ON THE RELATION BETWEEN THE CREEP MECHANISM AND CREEP FRACTURE

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ABSTRACT

An analysis was carried out to study the influence of the rate-controlling creep mechanisms on the cavity nucleation and growth rates and cavity growth mechanism. It is shown that the rate-controlling creep mechanism strongly affects the cavity nucleation rates as well as the cavity growth rate and mechanism. The theoretical predictions are found to be in good agreement with the experiment.

KEYWORDS

Rate-controlling creep mechanism; cavity nucleation; cavity growth; critical cavity radius.

INTRODUCTION

Failure of metals and alloys at elevated temperatures occurs by nucleation, growth and interlinkage of cavities at grain boundaries. The mechanisms controlling cavitation have been studied (Perry, 1974; Gittus, 1975) and several models for cavity growth have been suggested. Briefly, the proposed models can be combined in three groups, namely (a) those controlled by grain boundary vacancy diffusion, i.e. diffusion growth (Hull, 1959; Speight, 1967; Dobes, 1970); (b) those controlled by plastic slip within the grains, i.e. power-law growth (Hancock, 1976; Raj, 1978; Edwards, 1979); and (c) shear cracks formed at triple points growing by grain-boundary sliding, i.e. sliding growth (Williams, 1967; Greenwood, 1978). A common feature of the all the above cavity growth mechanisms is that they were developed independently of the creep mechanisms which control the overall deformation of the sample. It is the purpose of this paper to analyze the effect of the rate-controlling creep mechanisms on the dominant cavity growth mechanism. The data used in this analysis are those reported by Tippler and McLean (1970) for oxygen free high purity copper.

RATE CONTROLLING CREEP MECHANISMS

When a metallic specimen is deformed at elevated temperatures ($T \geq 0.4$-$0.5\ T_M$), T_M = absolute melting temperature) several creep mechanisms, i.e. Nabbarro-

Herring, Coble, grain-boundary sliding, dislocation climb, etc., (Mukherjee and coworkers, 1969) are competing, the one controlling the rate of deformation being determined by the test temperature, grain size and the applied stress. Fig. 1 shows a grain size - stress map (Mohamed and Langdon, 1974) for copper at 673°K. The constitutive equations used to construct the map and the values of the parameters in the constitutive equations are listed in Table 1.

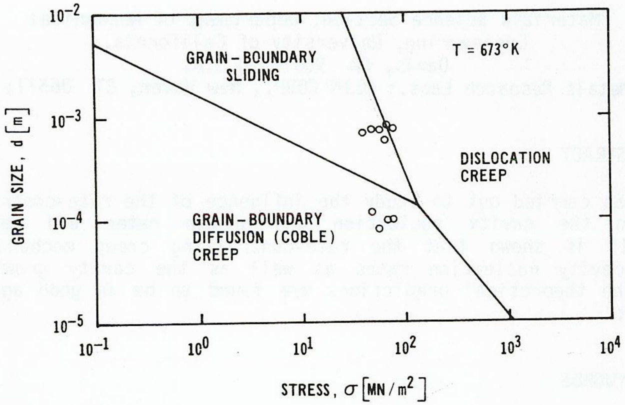

Fig. 1. Grain size vs. stress deformation mechanism map for copper. Circles are experimental points.

The map in Fig. 1 shows that at 673°K and over the range of stress and grain sizes represented, three creep mechanisms, i.e. grain-boundary diffusion (Coble) creep, grain-boundary sliding and dislocation climb, are rate-controlling each one in a different grain size-stress field. Superimposed on the map are experimental data taken from the work of Tippler and McLean (1970). It is evident from Fig. 1 that all experimental data but one fell into two fields, i.e. Coble creep and grain-boundary sliding, depending upon the grain sizes.

CAVITY NUCLEATION

In their investigation, Tippler and McLean (1970) observed two types of cavities, i.e. "bubble-type" which occurred along grain boundaries and "wedge-type" which occurred at triple points. They measured the rate of nucleation of each type of cavity separately and their results are replotted in Figs. 2 and 3 as grain size compensated applied stress versus the average rate of generation of "bubble-type" cavities, R_b (number of cavities per unit grain boundary length per unit time) and "wedge-type" cavities, R_w, respectively. Several pertinent observations can be made regarding Figs. 2 and 3, namely:

