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Creep Cavitation and Time To Failure

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ABSTRACT

intergranular fracture caused by the interlinking of cavities along the grain boundaries is an established phenomenon during creep failure. The significance of this failure mechanism is that the metal may fracture with little deformation and thus fail without much warning. From an Engineering point of view it is therefore extremely important to know the expected time to creep failure. This will of course depend on the service condition ot the metal.

The aim of the present work was to study the detailed mechanisms of cavity nucleation and growth in order to have a general understanding of the mode of failure and obtain quantitative relationships for creep ductility and time to fracture.

Creep tests were performed on copper at 500° C in argon atmosphers within an internally heated vessel. Some tests were carried out for constant strain and other tests for constant time.

High precision density measurements were made to determine the volume change due to the development of cavities in order to assess the extent of creep damage.

Metallographic studies were also made to understand the independent factors governing the nucleation and growth of cavities.

On the basis of experimental results it was shown that correlations between different parameters can be established. This brings together a number of experimental factors suggesting that the time to creep failure may be predicted.

INTRODUCTION

Materials are now increasingly being used at elevated temperatures under stressed conditions such as in pressure vessels, turbine blades, steam pipelines etc. At a temperature of about half the melting point materials may fail by creep due to the nucleation and growth and eventual linking together of cavities along grain boundaries [1,2,3], This failure occurs with a very little elongation under a small stress over a prolonged period [4,5], It should be noted that although the material is getting softer at this higher temperature yet it is showing greater brittleness.

This creep failure is controlled primarily by thermally activated processes such as migration of dislocations, grain boundary sliding and diffusion of vacancies. Materials have been developed with improved creep resistance but

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elimination of creep is not yet possible. It is therefore necessary to know the life time of materials in services from the stand point of replacement time, economy, improvement, etc.

There are primarily three factors that govern damage during creep, namely—stress, time and strain. Usually data are available with stress as constant The present study concentrates on the independant effects of time and strain on creep damage with stress as a variable under low stress condition.

EXPERIMENTAL PROCEDURE

The material used was oxygen free pure copper which is known to cavitate easily without structural complications.

Measurements for density change was carried out according to a differential method by the help of a dummy, developed by Ratcliffe[6]. Density changes smaller than I part in 10^6 could be detected.

Specimens were creep tested in a simple dead-loading creep rupture machine. The tests were performed under different stress conditions and were stopped either at constant strain or at constant time. All tests were carried out at a constant temperature of 500°C in an Argon gas atmosphere.

Electron fractography method is very useful In studying cavities but its application is limited to materials that fracture intergranually [7, 8]. So the specimens were studied by optical microscopic observations. They were sectioned in longitudinal as well as transverse directions. It has been found that the true profile of cavities and cracks may be destroyed by usual polishing or etching technique[9]. Thus, cavitated specimens were prepared with special care. To avoid smearing due to sawing the specimens were cut by electric spark. After the final diamond polishing and cleaning in the usual way the mounted specimens are put in an ultrasonic bath. Finally a skid polishing was carried out on a cloth placed on a glass plate using paste consistency of magnesia and a solution of 10gms/litre of ammonium persulphate in distilled water. This gave lightly etched specimens where the true shape of the cavities were retained. After the skid polish the specimens were again put in the ultrasonic bath under methanol.

After polishing, the specimens were studied under optical microscope and photographs were taken at a magnification of 200 times.

EXPERIMENTAL RESULTS AND DISCUSSION

The creep curves obtained from the creep testing machine are given in Fig. 1. The measurements of density change simply provided an assessment of the total volume of all the cavities present without discrimination of their shape, size or number. The stress (σ), time (t), strain (ζ) and change of density ($\triangle p/p$), which is a measure of increase in volume $\triangle v$ of the specimens experimented, are listed in Table 1. Calcu-

TABLE 1

Specimen Number	Creep Temp.°C	Stress Applied (σ) MN/m^2	Creep time (t) hrs,	Creep Strain (ζ) α	Density Change ($\triangle p/p$)x10^{-3}	Number of Cavities (N) N/mm^2 x10^{-2}
1	500	20	17.00	5.88	3.0	4.60
2	500	27	4.83	5.96	1.3	6.08
3	500	21.5	17.00	11.88	8.8	12,30
4	500	21.5	12.00	6.54	3.1	6.40
5	500	20	12.00	4.38	1.95	3.36
6	500	20	22.00	8.62	6.4	8,04
7	500	27	6.83	8.44	3.5	9.32

