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Transitions in Creep Behaviour

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Attempts to identify the mechanisms operating during creep are often made by examining plots which yield apparent activation energies, or the stress or grain size-dependences of creep-rate. The forms of such plots are here examined and the ambiguities which arise near transitions from one regime to another are noted. The ranges of temperature, stress and grain size commonly used are inadequate and serious errors in interpreting the results of creep tests will continue to be made until a better understanding of the interaction of the basic processes is developed, so as to enable the positions of transitions to be predicted.

1. Introduction

The way in which minimum creep-rate depends upon temperature, stress or grain size is often used as a means of attempting identification of the mechanisms of creep operating in particular circumstances. The resultant relationships are also useful as a systematic way of comparing tests and materials. This kind of behaviour may be formalised through the equation

$$\dot{\epsilon}_S = [(S\sigma^n)/d^m] \exp(-Q_S/RT) \qquad (1)$$

where $\dot{\epsilon}_S$ is the minimum creep-rate, σ is the stress, S is a structure factor, d the grain diameter, Q_S the activation energy for creep and n and m constants. R and T have their usual meanings.

Mechanisms of creep are identified by comparison of the values of Q_S, n and m which are found during creep with those appropriate to the various basic processes. Sometimes a series of tests will yield an answer which is unique and unambiguous, but more often the analysis is complicated by the presence of two or more mechanisms operating simultaneously. This leads to plots which show transitions between regimes of behaviour, and often to values of Q_S, n or m which do not match any of the probable mechanisms.

Aspects of this problem have been considered in the literature, particularly in connection with activation energies. For example, Crussard and Tamhankar [1] discussed the general form of the Arrhenius plots for various combinations of processes and this scheme has been used in the interpretation of results for several metals [2-6]. In some of these papers [3-5] the interaction of changes of values of S, m and n with those for Q_S is discussed, using an additional development of the analysis due to Munson and Huggins [7] (not available in the general literature).

There is a considerable literature on the stress-sensitivity of creep, although much of it is devoted to attempts to produce analytical expressions which characterise the complete range of stress, rather than to identification of the mechanisms of the various regimes [8]. A similar remark applies to grain size-dependence [8].

It is the purpose of this paper to explore the full range of types of transition behaviour and in so doing draw attention to the possibilities these give for extracting values of Q_S, m or n which appear to have high statistical significance but which may be mechanistically false or misleading.

2. Temperature-Dependence

Following Crussard and Tamhankar [1] it has become usual to describe creep processes in terms of thermally activated mechanisms occurring "in series" or "in parallel". This has semantic dangers, as revealed in the discussion to [6], where the confusion applied to processes in parallel. Parallel processes were considered synonymous with simultaneous, and series processes with those acting consecutively. Woodford [9] then pointed out that in the terminology

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of mechanical analogies both parallel and series are considered subdivisions of "simultaneous". It might therefore be better to speak of simultaneous processes in parallel as "concurrent" and series processes which are not simultaneous as "sequential", although we will here combine these terms with the older ones to assist in clarity.

The inset diagram in fig. 1 reproduces the scheme set out by Crussard and Tamhankar. According to this the observed rates will follow the full lines except near the crossover point where the appropriate broken line applies.

We shall now consider various possibilities for combining two processes, type A and type B, which proceed with rates given by the equations $\dot{\epsilon}_A = a \exp - Q_A/RT$ and $\dot{\epsilon}_B = b \exp - Q_B/RT$ respectively.

To aid in constructing the diagrams, explicit values for Q_B and Q_A have been assumed, namely 26 and 13 kcal mol^{-1} respectively; these values are approximately those for self-diffusion in the crystal and in the grain-boundaries respectively of lead.

2.1. Case 1: Parallel-Concurrent (PC)

This is taken to mean the simultaneous and independent operation of both processes; it implies that there are equal numbers of activatable volumes ("units") of both types, all contributing equal units of strain and that it is only the local temperature fluctuations which determine when a unit fires, not its proximity to other units, of either type. It is perhaps also worth emphasising, as an aside, that in creep and deformation the situation is that "firing" a unit does not generally remove it from the population of firable units; having fired, it is immediately in the position of being able to be fired again. This contrasts with a typical chemical reaction where the units (reactants) are gradually removed and the proportion of reaction product concomitantly built up and where measurements of this build-up may be used to identify the types of processes participating.

