FRACTURE IN CREEP

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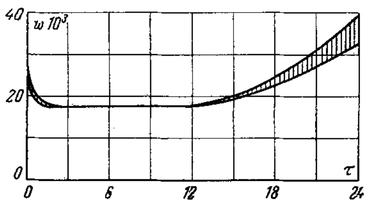
A material under load at elevated temperature behaves as a dissipative medium; its work is accompanied by creep and by the accumulation of damage which limits the life of a given structure to a



finite value. The problem in the case of any given body under the influence of external loads at elevated temperatures is to estimate the rate of creep at any given time at an arbitrary point of the body. It is convenient to use for this purpose the fundamental property of creep, i.e., its dissipative character, assuming that the process will be more intensive where the specific dissipation power of mechanical energy

$$W = \sigma_{ij}\eta_{ij} \tag{1}$$

is higher; here σ_{ij} and η_{ij} denote, respectively, components of the stress and strain rate tensors. It is evident that this criterion is identical with the Tresk and Mizes criteria of creep associated with their laws of flow; at the same time it is more general, not being tied up with, e.g., conditions of the isotropy of the medium. Let us take as the measure of damage accumulated during creep in any given time Δt_i the dissipated specific work

$$A(\Delta t_i) = \int_{t_i}^{t_{i+1}} \sigma_{ij}\eta_{ij}\,dt. \tag{2}$$

The latter hypothesis in a slightly different form was postulated in [1].

The above propositions were verified on several materials; the results of this work are described in this article.

The experiments were carried out on three types of materials, each of which fractured in a different way. In the first series of experiments we used D16AT alloy sheet specimens (4 and 2.5 mm thick, 60 mm gage portion length); these were tested at stresses 14–20 kg/mm^2 at a constant temperature of 250° C. These specimens failed by brittle fracture; the strain at fracture did not exceed 5% with only a small neck formed.

The second series of tests was carried out on cylindrical D16T alloy specimens (8 mm diam., 50 mm gage portion length) machined from a 14 mm diameter rod. These were tested at 250° C at stresses ranging from 9–15 kg/mm^2, the corresponding time-to-rupture being 100 and 3.5 hr. The character of fracture was in this case intermediate between brittle and ductile; there was clearly noticeable local neck formation and the strain at fracture was about 15%.

The specimens of the third batch were of the same shape and size as specimens of the second batch, but they were machined from a 20 mm thick soft duralumin plate. The creep tests were carried out at 200° C at stresses ranging from 6–9 kg/mm^2, the test duration varying correspondingly from 100–5 hr. The failure was ductile in character, several necks being simultaneously formed along the specimen gage portion. When a strain of 25–30% was reached, the test was terminated.

Creep curves obtained by plotting strain against time are not similar. Experiment shows that the higher the stress level, the smaller is the strain corresponding to the onset of the third creep stage; accordingly, the total creep strain (i.e., strain at fracture) also decreases with the applied stress level. On the other hand, if the specific dissipated work is plotted against time for each of the applied stress levels, one can easily see the geometrical similarity of the resulting curves in the sense that if for a certain stress σ_n we have $A_n = \varphi_n(t)$, then for any other stress σ_m we obtain $A_m = \varphi_n(k_m t)$.

And so, varying the time scale by a factor of k_m it is possible to reduce the dissipated work curves for various stress levels to a single curve, this applying to all the three creep stages. This was verified by experiment on all the three types of specimens tested at both constant and variable (in two or three steps) stress. In the latter case, the similarity coefficient k_m in reconstructing a dissipated work graph portion corresponding to a stress σ_m was taken to be the same as that used in reconstructing a graph at a constant stress of the same level as σ_m.

A clearer qualitative and quantitative picture of the relation between the time-to-rupture and the work dissipated in creep can be obtained by plotting the specific power of dissipation of mechanical energy against time. In this way a set of curves situated one under another is obtained. The lower the applied stress, the lower and the more elongated is the appropriate curve. Choosing a certain curve $W = W(t)$ as the basic curve, increasing (decreasing) the scale of the remaining curves along the axis of ordinates by a factor of k_m to make their horizontal portions coincide, and reducing correspondingly the scale along the axis of abscissas, one can reduce all the curves to a single beam. Curves of the specific dissipation power for a ductile material which were reconstructed in this way are reproduced in a figure, where $w = Wk_m$ is plotted against $\tau = t/k_m$. The specific work dissipated during creep in a certain time τ is numerically equal to the area bounded by the coordinate axes, curve w and a segment of a straight line τ = const. It will be seen that all the curves w practically coincide until the onset of the third creep stage after which they diverge occupying a zone indicated by cross-hatching in the figure.

Analogous graphs are obtained for other materials, the difference being that as the material becomes more brittle, the third creep stage becomes shorter and the slope of the curves in this stage steeper. A common characteristic of all the three types of materials studied is a certain increase in the steepness of curves w in the third creep stage with decreasing test stress level. In other words, when the test duration is increased, a material in the third creep stage behaves as increasingly brittle and the relative length of the third stage is reduced.

Curves in the figure (and analogous curves for other materials) indicate that the work dissipated during creep up to the onset of the third creep stage remains constant, accurate to a very high degree. Consequently, if one considers for instance the transition to the third creep stage as the beginning of fracture preceded by a certain accumulation of damage during the previous two stages, it is evident that the latter should be related in a definite way to the magnitude of work dissipated during creep.

Allowing a certain error, the work dissipated during the third creep stage up to any moment τ may also be regarded as constant and independent of the applied stress level. In view of this, it is advisable to adopt the specific dissipated work as one of the basic parameters characterizing the accumulation of damage during all the three stages of creep.

If only the first two creep stages are taken into account in the calculation (with the remainder regarded as a reserve of the time-to-rupture), the specific work

$$A = \int_0^{t^*} \sigma_{ij}\eta_{ij}\,dt \tag{3}$$

dissipated during these stages at a given temperature will be (for a given material) a constant independent of the applied stress (t^* is the time of the onset of the third creep stage).

It is possible to determine this constant by relatively short tests and also from formula (3), if the value $W = \sigma_{ij}\eta_{ij}$ as a function of time is known, and so to calculate the time-to-rupture under long-time working conditions. It is obvious that the known formula of linear additivity of creep damage automatically results from (3) and has a simple physical interpretation.

Without associating time-to-rupture with any point of the third creep stage, one can deduce the following useful conclusion from the data in Fig. 1: the time-to-rupture of two identical structures working at elevated temperatures is inversely proportional to their specific powers of dissipaton of energy during the steady-state creep stage.

REFERENCES

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