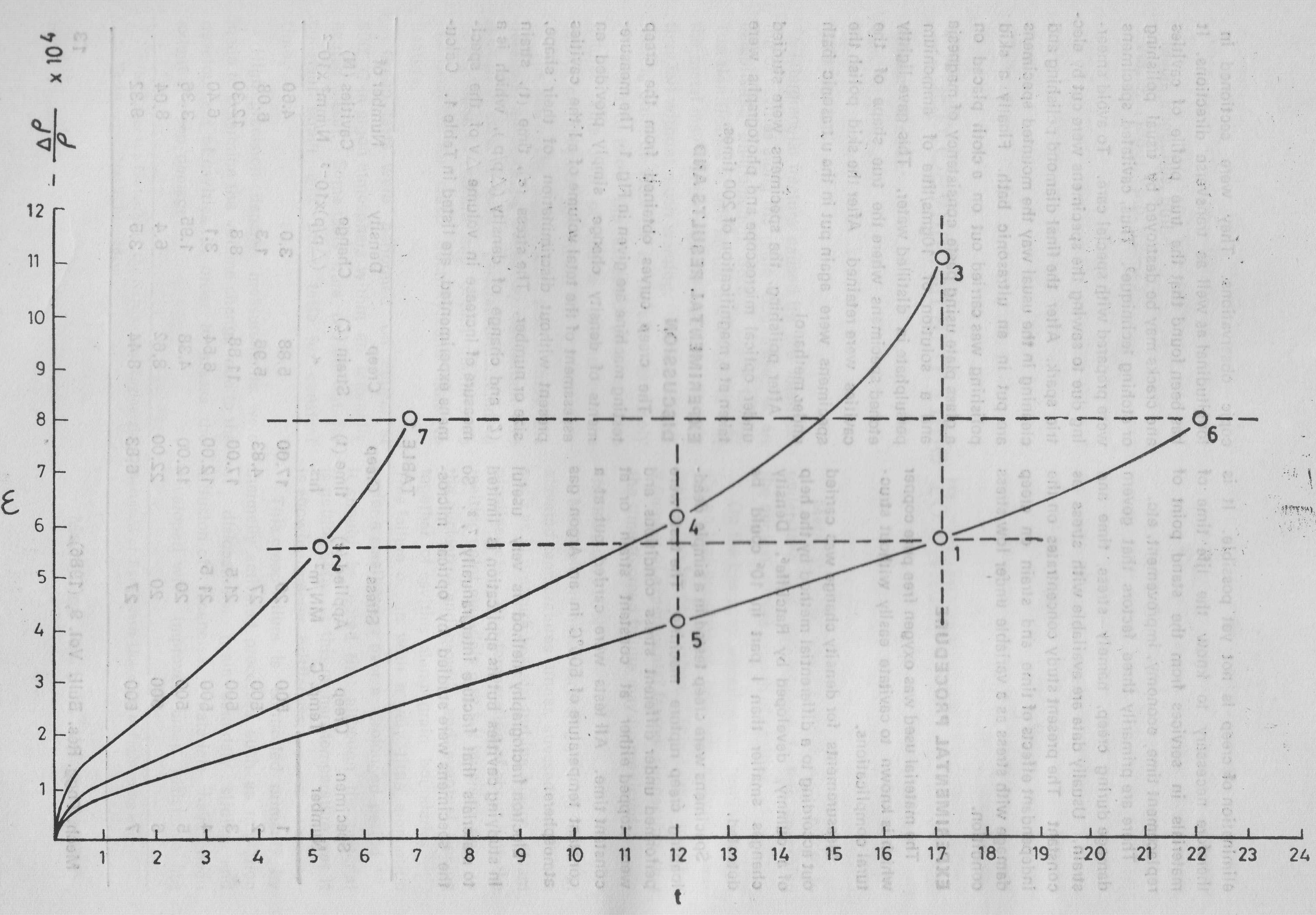

Fig. 1. The creep curves for different stress levels are marked with their specimen numbers.

lations were made to find out the relationships among the different parameters. The results were plotted on graphs (Fig. 2, Fig. 3 & Fig. 4).

Optical observations were made and typical distribution of cavities was seen. Isolated voids appeared to be rounded in section. The preservance of this round shape during growth indicates that diffusion process must play a major part here. When the cavities along a grain boundary link up to form an elongated crack, they are convincingly found oriented approximately normal to the stress axis in the longitudinal section (Fig. 5). This suggests that grain boundary sliding has little influence on growth which would have caused it in the 45° angle with the stress axis where slip is predominant.

The microstructure of specimen 1, (Fig 5), shows that many cavities have linked together to form quite large and wide cracks in the logitudinal section. This was compared with specimens 2 (Fig. 6) which has the same strain as specimen 1 with a higher stress. It may be assumed that the lower stress has produced a greater damage, probably due to the longer interval of time. Hence. diffusional process might be expected to dominate in the cavity growth. The creep time of specimen 3 (Fig. 7) is the same as that of specimen 1 but at a higher strain. The