In this parallel-concurrent type (PC), the overall rate of creep $\dot{\epsilon}_S = \dot{\epsilon}_A + \dot{\epsilon}_B$ and at the crossover point E_X at temperature T_E we have

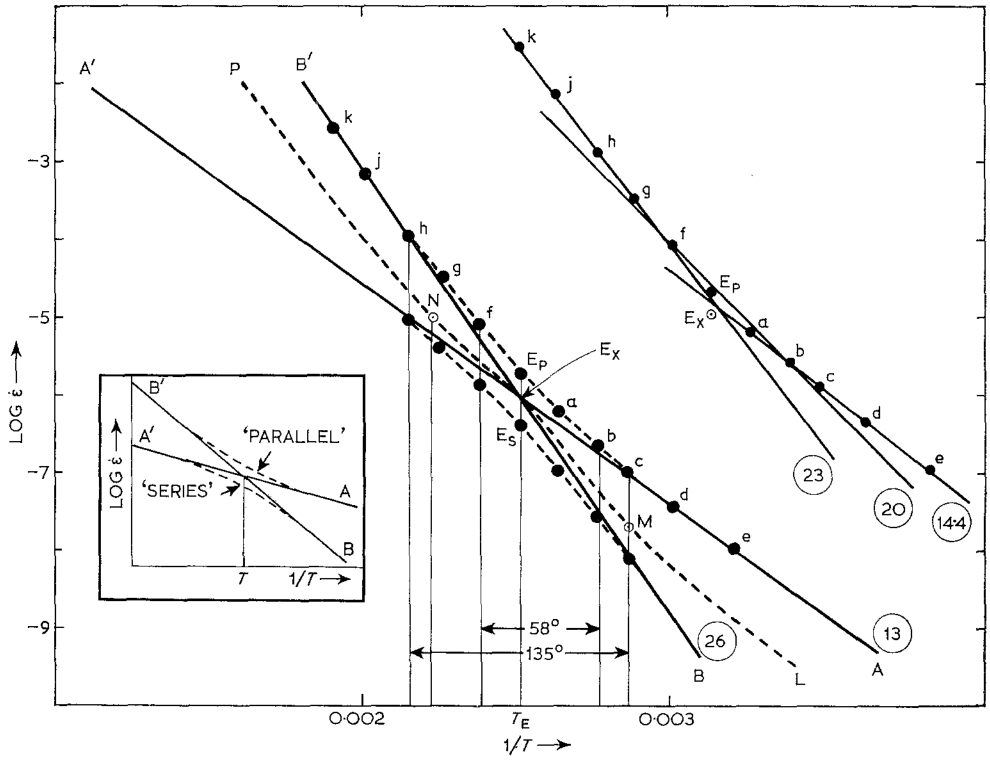

Figure 1 (Inset) Schematic, showing "parallel" and "series" processes in creep characterised by Arrhenius plots (after Crussard and Tamhankar [1]). The main lines show a detailed analysis of the combinations implied in the inset for a particular pair of processes having activation energies of 26 and 13 kcal mol^{-1} and giving equality of rates at a temperature T_E (for details, see text).

$\dot{\epsilon}_S = 2\dot{\epsilon}_B = 2\dot{\epsilon}_A$; that is, in fig. 1, the observed rate will plot as the point E_P which is log 2 above E_X. Other points will fall along the dotted line and the complete curve will be AE_PB'. The curved transition range becomes more extensive on the temperature scale and more symmetrical about E_X as Q_A approaches Q_B in value, but less distinguishable from the straight lines as Q_A and Q_B both become larger (i.e. as the lines become more steep).

It will be seen that, for the particular pair of values of activation energy chosen ($Q_A = 13$, $Q_B = 26$ kcal mol^{-1}) and for the value of $T_E = 400°$ K, the transition range extends from 330 to 465° K. If it is taken that a creep-rate can only be determined within a limit of ±25% (as indicated by the size of the points marked) this transition range is reduced to 58° K, marked by arrows in fig. 1.

Let it be supposed that the experimental points have been determined without experimental error and therefore are, as indicated by the points a-k, all lying along the theoretical curve AE_PB'. It is immediately clear that the determination of the true values of Q_A and Q_B can only be made from among this group of points using c, d, e for Q_A and h, j, k for Q_B; fitting lines to points over such comparatively narrow temperature ranges is inherently inaccurate. What is usually done is to include all points (except perhaps E_P) in the least squares determinations i.e. using a-e for Q_A and f-k for Q_B. When this is done in fig. 1, the values become $Q_A = 14.4$ and $Q_B = 23$ kcal mol^{-1} giving errors of approximately 10% *even if there is no experimental scatter*. Since it is generally more difficult to obtain reliable creep-rates at very high or very low rates, it is the more accurate (and, often, more numerous) points in the middle range that are biased by the effect just discussed. Thus, in the total analysis, it could be that the curvature at E_P might reinforce or cancel the overall experimental errors.

In general, this effect may not be too serious a source of error provided that the range of temperature is extensive enough to bring at least points equivalent to j, k and d, e into the plot. On the other hand, should only points between g and c be determined, a single and misleading value of $Q \simeq 20$ kcal mol^{-1} would appear to be indicated with a high level of statistical confidence (i.e. the scatter of points would appear to be small).

