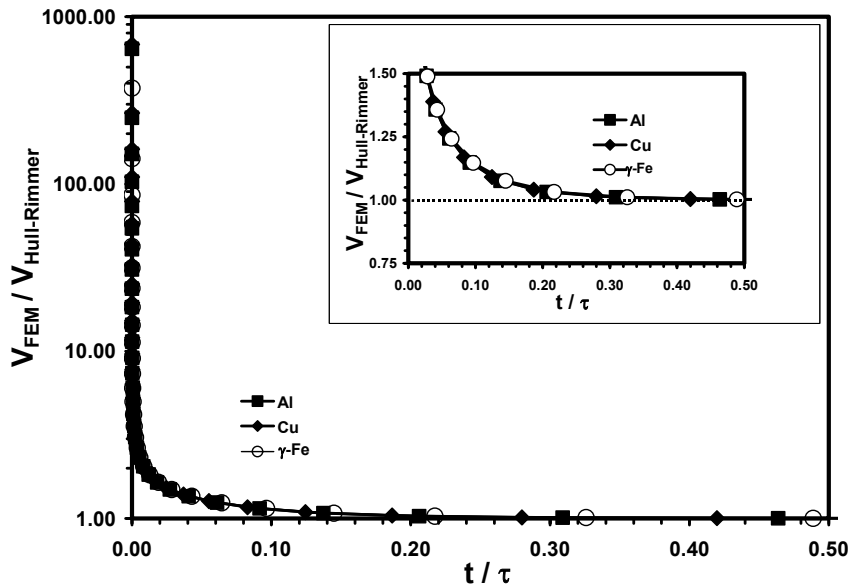


Figure 4. The temporal variations of void growth rates normalized with the respective rate predicted by Hull-Rimmer model for all the three metals.

CONCLUSIONS

The effect of elastic accommodation on the grain boundary diffusion-controlled void growth was analyzed using an axisymmetric unit cell model. In order to accomplish this we have extended the formulation of Needleman and Rice [2] to account for material elasticity. This extension also involved an incremental formulation of the virtual work principle of the boundary value problem involving grain boundary diffusion. The model accounts for void interaction effects. The results of the analyses on void growth rates agree well with the Hull-Rimmer model after the initial transient time for the three different metals considered. During the elastic transient, void growth rates can be several orders of magnitude higher than the steady state growth rate. Using the predictions of finite element analyses for several metals, we demonstrated that the characteristic time is appropriately given by equation (4). Indeed, Raj [7] was the first to suggest a similar form for the characteristic time. It was observed that the transient time is larger for larger a/b values (or larger volume fraction of cavities). Though the elastic transient time may occupy a small portion of the total rupture time, in metallic components experiencing cyclic loading conditions with short hold times, elasticity effects may be important.

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