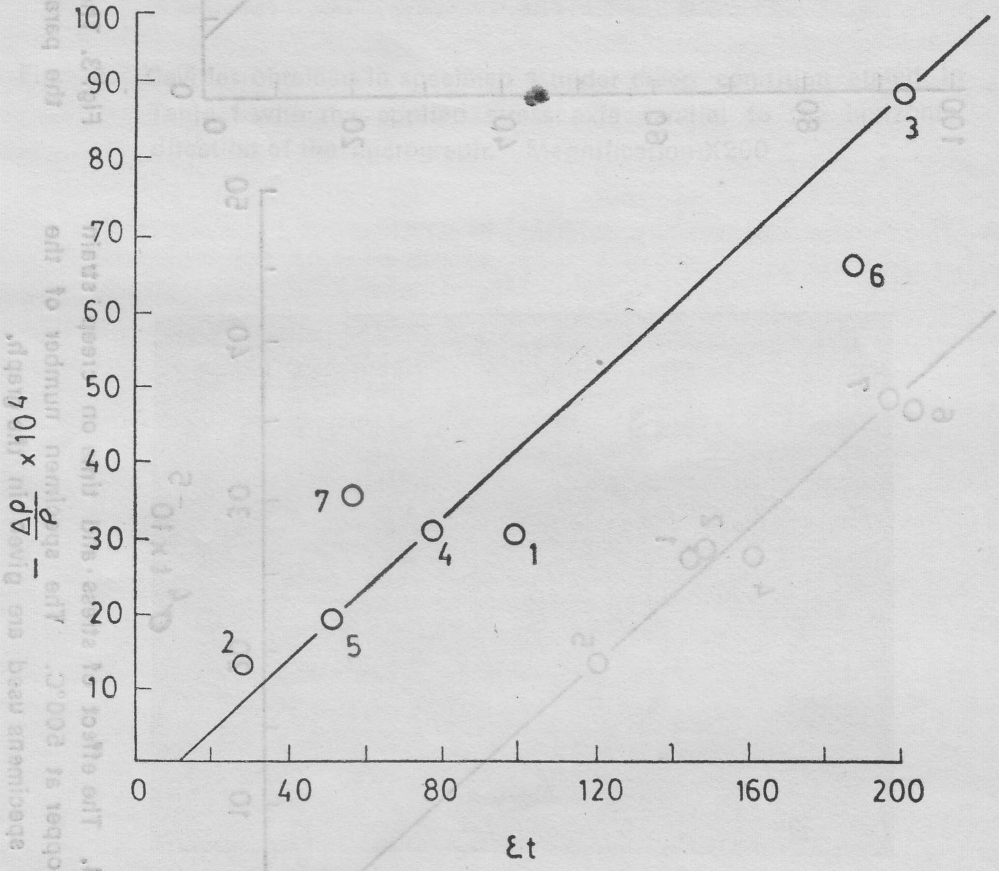

Fig. 2. The relationship between the fractional density change due to cavitation, in copper at 500°C. with creep strain and time. The data obtained from the specimens are numbered on the gragh.

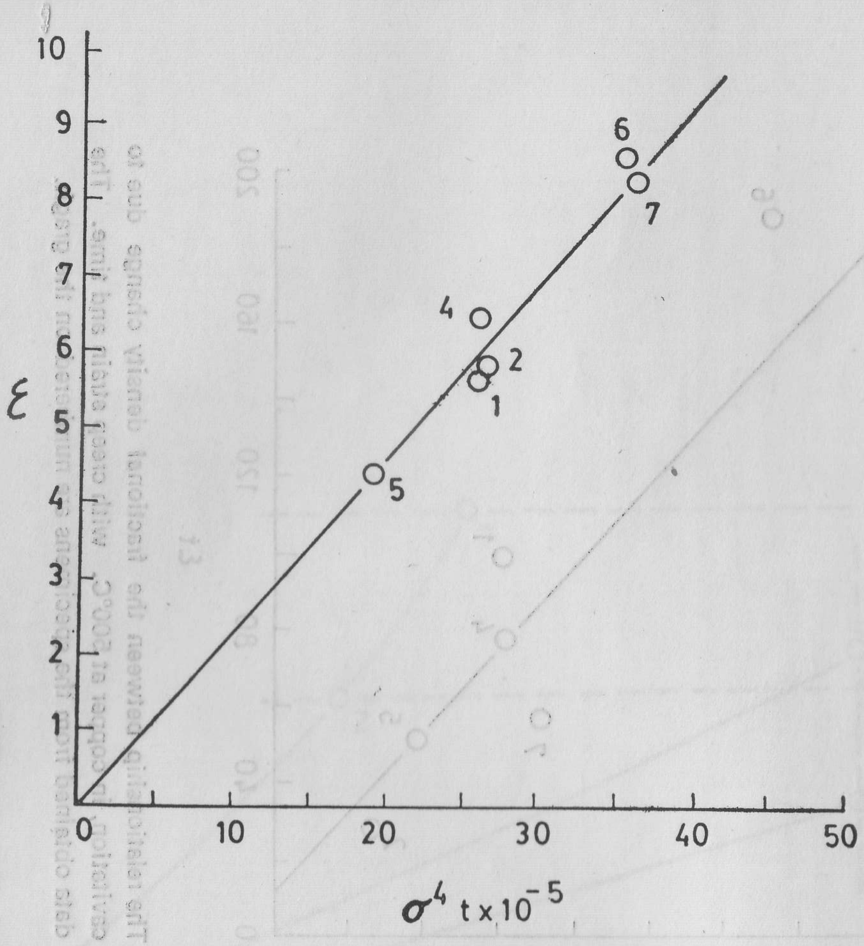

Fig. 4. The effect of stress and time on creep strain in copper at 500°C. The specimen number of the specimens used are given in the graph.