There are many examples in the literature of plots of the type shown in fig. 1 and sometimes it has been recognised that E_X falls below E_P. For example, Flinn and Duran [4] in their fig. 1 show Arrhenius plots for a series of tests on cadmium, and identify processes in parallel. However, they plot the pairs of lines using *all* the experimental points, so giving a spurious confidence in the least squares fit, bringing E_X too close to E_P and displacing T_E by nearly 20° C. Using a formula derived by Munson and Huggins [7] they also calculated the temperature range for the transition to be ± 45° C; this agrees well with that found using the present geometrical construction but not, in fact, with the plot they actually reproduce.

2.1.1. Parallel-Concurrent, Proportionated (PCP)

The processes are again simultaneous but some special geometrical factor operates to proportionate them within the specimen; this could be obtained if accommodation between units is independent of temperature and very rapid compared to either process, as could be the case for a purely elastic accommodation. The net result of this arrangement would be to give behaviour equivalent to two independent sub-specimens, one entirely of the A units and the other of the B units. The overall rate is thus obtained by adding appropriate proportions of the two basic rates:

$$\dot{\epsilon}_S = (y/100)\,\dot{\epsilon}_A + \{(100 - y)/100\}\dot{\epsilon}_B$$

where the percentage of A units is y.

The curve obtained for $\dot{\epsilon}_S$ is exactly the same as AE_PB' but it always passes through E_X, and E_P is displaced to the left or right of E_X according to the value of y; when $y = 50$, E_P coincides with E_X. Examples for $y = 10$ and 90 are shown in fig. 1 in the broken curves PNA and LMB'.

This means that it is not possible to decide from inspection of a transition curve of the PC type what the geometrical proportions of the two participating processes are. Any proportion of a process of high activation energy will always emerge to dominate at high temperatures; similarly, any proportion of a process of low activation energy will emerge to dominate at low temperatures, (low or high temperatures refer to T_E as the norm). An example of the latter could well be provided by the participation of grain-boundary sliding involving grain-boundary self-diffusion and occurring to a minor extent in parallel with slip controlled by climb. It is possible that the situation in practice could be further complicated by the value of y itself being dependent upon temperature. To take an extreme case, if y changes from 10 at low temperatures to 90 at high temperatures, the experimental plot would appear to be three straight lines LM, MN, NP (fig. 1) corresponding to activation energies Q_A, approximately $(Q_A + Q_B)/2$, and Q_B respectively, at low, intermediate, and high temperatures. The range of the intermediate temperature regime would, in this example, be considerable, viz. 130° K.

2.2. Case 2: Series-Sequential, Dependent (SD)

Here process A cannot proceed until process B has taken place in an appropriate group of units. Crussard and Tamhankar [1] sketched the experimental curve $A'E_SB$ (fig. 1) to be symmetrical with AE_PB'. This curve is not the one that corresponds to the simplest interpretation of the notion of series processes. It implies a special interaction whereby B units remain incapable of reactivation whilst their associated A units are firing, so that when $\dot{\epsilon}_A = \dot{\epsilon}_B$ at T_E we have $\dot{\epsilon}_S = \dot{\epsilon}_A/2$, and $\dot{\epsilon}_S$ drops below E_X by a distance of log 2, the curve being symmetrical to that for the PC case. This could be distinguished by calling it *series-alternating, dependent* (SAD).

The simpler case of SD is when B becomes immediately capable of firing again as soon as A begins; the overall rate is then always that of the slower of the two and points fall along BE_XA'. A situation in which this pattern might be expected is as follows. Suppose process B to be sliding along a grain-boundary AB in fig. 2 and process A to be slip (to form a triple-point fold) across BC in the neighbouring grain. It is clear that the slip movement always follows sliding but that the overall rate is determined either by the rate at which sliding "pushes" the slip process or by the rate at which slip accommodates the sliding, whichever is the slower.

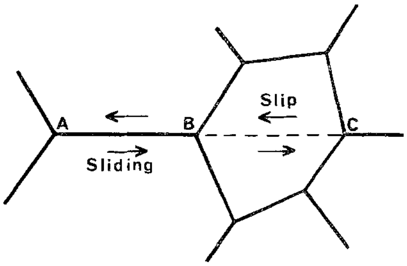

Figure 2 Sliding along AB, accommodated by slip along BC – a case of a series-dependent processes.

3. Stress-Dependence

The discussion here will be confined to a consideration of power laws of stress-dependence, as given in equation 1. The question of the correct form for the stress-dependence has been debated elsewhere [10]. However, this discussion could readily be adapted to an exponential law and similar conclusions reached.