TABLE 1 Constitutive Equations for the Rate-Controlling Creep Mechanisms

Mechanism	Constitutive Equation	Reference
Grain-Boundary Diffusion (Coble)	$\frac{\dot{\varepsilon}\, k\, T}{D_b\, G\, b} = 600 \left(\frac{b}{d}\right)^3 \left(\frac{\sigma}{G}\right)$	Burton (1970)
Grain-Boundary Sliding	$\frac{\dot{\varepsilon}\, k\, T}{D_\ell\, G\, b} = 1 \left(\frac{b}{d}\right) \left(\frac{\sigma}{G}\right)^2$	Langdon (1971)
Dislocation Climb	$\frac{\dot{\varepsilon}\, k\, T}{D_\ell\, G\, b} = 7.4 \times 10^5 \left(\frac{\sigma}{G}\right)^{4.8}$	Mukherjee (1969)

$$D_\ell = 6.2 \times 10^{-5} \exp\left(-\frac{207{,}000}{RT}\right) \frac{m^2}{s}, \quad D_b = 10^{-5} \exp\left(-\frac{104{,}000}{RT}\right) \frac{m^2}{s};$$

$$b = 2.56 \times 10^{-10}\ m \quad \text{(Ashby, 1972).}$$

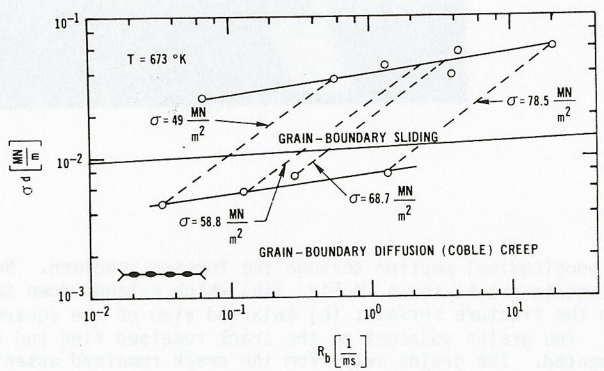

Fig. 2. Grain size compensated stress versus the rate of "bubble-type" cavities nucleation.

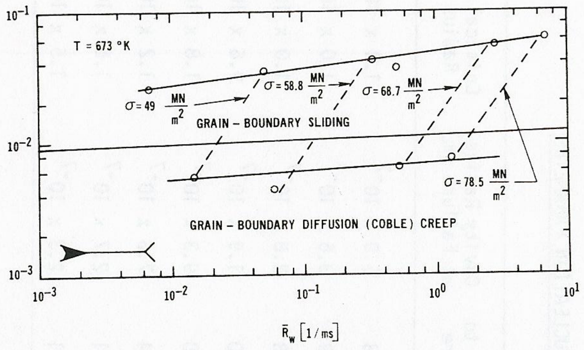

Fig. 3. Grain size compensated stress versus the rate of "wedge-type" cavities nucleation.

(i) The datum points fell onto two lines depending on the average grain size (7.6×10^{-4} m and 1.2×10^{-4} m, respectively).

(ii) The datum points obtained at the same applied stress can be connected by parallel lines (shown as broken lines in Figs. 2 and 3). This observation enabled us to separate Figs. 2 and 3 in two fields, the line separating the fields being obtained by cross-plotting the line separating the Coble creep and grain-boundary sliding fields in Fig. 1 as log (σd) vs. log σ.

(iii) The rate of nucleation of the "bubble-type" cavities as a function of grain size compensated stress is the same for all the datum points regardless of the deformation mechanism, i.e., the slopes of the lines in Fig. 2 are the same. On the other hand, the rate of nucleation of the "wedge-type" cavities is higher for the specimens deformed in the grain-boundary sliding regime, Fig. 3.

CAVITY GROWTH

Two cavity growth mechanisms were considered in this analysis, i.e. diffusion growth, and power-law growth. The constitutive equations used for each mechanism are shown in Table 2. The transition from one growth mechanism to another occurs at a critical cavity radius (Hancock, 1976; Miller and Langdon, 1980). The rate-controlling creep mechanism strongly influences the transition behavior, Figs. 4 and 5. When Coble creep is rate-controlling, the critical

radius is independent of the applied stress and, at constant temperature, depends only on grain size, Fig. 4. On the other hand, when grain boundary sliding is rate-controlling the critical radius depends both on the applied stress and grain size, Fig. 5. In Figs. 4 and 5 the broken lines show the calculated values for the data of Tippler and McLean (1970). Notice that the transition radii are one order of magnitude lower when specimens are deformed in the grain-boundary sliding regime.

TABLE 2 CONSTITUTIVE EQUATIONS FOR THE RATE-CONTROLLING CREEP MECHANISMS

Mechanism	Constitutive Equation	Reference
Power Law Growth	$\left(\frac{dr}{dt}\right) = \left(r - \frac{3\gamma_s}{2\sigma}\right)\dot{\varepsilon}$	Hancock (1976)
Diffusion Growth	$\left(\frac{dr}{dt}\right) = \frac{\Omega\ \delta\ D_b\left(\sigma - {}^{2\gamma_s}/_r\right)}{2\ k\ T\ r^2}$	Dobes (1970)

$\Omega = 4 \times 10^{-29}$ m ; $\delta = 4 \times 10^{-10}$ m (Ashby, (1972)

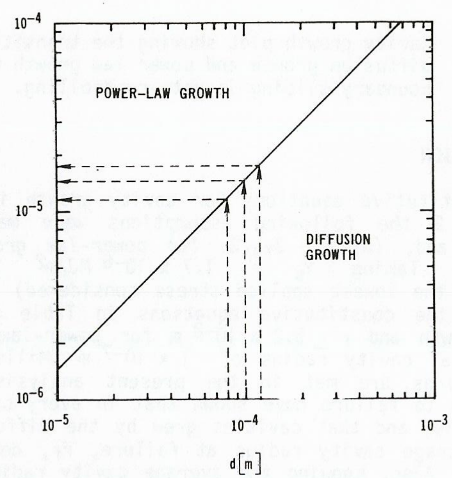

Fig. 4. Cavity growth plot showing the transition between diffusion growth and power law growth when Coble creep controls the creep rate.