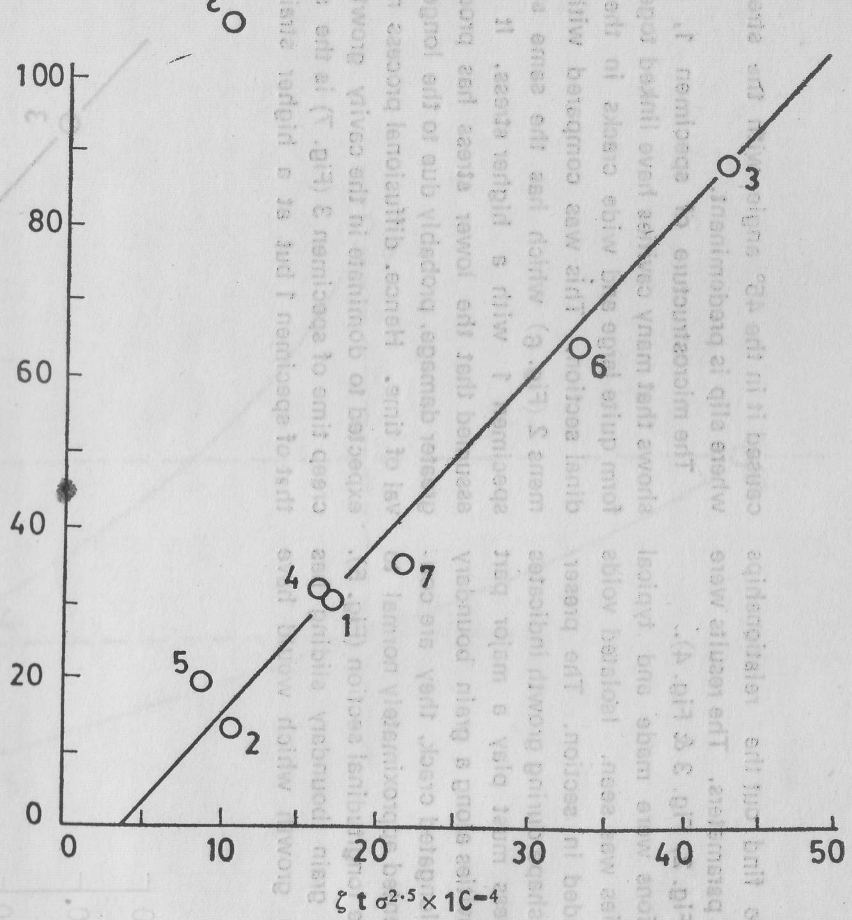

Fig. 3. The relation between the fractional density change and the parameter at $\sigma^{2.5}$ for creep of copper at 500°C. On the graph, the numbers refer to the specimens used.

comparison shows that the size and the linking together of cavities in both the cases are similar, only the number is much more in specimen 3. This suggests that strain has no part in growth of cavities, only time is the major factor in its growth and stress and may be the strain controls the nucleation. Specimen 4 has the same stress level as specimen 3 with a lower strain. Here also a large number of cavities were present but less than in specimen 3, indicating that nucleation is also governed by strain. Since the creep time of specimen 4 was less than that of specimen 3, this explains the smaller size of the cavities observed without much linking together (Fig. 8) Specimen 5 has the same creep time as specimen 4 but has a lower stress and naturally

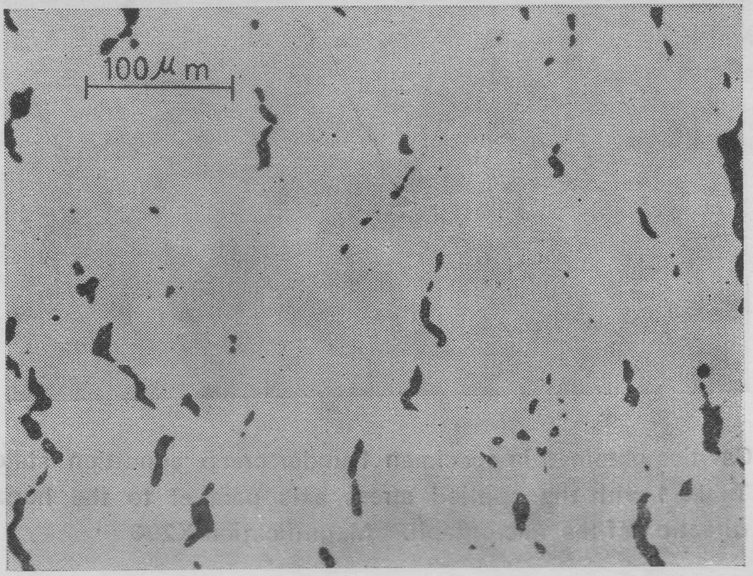

Fig. 7. Cavities obtained in specimen 3 under creep condition stated in Table 1 with the applied stress axis parallel to the horizontal direction of the micrograph. Magnification X200

