CREEP DAMAGE AND RUPTURE CRITERIA

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It is now generally accepted that creep rupture is preceded by the formation and growth of intergranular cavities which eventually link up either through coalescence or intercavity cracking. The time to rupture reflects the rate at which these damage mechanisms proceed. However, the ability to predict time to rupture requires, in addition to the knowledge of damage rates, a definitive cavity configuration at which catastrophic fracture occurs.

A model proposed by Hull and Rimmer [1] for predicting rupture life at elevated temperatures assumed a uniform distribution of cavities of equal size in a square array. Cavity growth rates were assumed to be governed by grain boundary vacancy diffusion rates and the chemical potential gradient along the grain boundary. Fracture was further assumed to take place when the cavity diameter equalled the cavity spacing. Criticism of this model was directed toward the assumption of an invariant cavity density. Greenwood [2] pointed out that cavity nucleation was a continuous process. Speight and Harris [3] also questioned the assumption that the criteria for rupture is associated with the time it takes for the cavities to meet.

While the assumption of equally sized cavities and uniform distribution is a reasonable idealization for characterizing cavity volume and density, it is a fiction insofar as cavity interaction and the configuration at fracture is concerned. Attempts to trace the progress of cavity growth by measuring the change in material density with time only reveal the volumetric cavity growth rate. This method fails to provide the ratio of the cavity size to its spacing, a crucial parameter for estimating cavity density and a convenient criteria for characterizing the cavity configuration at the inception of fracture. This parameter may also be useful in correlating cavity growth with the inception and progress of tertiary creep.

To illustrate the inability of material density measurements alone to define cavity configuration we postulate a cubical grain with equally spaced cavities as shown in Figure 1. The cavities, assumed square for convenience, are limited to the boundaries normal to the load axis. The change in density, ρ, of the material due to presence of the cavities is

$$\frac{\Delta\rho}{\rho_1} = \frac{\rho_2-\rho_1}{\rho_1} = - k^3 \frac{a}{d} \qquad (1)$$

where ρ_1 and ρ_2 are the initial and final densities of the material respectively and $k = b/a$, the ratio of the cavity size to its spacing. We

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see from equation (1) that the change in material density alone cannot give information about k independently of the cavity size, b.

What we need is another independent test that will establish another relationship between b and a. This may be provided by a measurement of the change in resistivity of the material with cavity growth. Using the model of the cubical grain shown in Figure 1, we find that the change in resistivity with cavity growth may be expressed by

$$\frac{\Delta\mu}{\mu_1} = \frac{\mu_2-\mu_1}{\mu_1} = \frac{k^3}{1-k^2}\ \frac{a}{d} \tag{2}$$

where μ_1 and μ_2 are the initial and final resistivity of the material respectively. Dividing equation (2) by equation (1) gives

$$\frac{\Delta\mu/\mu_1}{\Delta\rho/\rho_1} = -\frac{1}{1-k^2}$$

from which

$$k = \left[1 + \frac{\Delta\rho/\rho_1}{\Delta\mu/\mu_1}\right]^{1/2} \tag{3}$$

If we know the average grain size then

$$a = -\frac{d}{k^3}\ \frac{\Delta\rho}{\rho_1} = d\left(\frac{1-k^2}{k^3}\right)\frac{\Delta\mu}{\mu_1} \tag{4}$$

and

$$b = ak \tag{5}$$

Furthermore, the average stress, σ_{AV}, on the net cross-section for this model is

$$\sigma_{AV} = \frac{a^2}{a^2-b^2}\,\sigma_o = \frac{1}{1-k^2}\,\sigma_o \tag{6}$$

where σ_o is the creep stress defined by the load divided by the initial area of the homogeneous material.

In the event that the cavities are not cubical or spherical but are shallower in the direction normal to the grain boundary than the lateral dimension in the plane of the boundary, then the change in density and resistivity become, respectively

$$\frac{\Delta\rho}{\rho_1} = -k^3\,k_1\,\frac{a}{d}$$

$$\frac{\Delta\mu}{\mu_1} = \frac{k^3}{1-k^2}\,k_1\,\frac{a}{d}$$

where $k_1 = c/b$ and c is the dimension of the cavity normal to the grain. Since the ratio of the resistivity change to the density change is still $-1/(1-k^2)$, we may still determine the ratio of cavity size to spacing even for lenticular shaped cavities.

The precision with which k may be determined from experiment in terms of the measured parameters is

$$\delta k = \frac{\partial k}{\partial(\Delta\rho/\rho)}\,\delta\left(\frac{\Delta\rho}{\rho}\right) + \frac{\partial k}{\partial(\Delta\mu/\mu)}\,\delta\left(\frac{\Delta\mu}{\mu}\right) \tag{7}$$

which becomes upon substitution of equation (3)

$$\frac{\delta k}{k} = \frac{\delta\rho/\rho_1}{2k^2\ \Delta\mu/\mu_1} + \left(\frac{1}{k^2} - 1\right)\frac{\delta\mu}{\mu_1} \tag{8}$$

or

$$\frac{\delta k}{k} \approx \frac{1-k^2}{2k^5}\ \frac{\delta\rho}{\rho_1} + \left(\frac{1}{k^2} - 1\right)\frac{\delta\mu}{\mu_1} \tag{9}$$

The levels at which the cavity size to spacing ratio k may be detected with acceptable precision depends upon the sensitivity of the apparatus for measuring density and resistance. It is also dependent upon the initial resistance of the creep specimens, μ_1. This latter condition dictates a creep specimen having as large a length to diameter ratio as possible and a material of relatively high resistivity.