There has been an increasing body of evidence to show that at least two stress regimes commonly occur, with $n = 1$ at low stress and $n = 5$, 6 or 7 at higher stresses. Many workers allege their results support $n = 5$ and that this confirms Weertman's [11] creep theory, although this in itself is not convincing for there are other equally acceptable theories which also predict $n = 5$ (e.g. [12, 13, 14]). Perhaps the most extensive compilation for any material is that by Harris and Jones [15] for Magnox alloy; they used temperature-compensated plots to reveal three regimes with $n = 1$, 3.5 and 7. In fact, the general situation is less simple than this; a survey of all creep papers published in four international journals [16-19] from 1961 to 1968 shows that all values of n from 1 to 11 have been found; of these 25 were of 4 or below, 19 of 5 and 9 above 5. Non-integral values of n are not uncommon, particularly with ceramic materials.

3.1. Parallel-Concurrent

The point that will be made in this paper is that a variety of values of n may well be a natural consequence of the presence of parallel-concurrent mechanisms, such as have been discussed by Gifkins and Snowden [10].

The effect of combining various regimes is illustrated in fig. 3. In fig. 3a the lines CC′ and DD′ for $n = 1$ and $n = 5$ respectively are shown, and the points represent the expected experimental rates for specimens in which both processes operate in such a manner that the rates for the two processes are equal at F_X at a stress σ_F. As in the Arrhenius plots, we find the experimental curve CF_PD' passing through F_P a distance log 2 above F_X.

If it is supposed that only the points c-j have been determined, then these fall convincingly on two lines of slopes to give $n = 5$ (points f-j) and $n = 3$ (points c-f). Even including point b would not alter this deduction significantly, but perhaps give a fractional value such as 2.8 for n

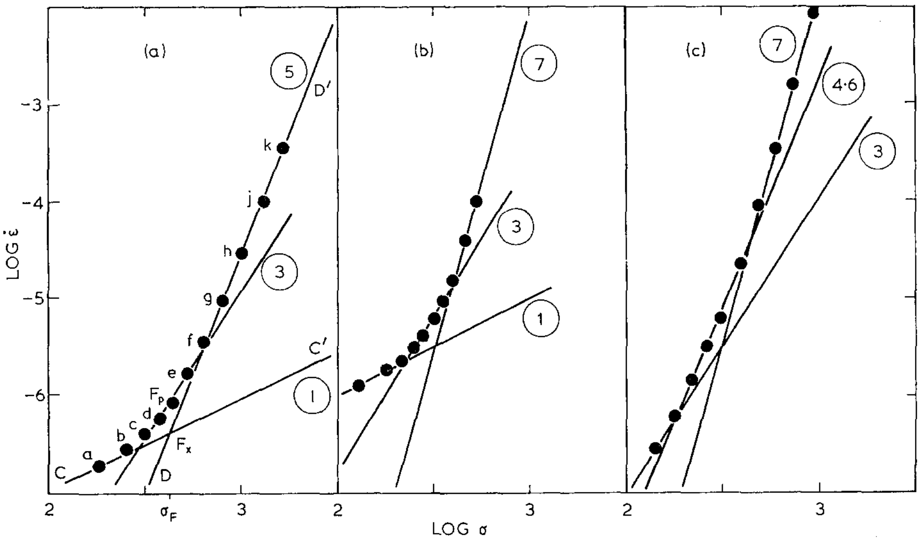

Figure 3 Parallel-concurrent processes involving various stress regimes which combine to give the points indicated and thus the possibility of "false" stress exponents. (a) Regimes with $n = 1$ and $n = 5$; (b) regimes with $n = 7$ and $n = 1$; (c) regimes with $n = 7$ and $n = 3$.

quite reproducibly. On the other hand, a very good fit for a line giving $n = 4.5$ would be found if only the points d-k were determined. It should be noted that all the cases just cited are for stress ranges involving a factor of 4 or 5 between extremes, which is reasonably typical of those used in practice.

The reason for this being typical is probably connected with the fact that it is difficult to extend creep tests to much faster or slower rates than those given by this kind of stress range. For example, if n does equal 5, then a 5-fold increase in stress gives $3\frac{1}{2}$ orders of magnitude increase in creep rate. Suppose it requires a strain of 10% to measure minimum creep rate and that the shortest tests cannot conveniently be run in less than an hour. Then the lowest stress in the range will require a test which will have to be for 3000 h $\simeq$ 120 days.