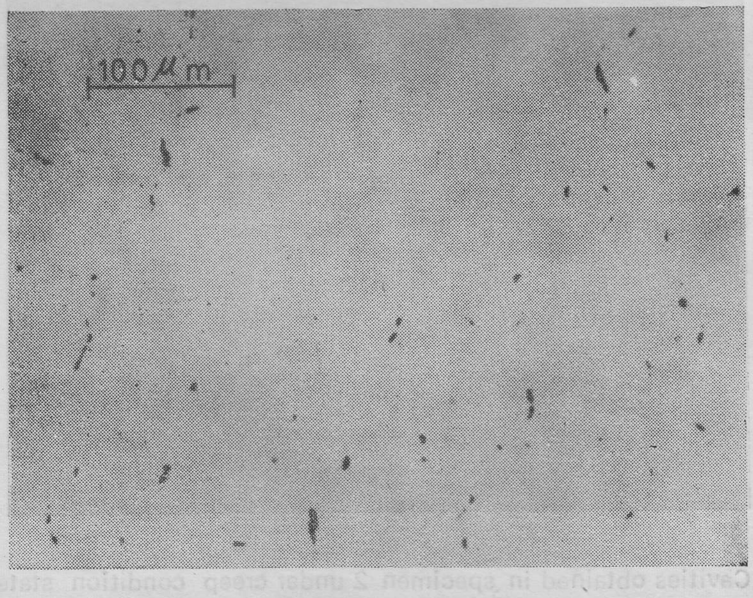

Fig. 8. Cavities obtained in specimen 4 under creep condition stated in Table 1 with the applied stress axis parallel to the horizontal direction of the micrograph Magnification X200

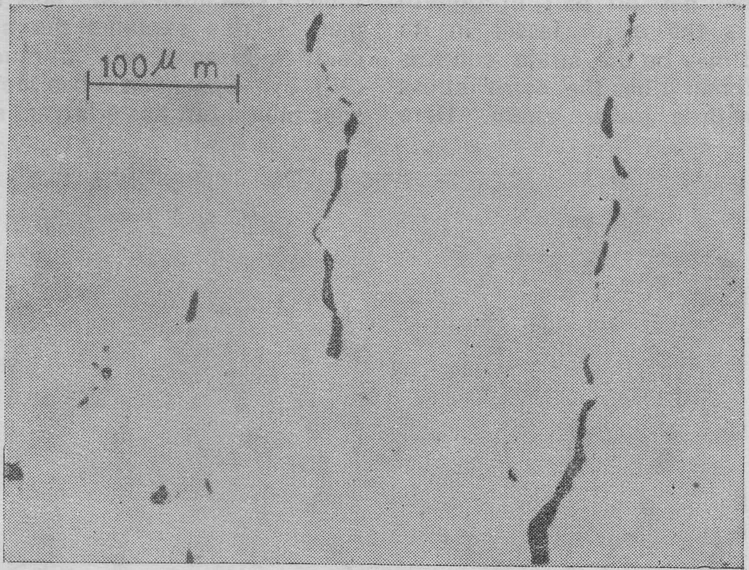

Fig. 5. Cavities obtained in specimen 1 under creep condition stated In Table 1 with the applied stress axis parallel to the horizontal direction of the micrograph. Magnification X200

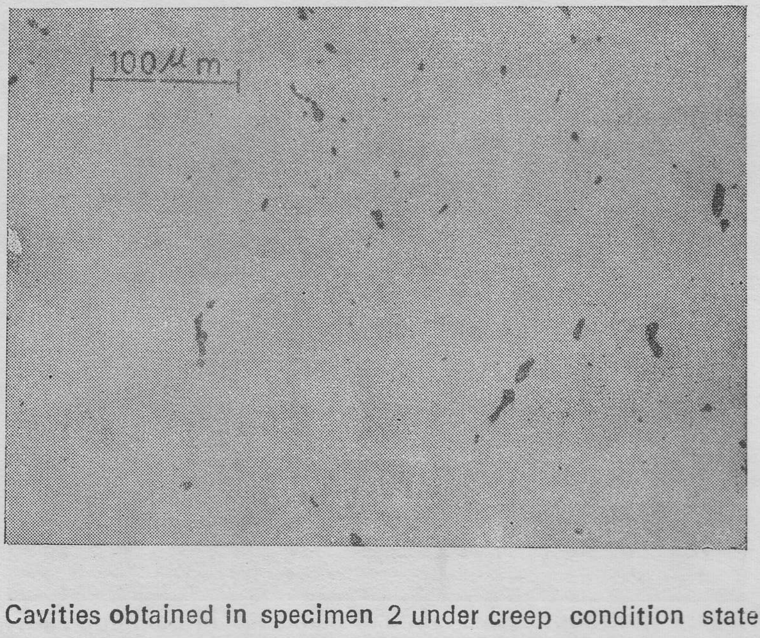

Fig. 6. Cavities obtained in specimen 2 under creep condition stated in Table 1 with the applied stress axis parallel to the horizontal direction of the micrograph. Magnification X200.

lower strain ; a much less number of cavities were seen (Fig. 9). This agrees that stress and strain dominate nucleation. Specimen 6 has got the longest creep time and the biggest cavity size was observed in it (Fig. 10), confirming that time or in other words diffusion is the controlling factor for cavity growth. Specimen 7 has the same strain as specimen 6 but with a higher creep stress. It showed a greater number of cavities (Fig. 11) than did specimen 6 confirming cavity nucleation is dependent on stress.

