

## CREEP FAILURE BY CAVITATION UNDER NON-STEADY CONDITIONS

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## ABSTRACT

*A wide variety of phenomena can lead to failure at elevated temperatures but in many situations four stages, (a) the nucleation stage (b) cavity growth (c) cavity coalescence and (d) the final stage of relatively rapid fracture, can be identified. Attempts to predict failure under non-steady conditions are difficult because there are different effects of stress and temperature changes on the different stages and because these stages are not independent of each other. The paper concentrates on the first two stages and shows how, in some instances, results of experiments can be linked with theoretical approaches. By distinguishing between the factors that principally govern cavity nucleation and growth, some methods of prediction of creep failure become possible where these processes are dominant for a major part of the creep life.*

## INTRODUCTION

Many metals and alloys that are normally considered to be ductile may fail after relatively small extensions during creep under a tensile stress at elevated temperatures [1, 2]. Metallographic studies show that features leading to fracture can be identified at an early stage because there is a progressive formation and growth of cavities or cracks on grain boundaries, particularly those that are approximately normal to the applied stress [3, 4].

The present paper concentrates on the situation where the form of creep 'damage' is, for a large part of the creep life, in the form of discrete cavities. Such cavities cause a readily detectable volume increase in the material and they have been described as 'r-type' voids [5, 6]. This terminology is appropriate in so far as the voids may be considered to have an effective radius but it must be emphasized that their true shape can depend on the ratio of the surface and grain boundary free energies that relates to the elongation of cavities in the boundary plane and, in many instances, the surfaces of the cavities are not sections of spherical caps, but are crystallographic planes of low energy [7]. Nevertheless, through the Wulff theorem [8], the effective radius concept can still be rigorously applied. This approach is valuable since it permits on estimation the minimum stress below which cavities cannot be nucleated [4]. There appear to be no instances where cavities have been observed at an effective radius less than  $2\gamma_s/\sigma$  where  $\gamma_s$  is the surface free energy and  $\sigma$  is the applied tensile creep stress. Below this value, surface tension forces would be too strong to permit the cavity to remain and this consideration is supported experimentally. A possible exception to this

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relationship may be expected to be the situation where gas is present in the cavities since the tendency to sinter by surface tension forces is then resisted by the gas pressure and so external stress can cause immediate enlargement. However, these circumstances only make a minor change and it has been shown [9] that it is only cavities of a radius greater than  $4\gamma_s/3\sqrt{3}\sigma$  that can grow since any enlargement of the cavity results in a decrease in gas pressure inversely proportional to the cube of the effective radius. Thus the gas is only a minor aid to cavity nucleation in causing an effective radius that is, only to a small extent, greater than that of the observed cavity size. It now seems that it is only in the special cases where additional causes of vacancy supersaturation occur that nucleation can be substantially aided, such as by radiation effects, when dislocation lines act as preferential sinks for interstitials or by diffusion fluxes where, in a chemical potential gradient, a vacancy supersaturation can exist locally [10].

Despite the value of these basic considerations governing cavity nucleation, it has not proved easy to obtain firm experimental information either of the metallographic aspects governing cavity formation or of the relationships of external variables to the process.

One reason is that cavities are often not simply nucleated at the beginning of creep life, as has occasionally been envisaged [4], but they can form progressively with creep strain. This feature immediately complicates their contribution to creep failure because metallographic observations cannot reveal the behaviour of specific cavities since their individual lifetimes are not known.

Of the many possible approaches to the study of cavitation, one is to establish, as far as possible, the cavity growth laws on a statistical basis and with a knowledge of the total cavity volume, the numbers of cavities existing at any instant can be subsequently derived. Thus, although the stages of nucleation and growth occur in parallel, the processes may be distinguished: the situation can be further clarified by the effect of hydrostatic pressure. The establishment of theories of the growth of cavities by diffusive fluxes leads to firm predictions about the laws governing cavity growth and, in the present paper, support is accumulated for lines of further theoretical development. The role played by hydrostatic pressure, in particular, provides strong support and permits data to be obtained on the factors governing cavity nucleation by dealing with situations where cavity growth rates are made constant, independently of the applied tensile stress. Such approaches are now also supported by work on the multi-axial stress systems.