The creep specimens are α-brass (70% copper, 30% zinc) rods .003 m. diameter which pass through a furnace long enough to allow a gauge length of about 0.20 meters in a uniform temperature and inert environment. This material is known to form grain boundary cavities within a temperature range of 200 to 400 deg. c. and has a fairly high resistance of about 7 micro-ohm cm. A length of rod cut from the same stock as the creep specimen is subjected to the same environment and will provide initial values of density and resistivity. After establishing the creep characteristics of this material through rupture, subsequent tests are aborted at intervals starting somewhat before the inception of tertiary creep and ending just before rupture is anticipated. The density is measured using a displacement method sensitive enough to detect density changes of 10^{-6}. Resistance is measured with a Kelvin bridge which detects resistance changes of one micro-ohm.

The levels of precision that are achievable with this experiment for determining the cavity size to spacing ratio is shown in Figure 2. Ratios with a precision greater than 5% are expected for cavity size to spacing ratios greater than 0.15. To detect smaller ratios with equivalent precision requires more sensitive equipment and a creep specimen with a larger length to diameter ratio.

REFERENCES

1. HULL, D. and RIMMER, D. E., Phil. Mag., 4, 1959, 673.
2. GREENWOOD, G. W., Phil. Mag., 8, 1963, 707.
3. SPEIGHT, M. V. and HARRIS, J. E., Met. Sci. J., 1, 1967, 83.

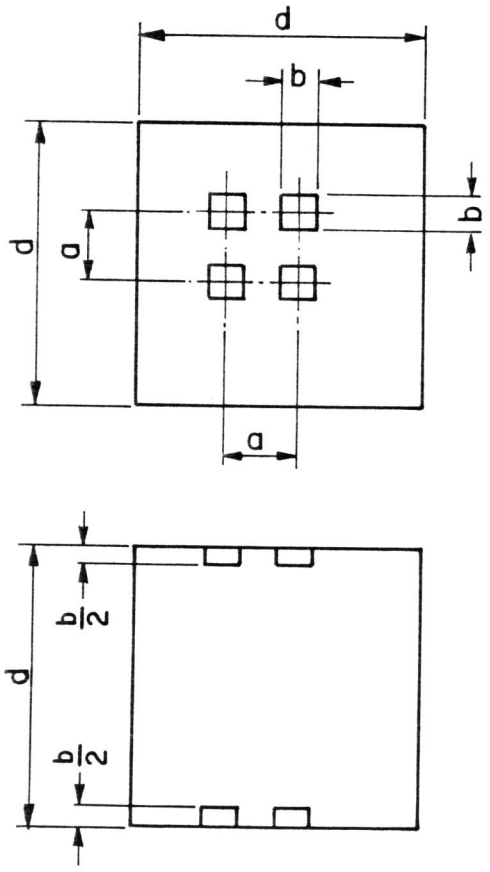

Figure 1 Hypothetical Cavity Configuration on Boundaries of Cubical Grain

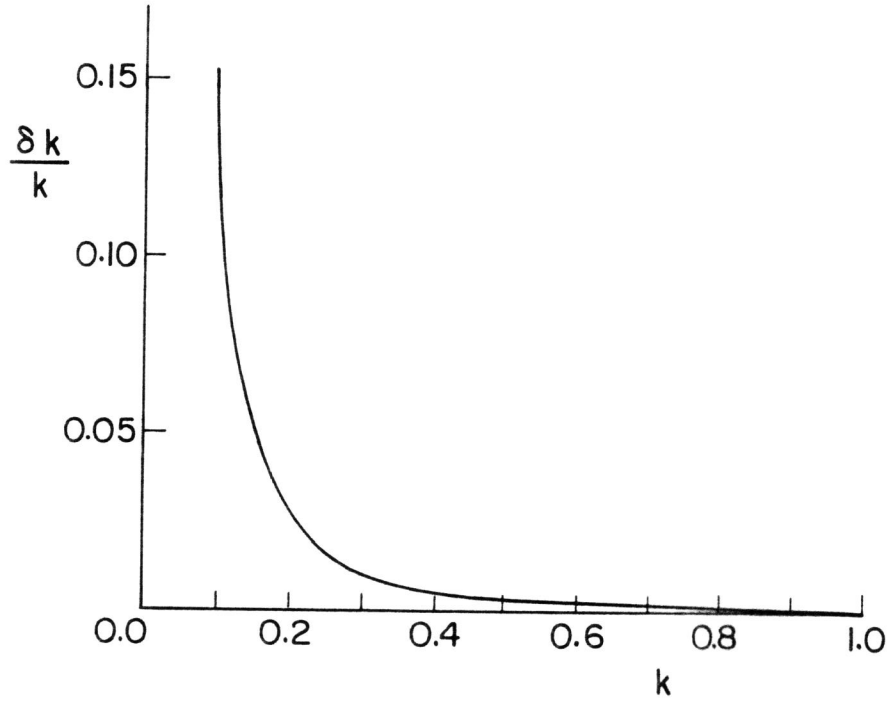

Figure 2 Precision of Experimentally Derived Cavity Size to Spacing Ratio, $\delta k/k$ versus k