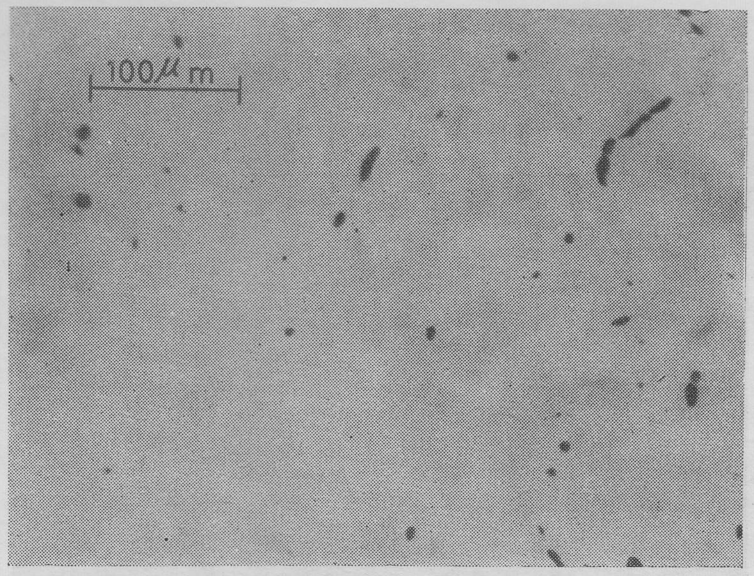

Fig 9. Cavities obtained in specimen 5 under creep condition stated in Table 1 with the applied stress axis parallel to the horizontal direction of the micrograph Magnification X200

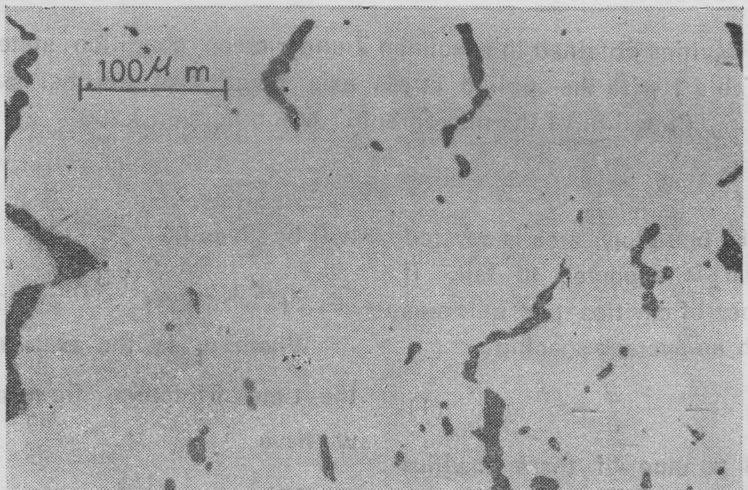

Fig 10. Cavities obtained in specimen 6 under creep condition stated in Table 1 with the applied stress axis parallel to the horizontal direction of the micrograph Magnification X200

The number of cavities increases approximately linearly with strain (Fig. 12). It may also be suggested from the graph that at any given strain the specimen at higher stress undergoes more nucleation. It was observed in Fig. 13. that nucleation increases almost linearly with stress time strain.

Creep damage must be inherently related to creep life and ductility. Hence the evaluation of creep damage should lead to a prediction of the time, t_f at which fracture is expected and the strain ζ_f reached at this time.

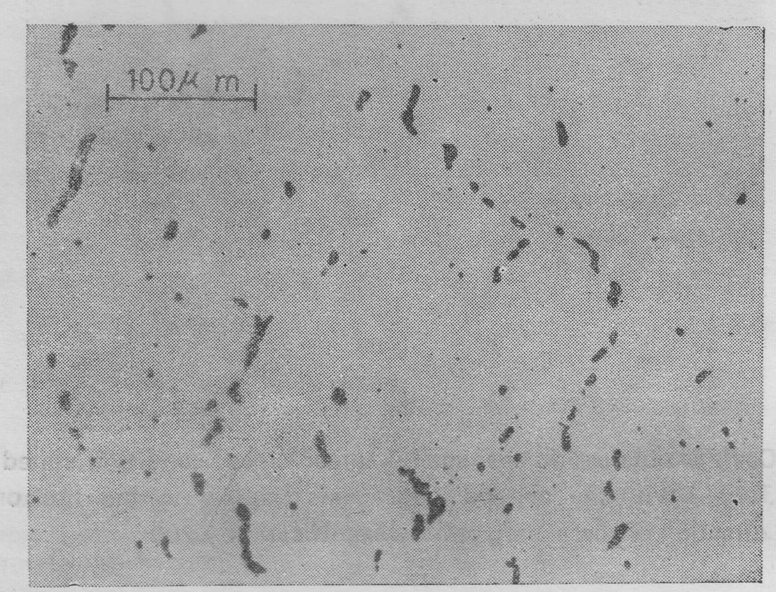

Fig. 11. Cavities obtained in specimen 7 under creep condition stated in Table 1 with the applied stress axis parallel to the horizontal direction of the micrograph. Magnification X200

When a large grain boundary area is covered by cavities the material is expected to fail. If N is the average number of cavities per unit area of grain boundary with an average spacing

x, then $N, = X^{-2}$ — — (1)

If v is the average volume of these cavities they will coalesce when their average linear dimension L in the plane of the boundary is equal to X. With the assumption that cavities are of similar shape, L becomes proportional to $v^{1/3}$, so the cavity specing X_f at which fracture occurs will be given by

$x_f = L \propto v_f^{1/3}$ — — (2)