In figs. 3b and c combinations of $n = 7$ with $n = 1$ and $n = 3$ respectively have been plotted in a similar manner to fig. 3a. It is clear that the (7-3-1) combination, approximately that found for Magnox, is readily simulated by combining $n = 1$ and $n = 7$ and that a fractional value like $n = 4.5$ (which is quite commonly cited) may also arise rather convincingly from $n = 7$ and $n = 3$. A little less confidence in fitting the points a-h in fig. 3c gives the spurious value of $n = 5.2$, which is typical of other non-integral values found experimentally.

It is clear, then, that combining processes with $n = 1$ and a value of 5 or higher can yield very convincing plots which simulate values like $n = 3$ or 5 at intermediate stresses, particularly if the stress range is kept to within a five-fold increase.

3.1.1. The Zener-Holloman Plot

Many workers have realised some of the dangers and difficulties of the normal log-log plot and tried to extend their results to a wider range of stresses by varying the temperature, increasing it to speed up low-stress tests and lowering it to slow down the high-stress ones. The results are then plotted to yield a single line using the Zener-Holloman parameter, Z, to compensate for the changes in temperature. Z is $\dot{\epsilon}_s \exp (Q_S/RT)$, and therefore may only be used for tests which keep within a particular temperature regime (e.g. $Q_S = Q_A$ or Q_B here). However, there is evidence [10] that the critical stress σ_F (fig. 3) depends on temperature in the manner indicated by the series of lines for temperatures T_1, T_2, T_3 and T_4 as shown in fig. 4. Since the tests at higher temperatures are often undertaken principally to explore the low-stress range giving points such as those shown in fig. 4, they may not be plotted on the simple log-log display of section A of the diagram which reveals the temperature-dependence of σ_F. Instead they would be transferred by the appropriate distance equivalent to

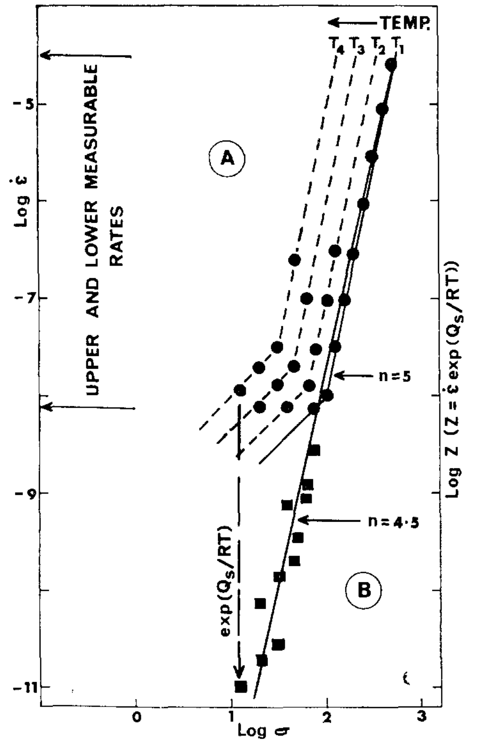

Figure 4 Showing how a Zener-Holloman plot of temperature-compensated creep-rate may give a false value of the stress exponent when two stress regimes are present.

exp (Q_S/RT) and plotted, as in section B of fig. 4, to produce the line of slope to give $n = 4.5$ (compare the "true" line with $n = 5$). In practice the misleading nature of this plot would be further disguised by inherent experimental scatter. It should be noted that this effect would obtain even if points at higher stresses on the high-temperature lines were obtained, although some warning of the trouble would be given if simple log-log plots were examined.

3.2. Parallel-Concurrent, Proportionated

There is another case which could be of importance during creep, when parallel-concurrent mechanisms operate, but their proportions change as a function of stress; this could happen if there is a critical stress σ_F such that a particular mechanism only took place at stresses above σ_F. A possibility is that σ_F is the critical resolved shear stress for the mechanism concerned. Under these conditions the proportions of the two mechanisms operating then depend upon the actual stresses present on various units of the specimen concerned. To take a specific case, let us suppose that grain-boundary sliding occurs as a major mechanism and that below σ_F it is controlled by an accommodating process with $n = 1$ [10] and above σ_F by one with $n = 5$.

The stresses which concern us in calculating the form of the dependence of rate-of-sliding upon stress are now the shear stresses on grain-boundaries in the specimen [20]. These depend on the angle θ between each grain-boundary and the direction of the applied stress σ. Since there will be grain-boundaries with all values of θ, the shear stresses on them will range from 0 to 0.5 σ. As the value of σ is increased from below σ_F, the number of boundaries experiencing a shear stress greater than σ_F will also increase, in a manner which may easily be calculated from comparisons of resolved shear stresses and σ_F. It is then possible to calculate the average contribution of the two mechanisms to the overall strain.