#### LAWS GOVERNING CAVITY GROWTH

Discussion has ranged over many years on the possible factors that may contribute to cavity growth [2]. The main problem has been to decide the extent to which essentially diffusive processes [11] can contribute to growth compared with the contribution of mechanisms related to overall plastic deformation. Even major reviews [6] of creep fracture have found it difficult to draw firm conclusions from critical assessments of the overall situation, because there is much evidence that different materials or the same material under different conditions may act in quite different ways. The use of 'fracture maps' [12] goes some way towards resolving the situation in categorising behaviour in the different regimes of stress and temperature whereby the roles of the various parameters relating to creep

failure may be considered in relation to the specific circumstances. Detailed additional features, however, urgently require examination, such as the extent to which grain boundaries can act as vacancy sources, the effectiveness of diffusive processes in preserving cavity shape in a near equilibrium form and the further possibility [13] of the need for the matrix to be deformed at an adequate rate to accommodate cavity growth.

Without ignoring the complications referred to above, it is the regime where diffusive processes are likely to be most significant that is most generally of technological concern. Moreover, the influence of diffusion along grain boundaries often predominates over that of lattice diffusion [14]. The theoretical analysis of cavity growth under these conditions has been developed [15, 11] in a satisfying way although the variability of extent of experimental support [6] has often limited the appreciation of its range and value.

Recently, small errors in the analysis have been detected and improvements made, but in all cases the cavity growth rate  $dv/dt$  has the form

$$dv/dt = f D_B \delta z [\sigma - P - (2\gamma_s/r)] \Omega/KT \quad (1)$$

where  $\sigma$  is the tensile creep stress,  $P$  is the superimposed hydrostatic pressure and  $f$  is a dimensionless constant, which is also a function of the ratio of cavity radius to spacing ( $r/x$ ).

The influence of the ratio ( $r/x$ ) is illustrated in Figure 1 which summarises the results of four analyses [11, 16, 17, 18] shown as curves (a), (b), (c) and (d) respectively and there now seems common agreement [14] that (d) is the most accurate. It is possible to make reasonable approximations, since, from Figure 1,  $dv/dt$  becomes independent of ( $r/x$ ) for large cavity spacings, but as cavities become closer, their volumetric growth rate increases. There have been very few valid examinations of this expression because, as indicated earlier, cavity lifetimes cannot be individually determined, true cavity shape makes volume assessment difficult and they are, in the early stages, too small for precise measurement by optical microscope, though too large for study in thin foils by transmission electron microscopy even at LMV. Observations that appear most free from criticism involve careful sectioning and surface preparation followed by ion bombardment etching and examination by scanning electron microscope. In testing equation (1), it would seem most appropriate to determine the size of the largest cavity since this would have the highest probability of being created near to, or at, the start of creep life. The difficulty is to observe a sufficiently large area and there is the further problem of the orientation of the grain boundary with respect to the tensile stress axis. These problems, however, are somewhat eased since the linear growth rate is expected to be proportional to  $t^{1/3}$  and so the rate of increase of linear dimensions becomes progressively smaller until coalescence takes place. This conclusion is supported by observations.

A less direct way of evaluating cavity growth is to determine, by density measurements, at stages of creep life, the total volume of all the cavities that are present and such measurements have recently become very common [19]. In no instances, however, have they given close agreement with equation (1) and probably the main, though not the only, reason is that no account is taken of the effect of cavity formation during creep.

Most information is available on copper and early studies [20, 21] have been analysed and interpreted in a particularly clear way [22], showing that the total volume of all cavities  $\Delta V$  is given by

$$\Delta V \propto \epsilon t \sigma^{2.3} \exp(-Q_B/RT) \quad (2)$$

where  $Q_B = 94 \text{ kJ/mol}$  which is about the value expected for the activation energy of grain boundary self diffusion and similar to those derived from low temperature diffusion creep experiments [23].

Equation (2) was interpreted to show that the growth law for individual cavities took a form similar to that predicted by equation (1) when a self consistent analysis was made and this also indicated that the number of cavities was proportional to strain but the separate effects of stress on nucleation and growth could not be identified. Such an interpretation receives strong support from studies of the effects of hydrostatic pressure [24, 25]. From the growth law of equation (1), at large cavity spacings, cavity volume should be proportional to  $\epsilon t$  at constant temperature and this is closely borne out by results on magnesium alloys [26] which are illustrated in Figure 2.