Where v_f is the average cavity volume at the time of fracture, from equation (1) and (2) we have

$N_f^{-\frac{1}{2}} \propto v_f^{1/3}$ — — (3)

Thus the fracture criterion can be written :

$N_f^3 v_f^2 = F$ — — — (4)

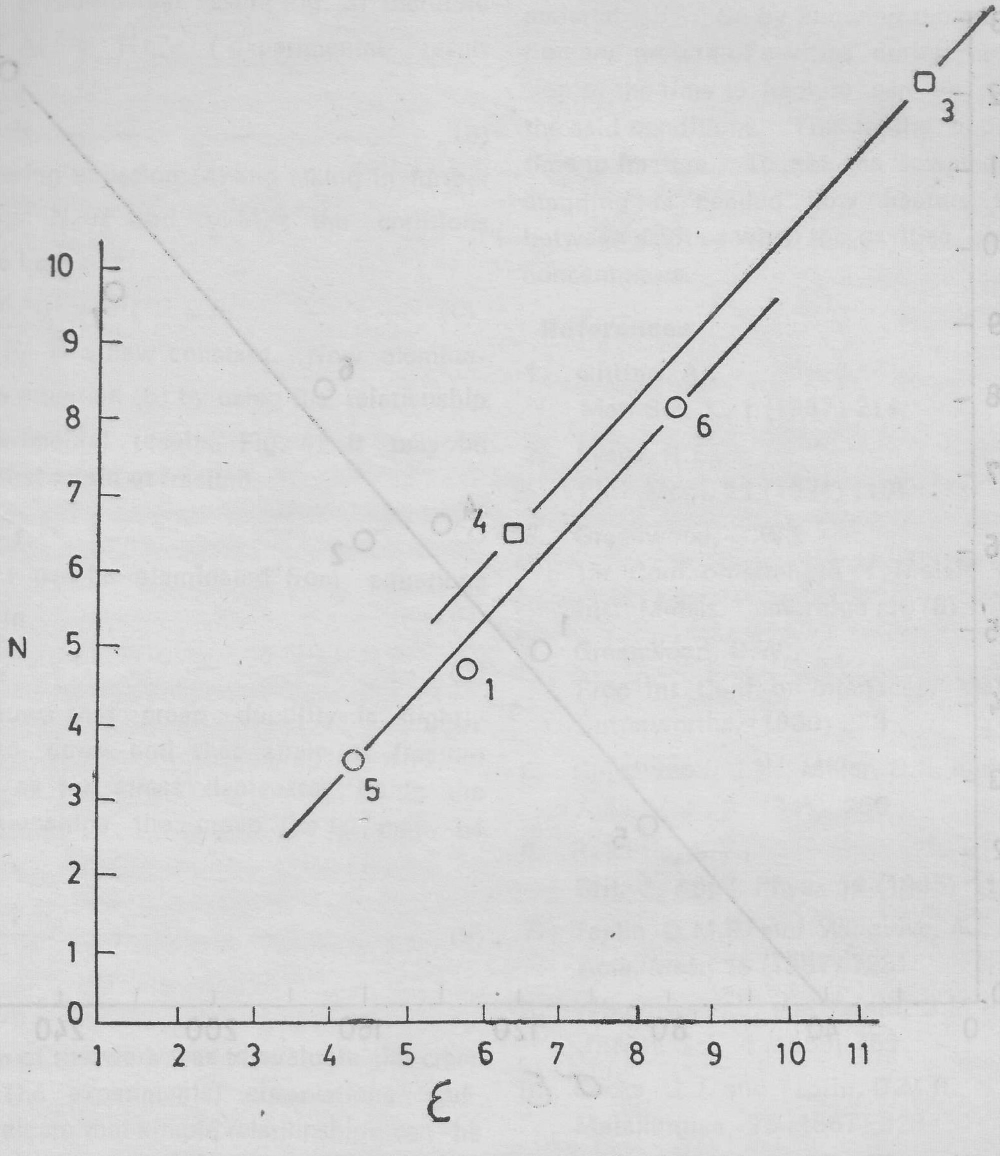

Fig. 12. **The variation in the number of cavities per unit area with strain under constant stress conditions, The numbers on the graph refer to the specimens used.**