In fig. 5 this has been done for regimes of deformation having $n = 1$ and $n = 5$ and a particular value of σ_F, the points shown in the diagram being those computed. This leads to the drawing of lines having slopes $n = 1$ and $n = 5.5$ whereas, in fact, the mechanisms concerned are those with $n = 1$ and 5. The effect of the presence of a proportion of boundaries having a resolved shear stress below σ_F persists over three orders of strain rate; this means that the

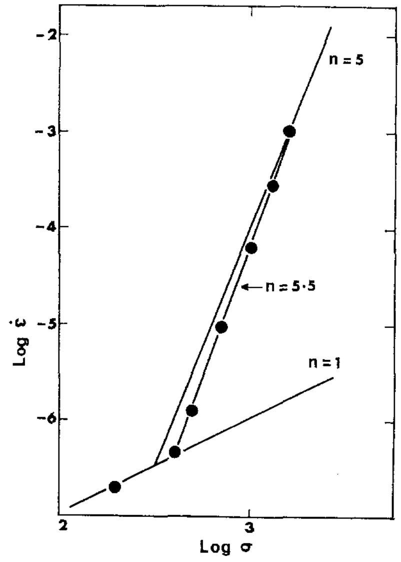

Figure 5 Combining stress regimes in parallel but proportionated according to a resolved shear stress law for grain-boundary sliding.

computed points (i.e. those which would be found experimentally) do not come back to the line with $n = 5$ unless an even wider range of strain rates is determined. The range of rates shown in fig. 5 is as wide as would usually be practicable or convenient to examine; it thus becomes difficult to establish the true value of n in the upper regime, particularly as experimental errors of other kinds might pull the value even further from the true one.

In fig. 6 some experimental values of rate-of-sliding $\dot{\gamma}$ and of creep $\dot{\epsilon}$ for a lead-thallium alloy [20, 21] are examined in the light of the foregoing discussion. The points shown are the experimental ones. In figs. 6a and c the lines shown have been calculated using the method described for fig. 5 but using values of $n = 1$ and $n = 3$ and with σ_F chosen to give good fit. The resulting lines with slopes $n = 1$ and $n = 3.4$ give excellent fit for both rates of creep and of sliding. For comparison, in figs. 6b and d these same points are superimposed on curves obtained by combining mechanisms having $n = 1$ and $n = 5$ according to the parallel-concurrent case discussed in connection with fig. 3a. The fit is again very good but there is a falling away from the curve at the highest stress for both creep and sliding and this feature was present for some other creep results for lead-thallium alloys. If this departure from good fit is significant the proportionated case in figs. 6a and c is the more acceptable analysis. It is clear that it is difficult to distinguish between these two cases unless more extensive results are available. This would not be easy to achieve experimentally, being more difficult for measurements of sliding than for creep at the higher stresses, because the amounts of sliding become small and the surfaces of the specimens distorted.

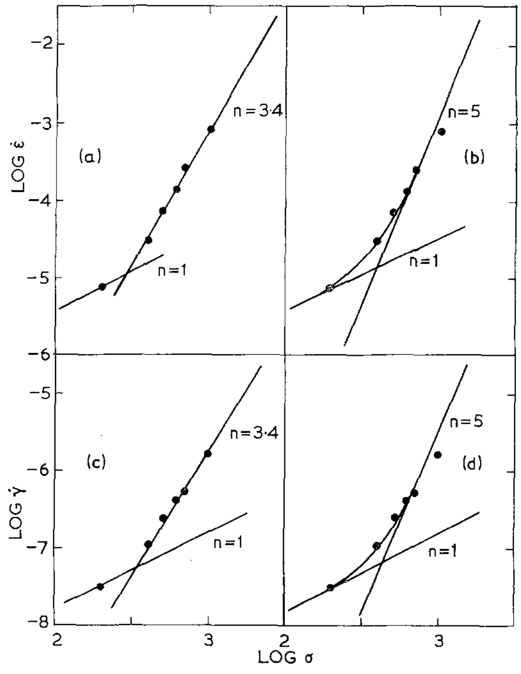

Figure 6 Creep-rates and sliding-rates for a lead-thallium alloy (experimental points) compared with two types of theoretical curve: (a) and (b) are for creep-rates; (c) and (d) for sliding-rates.

4. Grain Size

Various mechanisms have been put forward which give values of m in equation 1 of 1, 2 or 3, (i.e. $1/d$, $1/d^2$ or $1/d^3$) particularly for variations of Nabarro-Herring diffusional creep [22]. Quite often, especially with ceramics, fractional values of m have been found experimentally, thus throwing doubt upon mechanisms tentatively identified by the values of n or Q_S found.