There is now substantial further evidence from studies both of magnesium and of copper, that results can be presented in a simple schematic form as shown in Figure 3. When  $(\sigma - P)$  is maintained constant, a series of creep curves can still be obtained because creep rate depends primarily on  $\sigma$ , although the influence of  $P$  on this rate has been found [25, 27] to be greater than that anticipated. In Figure 3, the primary and secondary stages of creep are shown, all at constant  $(\sigma - P)$  but with the top left creep curve corresponding to the highest value of  $\sigma$ . Because the total volume change  $\Delta V \propto \epsilon t$ , then lines which are rectangular hyperbolae corresponding to constant values of  $\Delta V$  can be drawn, the lowest value of  $\Delta V$  being represented by the line FG and the highest by JK. It follows that a simple geometrical construction can be drawn to deduce the total volume change at any instant, since this is proportional to the area of the rectangle OABC for the conditions corresponding to point B on the creep curve OB. The validity of this construction has only been demonstrated for magnesium and for copper and further work is required to determine the extent of its applicability. In such determinations, however, it should be borne in mind that it cannot be expected to hold where conditions are outside the regime for which a 'fracture map' would predict this behaviour, or where grain boundaries are not efficient sources of vacancies and/or where cavity nucleation is not proportional to strain.

#### CAVITY NUCLEATION

The mechanism of nucleation continues to give rise to much speculation in many areas of metallurgy [8] and the nucleation of cavities in creep is no exception to this. Information on which there is common agreement [6] is mainly restricted to a consideration of a critical minimum size which depends on the applied stress. This means that in typical creep experiments on copper and magnesium this critical size has usually been greater than about 0.3 microns, though in nickel alloys and in other creep resisting materials capable of withstanding high stresses with little deformation at elevated temperatures the effective radius can be as small as 0.05 microns. There are numerous instances where particles are found to be associated with cavities [4] but this is not invariably the case. There is, however, always the possibility that particles may fall away from the cavities or

that they may exist in the remaining part of the specimen. Very occasionally it has been possible to establish by scanning electron microscopy of creep fracture surfaces, cavities without particles on one side of a specimen that are matched by the corresponding cavities with particles on the other side of the fracture.

One interesting speculation [14] is that cavity nucleation in creep follows the relatively well-developed thermodynamic theories of nucleation. With such laws then predictions can be made of the influence of stress and of temperature. There is clearly an urgent need for more experiments on this aspect but first indications are that classical nucleation theory over simplifies the true situation.

In a number of instances, it has been observed that the number of cavities is linearly proportional to strain [28, 29] although it would seem that there is likely to be an exhaustion in the total cavity nuclei and that, as strain proceeds, there is a progressive departure from linearity [30]. Nevertheless, over a large part of the creep life, for a number of metals, it may be taken as a reasonable approximation that the number of cavities is linearly proportional to strain at a constant stress and temperature. It is the lack of sufficient experimental investigations with the latter two parameters kept constant that has limited the degree of confidence that can be placed in the nucleation/strain relation.

A further exploration, which has only been made to a limited extent, is that of determining the variation of the number of cavities at constant strain with the level of stress. The few results that have been obtained here differ to some extent between different materials and conditions but there appear to be some clear instances where the number of cavities at constant strain and temperature is proportional to the square of the applied stress [31, 32]. There is, however, support for this relationship from assessments of the strain, time, stress and temperature relationship governing the change in volume due to cavitation as expressed in equation (2). The change in volume can be measured relatively easily by change in density and this measurement is not destructive and so many of the variables inherent in other experiments can be eliminated as the progressive change in volume due to cavitation is determined by interrupting the creep test at various appropriate intervals. More recent work has indicated a stress exponent for volume change close to 3, and so, taking the growth law of widely spaced individual cavities derived from equation (1), for  $P = 0$  and  $r$  large, as

$$dv/dt \propto (\sigma/T) \exp(-Q_B/RT) \quad (3)$$

we arrive [32] at this relationship for nucleation in the form

$$dn/d\epsilon \propto \sigma^2 \quad (4)$$

Since  $v$  and  $n$  (= number of cavities) are both zero, for zero time and strain, and the total volume change  $\Delta V = \sum n_i v_i$ , then equations (3) and (4) are compatible with equation (2) when the exponent of  $\sigma$  in equation (2) is increased to 3.