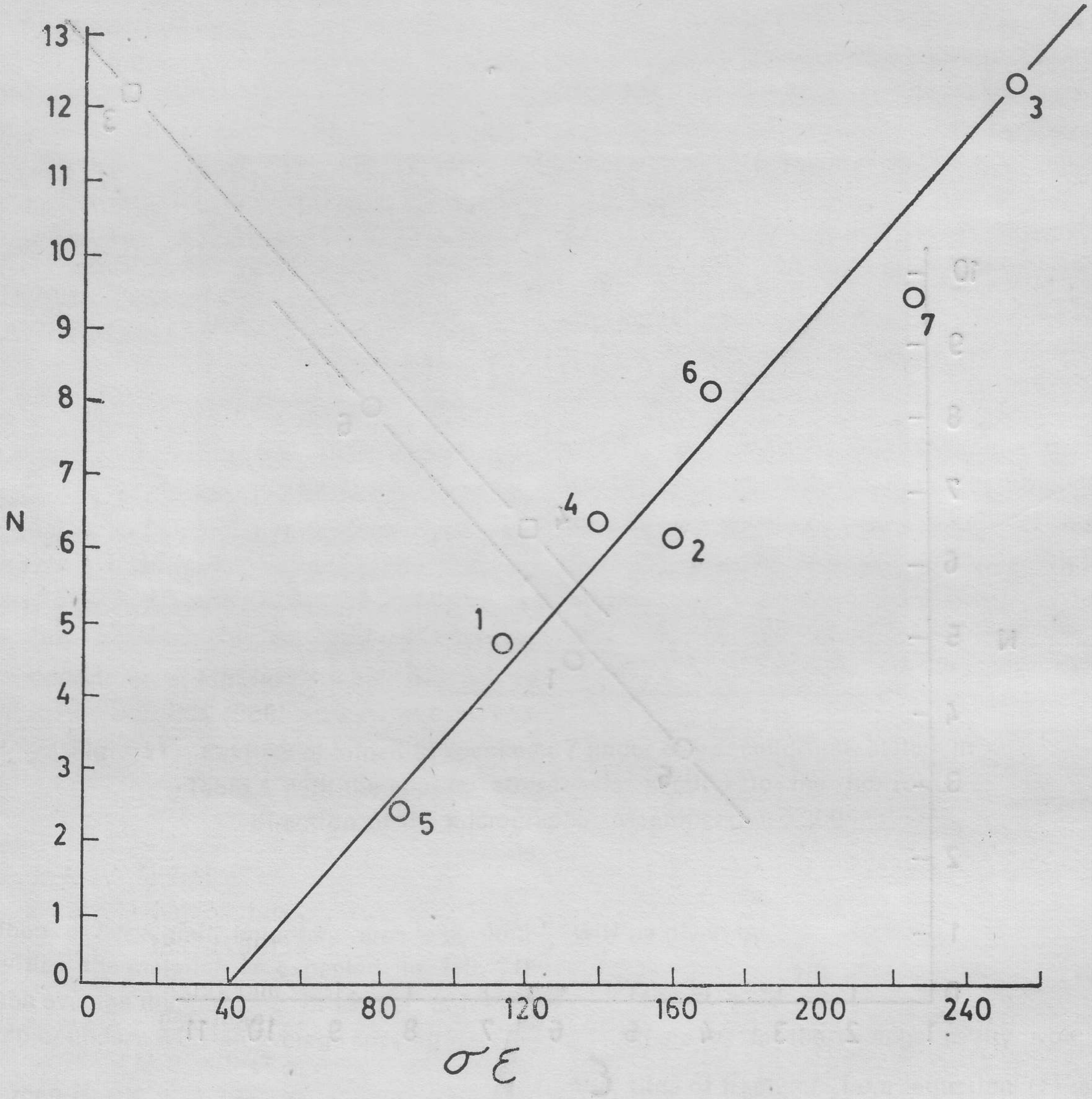

Fig. 13, The variation in the number of cavities per unit area with stress and strain. The numbers on the graph represents the specimens used.

Where N_f is the number of cavities per unit area at the instant of fracture, and F is a constant.

Since the volume increase $\triangle V$ caused by the cavity formation is proportional to Nv and $\triangle V \propto \zeta t \sigma^{2.5}$ (experimental result, Fig. 3) therefore $NV \propto \zeta t^{2.5}$. Again $N \propto \zeta \sigma$ (experimental result Fig 13) so

$$V \propto \sigma^{1.5} t \qquad — \qquad — \qquad — \qquad (5)$$

Considering equation (4) and taking in further relationships $N \propto \sigma \zeta$ and $V \propto \sigma^{1.5} t$ the coditions for fracture becomes

$$(\sigma \zeta)^3 (\sigma^{1.5} t)^2 = \sigma^6 \zeta^3 t^2 = F_1 \qquad — \qquad — \qquad (6)$$

Where F_1 is a new constant. Now eleminating σ from equation (6) by using the relationship $\zeta \propto \sigma^4 t$ (experimental results, Fig. 4), it may be deduced that strain at fracture

$$\zeta_f \propto 1/t_f^{\ 0.11} \qquad — \qquad — \qquad — \qquad (7)$$

Again t can be eleminated from equations (6) to obtain

$$\zeta_f \propto \sigma^{0.4} \qquad — \qquad — \qquad — \qquad (7)$$

This shows that creep ductility is slightly sensitive to stress and that strain at fracture is reduced as the stress decreases. Using the same relationships the creep life t_f may be given by

$$t_f \propto \frac{1}{\sigma^{3.6}} \qquad — \qquad — \qquad — \qquad (9)$$

Conclusion

The aim of the work was to evaluate the creep damage. The experimental observations and analysis indicate that simple relationships can be developed to account for many features relating to nucleation and growth of cavities in copper causing damage during creep at lower stresses and at a temperature of about half the melting point of the metal.

When a large grain boundary area is covered by cavities that is when cavities coalesce the material fails. So by knowing the rate of nucleation and growth of cavities during creep prediction of the time to fracture can be made under the said conditions. This is the upper limit of time to fracture. To get the lower limit understanding is needed how fracture takes place between cavities when the cavities act as stress concentrators.

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