4.1. Parallel-Concurrent

Fig. 7 shows the resultant curve AE_PB' for parallel-concurrent mechanisms having grain size-dependences with m in equation 1 equal to

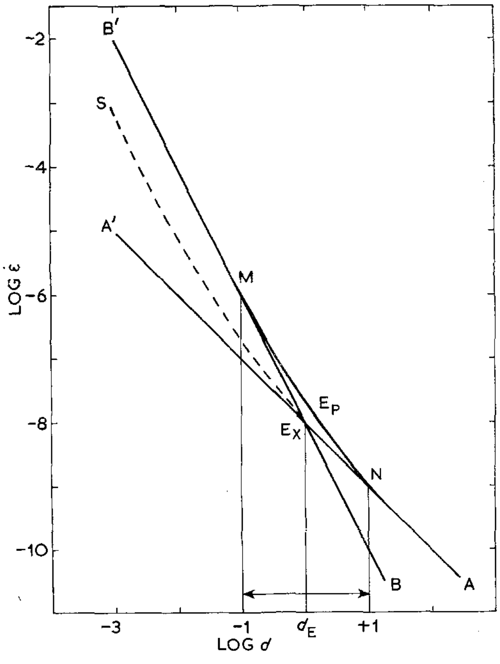

Figure 7 Combining mechanisms having grain size-dependence for creep- (or sliding-) rates of $1/d$ and $1/d^2$.

1 and 2 (i.e. creep-rates depending on $1/d$ or $1/d^2$). As with temperature- or stress-dependence, the critical factor in determining whether a false value of m is obtained from experimental results is the position of the crossover point E_X. Sometimes it may be possible to calculate the value of the critical grain size d_E (corresponding to E_X) from the pre-exponential factors in the creep equations e.g. in variants of N-H creep. If the experimental grain sizes are then at least an order of magnitude greater or smaller than d_E the value of m should not be in error as a result of this parallel-concurrent effect. Otherwise it is desirable to have a range of grain size equal to at least two orders of magnitude, to ensure that false, intermediate, values of m are not derived. In practice, such a range of stable grain sizes is difficult to achieve.

It will be seen in fig. 7, that values of m such as 1.7 or 1.8 would be found if the curve E_PM were determined and values of about 1.2 would be found for points from E_P down to about N. A similar situation applies to a parallel-concurrent combination with $m = 1$ and 3 or $m = 2$ and 3; just as in fig. 7, there is a transition range of $1\frac{1}{2}$ to 2 orders of magnitude for grain size.

Should there be a suitable geometrical arrangement within the specimen such that the mechanisms are proportionated as previously suggested for the temperature-dependence, the curve AE_PM is shifted to pass through E_X and is moved, according to whether the mechanism with $m = 1$ or $m = 2$ is in the greater proportion. For example, with 90% of the ($m = 1$) mechanism and 10% of the ($m = 2$), the dotted line SE_XA results. Once again it turns out that mere inspection of the slope of the curve, even if it is extensive enough to show its complete form, is not sufficient to distinguish between parallel-concurrent and parallel-concurrent proportionated mechanisms. Also, whatever the proportions, it is always the mechanism with the highest value of m that emerges as the only apparent one at small enough grain sizes. Conversely the lowest value of m dominates at large enough grain sizes.

5. Complex Situations

It is likely that many cases in creep are more complex than any of those described so far. For example, grain-boundary sliding A may be accommodated by slip B (in a series-sequential process) and the resultant itself combined with slip B within the grains in a parallel-concurrent manner. If the pre-exponential terms are different for the two kinds of slip, as is possible because of stress concentrations at the grain-boundary or the influence of grain or sub-grain size, then the situation in fig. 8a could arise. The kink in the true plot could easily be confused by scatter, and the inference perhaps drawn that only a single process D operates over the whole range. A further implication of this would be that similar complex plots for stress- or grain size-dependence should arise; these can readily be constructed following the methods used in this paper. Again, these could suggest how false values of the appropriate indices could arise, or on the other hand, show that tripartite plots for stress or grain size-dependence are not unlikely.

On the other hand, if the second slip process has a higher activation energy, C, the situation might be characterised by fig. 8b, and the inference drawn that process D was acting in a parallel-concurrent manner with process C.

If combinations such as those plotted in figs. 8a and b are encountered experimentally, it is probable that experimental scatter would further disguise the true situation. The possibilities of such combinations are so numerous that it is clearly not possible to disentangle them merely by inspection. As should always be the case in this kind of analysis,the inferences drawn should be guided and illuminated by consideration of probable mechanisms. This implies not only that the theoretical model for such mechanisms be known, but that the values of basic parameters in the equations (such as activation energy for self-diffusion) also be reliably known; unfortunately, this is seldom the case, and this limitation must be recognised.

6. Summary and Conclusions

(i) The analyses discussed show very clearly that there are dangers in deriving temperature-, stress- or grain size-dependences from too narrow ranges of the appropriate variable. This is not a new finding, but the present discussion shows the extent of transition ranges to be expected under various conditions. These ranges are often about the same as can be encompassed readily experimentally, e.g. without involving either very short or very long times for tests, or very coarse grain sizes.