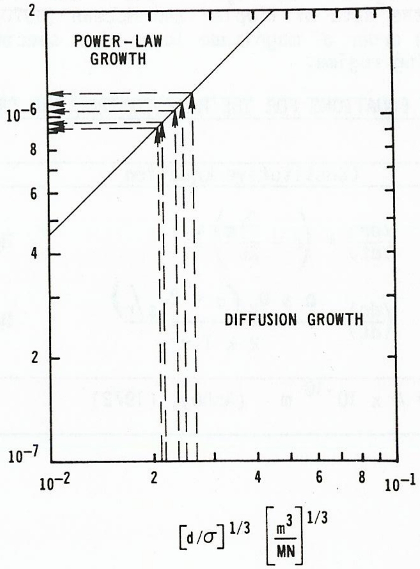

Fig. 5. Cavity growth plot showing the transition between diffusion growth and power law growth when grain-boundary sliding is rate-controlling.

DISCUSSION

In using the constitutive equations for cavity growth in the simplified forms listed in Table 2 the following assumptions were made (a) $r > 2\gamma_s/\sigma$ for diffusion growth and, (b) $r > 3\gamma_s/2\sigma$ for power-law growth, where γ_s is the surface energy. Taking $\gamma_s = 1.7 \times 10^{-6}$ MJ/m^2 (Tippler, 1970) and $\sigma = 49$MN/m^2 (i.e. the lowest applied stress considered) the conditions for the applicability of the constitutive equations in Table 2 are $r \geq 6.9 \times 10^{-8}$ m for diffusion growth and $r \geq 5.2 \times 10^{-8}$ m for power-law growth, respectively. Assuming an initial cavity radius of 1×10^{-7} m (Miller and Langdon, 1979), the above conditions are met in the present analysis. Calculations using experimental times to failure have shown that in every case the critical radius had not been reached and that cavities grew by the diffusion growth mechanism, Table 3. The average cavity radius at failure, $\bar{r}_f$, decreased as the applied stress increased. Also, knowing the average cavity radius at fracture and the total strain at fracture, ϵ_f, it is possible to calculate the average nucleation factor per unit grain boundary area, P, using the following relation (Miller, 1979):

$$\bar{P} = \frac{\sqrt{2}\left(\bar{r}_f\right)^{1/2}}{\epsilon_f} .$$

TABLE 3 CAVITY RADIUS AT FAILURE AND NUCLEATION PARAMETER

Rate-Controlling Creep Mechanism	Applied Stress (MN/m^2)	Grain Size (m)	Time to Failure (s)	Strain to Failure	Cavity Radius at Failure (m)	Critical Cavity Radius (m)	P (m^{-2})
Grain-Boundary	49.0	7.5×10^{-4}	7.65×10^{4}	0.068	6.9×10^{-7}	1.1×10^{-6}	1.7×10^{-2}
Sliding	58.8	7.4×10^{-4}	9.12×10^{3}	0.049	3.6×10^{-7}	1.0×10^{-6}	1.7×10^{-2}
	68.7	8.3×10^{-4}	3.6×10^{3}	0.058	2.8×10^{-7}	1.0×10^{-6}	1.3×10^{-2}
	78.5	7.9×10^{-4}	1.02×10^{3}	0.140	1.9×10^{-7}	9.6×10^{-6}	4.4×10^{-3}
Coble Creep	49.0	1.2×10^{-4}	1.91×10^{5}	0.140	9.3×10^{-7}	1.8×10^{-5}	9.7×10^{-3}
	58.8	0.8×10^{-4}	8.85×10^{4}	0.174	7.6×10^{-7}	1.2×10^{-5}	7.1×10^{-3}
	68.7	1.0×10^{-4}	3.48×10^{4}	0.191	2.7×10^{-7}	1.5×10^{-6}	3.8×10^{-3}
	78.5	1.0×10^{-4}	1.86×10^{3}	0.191	2.3×10^{-7}	1.5×10^{-6}	3.8×10^{-3}

The calculated values of P are listed in Table 3 and it is evident that P is two to four times higher at the same stress when grain-boundary sliding is the rate-controlling mechanism. This agrees extremely well with the nucleation rates determined experimentally, Figs. 2 and 3.

CONCLUSIONS

The rate-controlling deformation mechanism has a strong influence on both cavity nucleation and cavity growth rates. For the experimental data used in the analysis the rate-controlling mechanism affected only the cavity nucleation rates since the fracture occurred before the critical radius for transition from diffusion growth to power-law growth has been reached.

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