It is to be noted that no temperature term is included in equation (4). This is a somewhat surprising feature and requires more extensive experimental study but direct support appears to be forthcoming [38] from metallographic studies of copper after creep at constant stress to a given strain

over a relatively wide range of temperature.

Although it would be unrealistic to presume that these relationships have general application covering all materials under a wide range of conditions, nevertheless, when this simple approach can be adopted, the pattern of behaviour can be fully described and it will be shown later that such relations have considerable promise for assessing behaviour under more complex and non-steady conditions. Before dealing with this situation, however, it is appropriate to consider some aspects of the final stage of fracture.

#### THE FINAL STAGES OF CREEP FRACTURE

There is much evidence to suggest that heavily cavitated material may sometimes still possess a large measure of ductility. Indeed, in ultra-fine grain materials it has been shown [2, 33] that superplastic behaviour may occur, leading to elongations of more than 1,000% even when cavities have existed throughout most of the deformation process. Thus it is not appropriate in general cases to assume that when cavities on any one grain boundary link completely together then fracture automatically and immediately results. The reason is that, in such fine grain material, the cavities which coalesce do not result in the propagation of cracks perpendicular to the principal applied tensile stress but the cavities may begin steadily to elongate in the direction of this stress [34] and have only a small effect in reducing the ductility. This observation supports many reports of an increase in creep ductility with decrease in grain size [2]. This may suggest an easy way of eliminating creep failure but it often carries the penalty of reducing creep strength particularly at low stresses where diffusion creep processes can have an important effect [23].

It is with coarse grained materials, in general, and under relatively high stresses, that crack propagation is found to be important. The analysis of this situation has, not unnaturally, been linked closely with that of the interpretation of fracture toughness at low temperatures. In some cases, the stress intensity approach has been adopted to predict the conditions under which fracture would occur suddenly. Such an approach, however, has not often been found appropriate since, at elevated temperatures, relaxation processes become important and it may be argued that the stress across any grain boundary perpendicular to it tends to become nearly constant. This again is an approximation and particularly in studies of the progress of creep cracks introduced into materials prior to creep deformation, it is usually inadequate. Interpretations have varied from a 'net section stress approach' where the stress on grain boundaries perpendicular to the load is assumed constant to the other extreme where the criterion for crack extension has been taken to be the critical stress intensity. Results have generally fallen between these two extremes but, in the metals principally considered here, there is evidence that cavities become very close before cracks propagate between them and, providing the grain size is sufficiently large, for example - greater than 200 microns, failure of the metal occurs soon after this coalescence. The result of this is that, for copper and magnesium, the creep life only appears to be affected to a small extent by the final fracture stage although this stage may contribute significantly to the elongation in tertiary creep.

There is clearly a need for much further work in this area and information already available shows the great importance of microstructure [35]. It is this final stage of creep failure that is most difficult to evaluate

under non-steady conditions. In the situations where crack growth processes predominate over the majority of creep life, then acceptable analysis of varying conditions and their effects has hardly begun. On the other hand, where processes of cavity nucleation and growth to the stage of their link-up occupy a major part of the creep life, then the situation is considerably different and the approximate formulae mentioned previously that enable separations to be made of the processes of cavity nucleation and growth, also give hope that the effects of changes in stress levels and changes in temperature can be predicted. This aspect will now be considered in further detail.

#### THE INFLUENCE OF STRESS AND TEMPERATURE CHANGES ON CAVITATION

By extending considerations of the relationships outlined earlier, it is possible to make some predictions about the influence of non-steady conditions. The most convenient way of assessing the applicability of these considerations experimentally is to determine the cumulative change in volume caused by creep at different stress levels. The theory can be developed as follows.