(ii) Where more than one mechanism operates, characteristic curves result for combinations in parallel and concurrent (PC), in parallel-con-

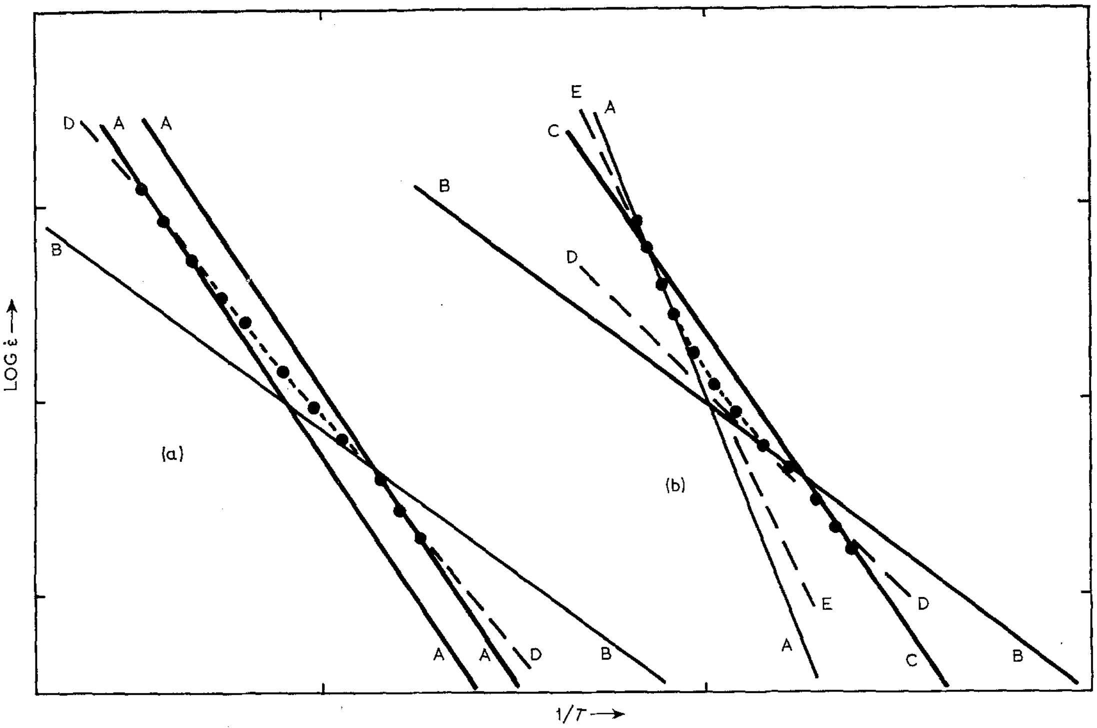

Figure 8 Arrhenius plots (a) combining A and B in a series-dependent manner and their resultant in parallel-concurrent with A having a different pre-exponential factor. (b) as in (a) but with the second A process replaced by C. In both cases a false value of D could emerge.

current but proportionated (PCP), or in series and dependent (SD). Each of these combinations may yield apparent straight lines over limited regions in the transitional ranges and thus false values of activation energy Q_S, stress exponent n, or grain size exponent m may be deduced.

(iii) The various combinations mentioned in (ii) may arise in processes like creep because of the special nature of the activated units and their ability to be reactivated and to interact elastically; the temperature-dependence of such processes may thus have characteristics not found in normal chemical rate processes. A particular case of this kind concerns situations where a geometrical factor proportionates the strain increments among two (or more) kinds of unit (e.g. slip planes and grain-boundaries). In such cases a small proportion of a process with a high activation energy always emerges as dominant at high enough temperature, or one of low activation energy at low enough temperatures. A similar situation exists with respect to grain size-dependence.

(iv) It is shown that one popular method of attempting to increase the range of stress studied, viz, using the Zener-Holloman parameter to give a temperature-compensated creep-rate, also has dangers. It may easily give a single, convincing but false, value of n when two values should be found.

(v) The interpretation of the various plots should be made with specific models, interactions and geometries in mind. The range of models available is wide and probably reasonably complete and acceptable. There is very much less information and confidence about the factors which determine the transitions between regimes of temperature-, stress- or grain size-dependence.

(vi) Only combinations of pairs of processes have been considered systematically here. It is likely that greater numbers of processes are involved in practice; for example, a sequential-dependent pair of processes (grain-boundary sliding and accommodating slip) might combine in a parallel-concurrent manner with a process of slip within the grains. This could easily produce a diagram which gives no indication of such complexity of behaviour.

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