Let  $n_1$  cavities be created during a creep strain  $\epsilon_1$  in time  $t_1$  at a stress  $\sigma_1$  so that at time  $t_1$  their average volume is  $v_1$ . Then the total volume change  $\Delta V$  due to all these cavities is given by  $\Delta V_1 = n_1 v_1$ . Now where the relationships discussed previously apply,  $n_1 = p \sigma_1^2 \epsilon_1$  and  $v_1 = q \sigma_1 t_1$  at constant temperature, where  $p$  and  $q$  are constants, so that:

$$\Delta V_1 = n_1 v_1 = pq (\sigma_1^2 \epsilon_1) (\sigma_1 t_1) = pq \sigma_1^3 \epsilon_1 t_1,$$

in reasonable agreement with results on copper and magnesium. In the next time interval  $t_2$ , let the stress level be changed to a new value  $\sigma_2$  which causes an increment of strain  $\epsilon_2$ . During this increment  $n_2$  new cavities are created and since  $dn/dc \propto \sigma$ ,

$$n_2 = p \sigma_2^2 \epsilon_2$$

and these cavities grow to an average volume:

$$v_2 = q \sigma_2 t_2$$

The  $n_1$  cavities formed previously, continue to grow and increase their average volume during this period by an amount equal to  $2q\sigma_2 t_2$  since they grow over the whole of this period. Thus the increment of volume change during this interval is

$$\Delta V_2 = (2n_1 v_2 + n_2 v_2) = pq (2\sigma_1^2 \epsilon_1 + \sigma_2^2 \epsilon_2) \sigma_2 t_2.$$

These relationships can be further extended to cover any change in stress level giving rise to a known strain in a specific time interval at a fixed temperature. The total volume change is obtained by adding up these individual increments.

$$\Delta V_1 = pq(\sigma^2 \epsilon) (\sigma t_1)$$

$$\Delta V_2 = pq(2\sigma_1^2 \epsilon_1 + \sigma_2^2 \epsilon_2) (\sigma_2 t_2)$$

$$\Delta V_3 = pq(2\sigma_1^2 \epsilon_1 + 2\sigma_2^2 \epsilon_2 + \sigma_3^2 \epsilon_3) (\sigma_3 t_3)$$



and we may write

$$\Delta V_j = pq[2(\sum_{i=1}^{j-1} \sigma_i^2 \epsilon_i) + \sigma_j^2 \epsilon_j] (\sigma_j t_j)$$

Adding to obtain the total volume change  $\Delta V_{\text{tot}} = \sum_{j=1}^k \Delta V_j$

$$\Delta V_{\text{tot}} = pq \sum_{j=1}^k [2(\sum_{i=1}^{j-1} \sigma_i^2 \epsilon_i) + \sigma_j^2 \epsilon_j] (\sigma_j t_j)$$

This expression is amenable to experimental checking and further studies are required to evaluate the extent of its applicability. The expression however, does not directly lead to a prediction of creep life, since this is not uniquely related to cavity volume. This link is not easy to obtain because of the uncertainty of predicting the condition for the onset of rapid failure due to final crack propagation. If, however, as may be the case in relatively large grained materials, cavity nucleation and growth form the greater part of creep life, then a relationship can be obtained for the total area of grain boundary removed by cavitation under varying stress and this may be related to the creep failure.

Following the concept of loss of continuity of material [36, 37] by progressive removal of grain boundary area, an approximate fracture criterion [32] may be written in the form  $F = \sum n_i v_i^{2/3}$  where  $F$  is a dimensionless constant which must be exceeded before failure occurs and  $\sum n_i v_i^{2/3}$  is the fractional area of grain boundary removed by the cavities. Hence, if  $A_1$  is the fractional area of grain boundary occupied by  $n_1$  cavities of average volume  $v_1$  which form after a strain  $\epsilon_1$  under a stress  $\sigma_1$  for time  $t_1$ , then  $A_1 = n_1 v_1^{2/3}$ . If, in the next time interval  $t_2$  under a stress  $\sigma_2$ ,  $n_2$  voids are formed which grow to an average size  $v_2$ , then they occupy a fraction of area  $n_2 v_2^{2/3}$ . In addition, during this time interval, the  $n_1$  voids already present have grown throughout and so their average volume has increased by  $2v_2$ . Thus the increase in fractional grain boundary area that they occupy is given by  $n_1(v_1 + 2v_2)^{2/3} - n_1 v_1^{2/3}$ .

We can now describe the progressive increase in fractional area of grain boundary removed by the relations:

$$A_1 = n_1 v_1^{2/3}$$

$$A_2 = n_2 v_2^{2/3} + n_1(v_1 + 2v_2)^{2/3} - n_1 v_1^{2/3}$$

$$A_3 = n_3 v_3^{2/3} + n_2(v_2 + 2v_3)^{2/3} - n_2 v_2^{2/3} + n_1(v_1 + 2v_2 + 2v_3)^{2/3} - n_1(v_1 + 2v_2)^{2/3}$$

Hence, by addition, the total fraction of area removed

$$\begin{aligned} A_{\text{tot}} &= \sum_{j=1}^j A_j \\ &= n_j v_j^{2/3} + n_{j-1}(v_{j-1} + 2v_j)^{2/3} + n_{j-2}(v_{j-2} + 2v_{j-1} + 2v_j)^{2/3} \\ &\quad \dots + n_2[v_2 + 2(\sum_{i=3}^j v_i)]^{2/3} + n_1[v_1 + 2(\sum_{i=2}^j v_i)]^{2/3} \end{aligned}$$

This expression can now be directly related to changes of stress for known intervals of time by substituting for  $n_j$  and  $v_j$  from the relations  $n_j = p\sigma_j^2 \epsilon_j$  and  $v_j = q\sigma_j t_j$  and fracture is predicted to occur when  $A_{\text{tot}} = F$ .

This approach can be further extended to assess the effects of changes in temperature by writing the rate of change of cavity volume as indicated in equation (3). Thus the volume  $v_1$  of a cavity growing for a time  $t_1$  under a stress  $\sigma_1$  at a temperature  $T_1$  can be written

$$v_1 = q_1(\sigma_1 t_1 / T_1) \exp(-Q_B / RT_1)$$

where  $q_1$  is a new constant. The fraction of grain boundary area  $A_1$  removed by the  $n_1$  cavities continually nucleating and growing to an average volume  $v_1/2$  during this time, when a strain  $\epsilon_1$  is reached is given by

$$A_1 = (p \sigma_1^2 \epsilon_1) [(q_1/2)(\sigma_1 t_1 / T_1) \exp(-Q_B / RT_1)]^{2/3}$$

By making appropriate substitutions, the conditions leading to failure can be evaluated and this approach can be further developed to allow the effects of both stress and temperature changes to be taken into account. Moreover, the effect of stress systems can also be incorporated because of knowledge of the influence of hydrostatic pressure.

An extensive experimental programme is clearly required to assess the validity of these developments but first results indicate the relevance of this analysis to studies on copper. In materials where crack propagation predominates in controlling behaviour, however, close agreement cannot be expected. The analysis is directed towards materials where cavity nucleation and growth mainly influence creep life and, even though substantial modifications may be found necessary in the approximations taken for cavity growth and for nucleation in particular, computer programmes can readily take into account the factors not included in the simple equations manipulated here.

## CONCLUSIONS

Because of the many variables that influence fracture during creep, much information is still required before general predictions become possible of the likelihood of creep failure when the conditions of stress, stress system, or temperature are not steady. The present paper has dealt with situations that can be analysed in a relatively simple way, using approximate relationships that are becoming established for a few metals when factors that separately govern cavity nucleation and growth can be established and these processes occupy the major part of the creep life. Although there are likely to be different relationships for other materials and under different sets of conditions, the present approach indicates, nevertheless, how useful analyses may be developed for evaluating approximately the creep life when changes of stress or temperature take place.

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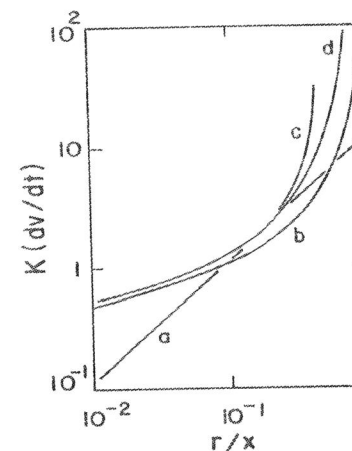


Figure 1 The variation in the rate of increase of cavity volume  $dv/dt$  with the ratio  $(r/x)$  where  $r$  is the effective cavity radius and  $2x$  is the cavity spacing.  $K$  depends on the parameters that are independent of  $(r/x)$  in equation (1). Curve (a) corresponds to the results derived in reference [11]; curve (b) to reference [16]; curve (c) to reference [17] and curve (d) to reference [18].

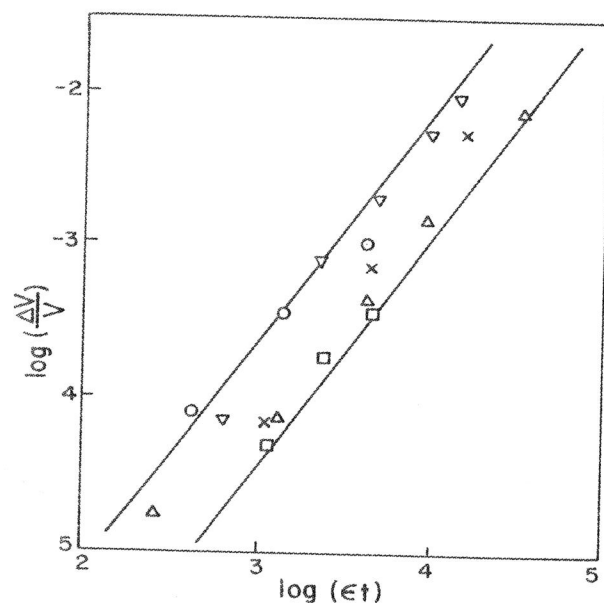


Figure 2 The variation of fractional volume increase  $\Delta V/V$  due to cavitation with the product  $\epsilon t$  where  $\epsilon$  is the creep strain (in percent) that occurs in  $t$  hours for magnesium at  $300^\circ\text{C}$  [26]. In all cases, the value of  $(\sigma - P)$  is constant where  $\sigma$  is the tensile creep stress and  $P$  is the independently superimposed hydrostatic pressure.

|                       |                |  |
|-----------------------|----------------|--|
| $\Delta$ and $\nabla$ | correspond to  | $\sigma = 4.67 \text{ MPa}$ and $P = 2.00 \text{ MPa}$ |
| $x$                   | corresponds to | $\sigma = 2.67 \text{ MPa}$ and $P = 0.00 \text{ MPa}$ |
| $o$                   | corresponds to | $\sigma = 6.67 \text{ MPa}$ and $P = 4.00 \text{ MPa}$ |
| $\square$             | corresponds to | $\sigma = 9.33 \text{ MPa}$ and $P = 6.67 \text{ MPa}$ |

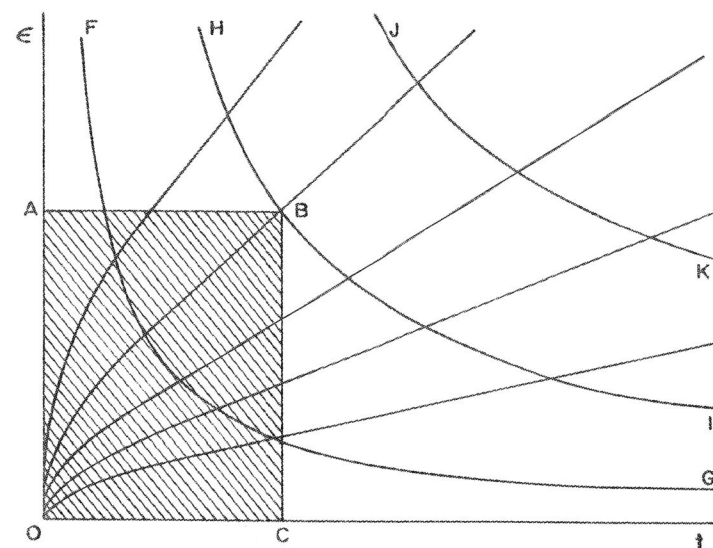


Figure 3 An illustration of a geometrical method for determining the fractional increase in the total volume  $\Delta V/V$  of cavities formed during creep. Since this volume is approximately proportional to the product  $\epsilon t$  of creep strain and time, then the volume increase at a point B on the creep curve OB corresponds to the area of the rectangle OABC. When the tensile creep stress  $\sigma$  is varied, but the superimposed hydrostatic pressure  $P$  is adjusted so that  $(\sigma - P)$  is kept constant, then a series of creep curves can be drawn (only primary and secondary creep stages are illustrated) with the top left curve corresponding to the highest value of  $\sigma$ . The relationship between  $\Delta V/V$  and  $\epsilon t$  is not altered and each of the lines FG, HI and JK corresponds to a specific value of  $\Delta V/V$ , with FG the lowest value, and these lines take approximately the form of rectangular hyperbolae. The volume change can be obtained from the points of intersection of the creep curves at constant  $(\sigma - P)$  with these hyperbolae.