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BRIEF NOTES

On experimental modellin gof the growth of damage in the tertiary creep of metals

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In this note a simple experimental model simulating a possible mechanism of the evolution of the damage parameter in tertiary creep is presented. This mechanism consists in the progressing process of micronecking of narrow ligaments in the presence of a system of microcracks.

Metals subjected to constant tensile stress at temperatures above 0.3 T_m, where $T_m(K)$ is melting temperature, undergo time-dependent deformation referred to as creep. The time during which the material can sustain stress is limited, the time of rupture being referred to as the rupture time. At the stress levels frequently encountered in engineering design failure occurs as a result of growth of damage in the metal. The damage usually occurs in the form of fissures and voids (see for example Leckie and Hayhurst [1] and also [2]). It is usually observed that the damage in the metal is accompanied by an increase in the strain rate, which occurs in the so-called tertiary region.

In order to account for the increase in strain rate during the constant tensile stress test in the tertiary region it is convenient to introduce a new variable ω referred to as the damage parameter. In the undamaged state we have $\omega = 0$; the limit value $\omega = 1$ corresponds to total separation of the material. The idea to introduce such a parameter is due to Kachanov [3] (see also Rabotnov [4]). The strain rate equation for the tertiary region may be written in the general form

$$\dot{\varepsilon} = f(\sigma, \omega), \tag{1}$$

where f is a function which must be defined experimentally, and σ is the applied stress. To define the strain rate at an arbitrary instant of the tertiary period of creep we must know the value of ω. Assuming that the rate of damage $\dot{\omega}$ depends on the stress level and on the damage parameter itself we may write the equation of evolution of damage in the general form

$$\dot{\omega} = g(\sigma, \omega). \tag{2}$$

The two functions f and g may be established on the basis of experimental results. Particular forms of the two functions have been given in the works [3] and [4] mentioned above.

In some works the damage parameter ω is interpreted as the relative reduction of the cross-sectional area. However, it should be noted that no precise physical interpretation of the parameter ω is attempted. Metallographic studies (see [2] and [5]) show that in some metals, such as copper and some copper alloys, the damage occurring along the grain boundaries may be observed by visual inspection. However, in other metals the progressing damage is much more difficult to observe. In some works (see for example [5] and [6]) theoretical models of intercrystalline coalescence of cavities leading to crack formation is analysed.

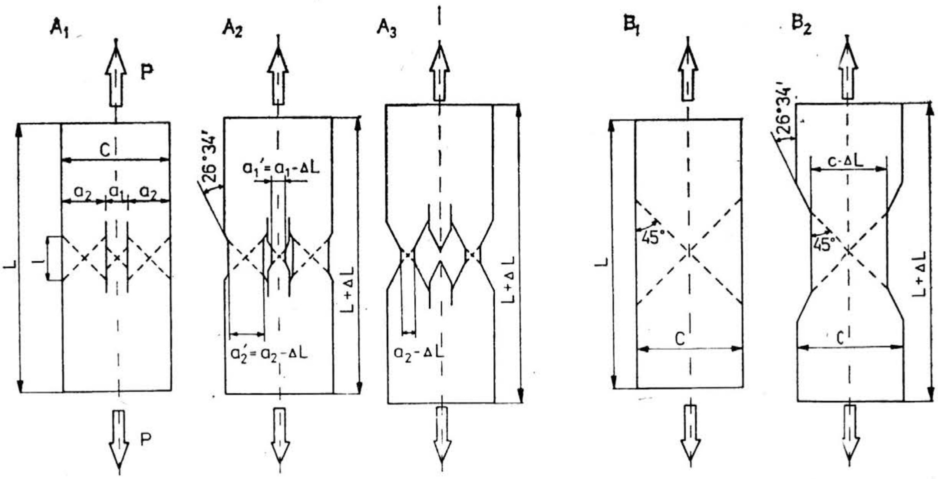

FIG. 1.

In the previous works [7] and [8] a mechanism of internal micronecking has been proposed as a possible factor of the process of ductile fracture of metals. This mechanism will be shortly discussed below since an analogous mechanism may contribute to the evolution of damage during the tertiary stage of creep. Simple theoretical analysis based on the slip-line technique shown in Fig. 1 indicates that, in the presence of parallel cracks oriented along the loading direction, internal necking leads to local microfractures reducing the cross-sectional area. In order to analyse the deformation history of our model shown in the sequence of the deformation stages from A_1 to A_3 we assume that the material is rigid-ideally plastic. We will discuss the process of internal necking in terms of the plane strain theory of plastic flow. Plastic yielding begins when the tensile force P per unit thickness reaches the value $P^* = c\sigma_{pl}$, where σ_{pl} is the yield locus of the material. Dashed lines in Fig. 1A$_1$ show the initial scheme of slip-lines. Fig. 1 A$_2$ illustrates how the strips between slits begin to neck. In Fig. 1 A$_3$ the central strip of the smallest width a_1 is separated by the necking process, while the necking in the two wider strips is only slightly advanced.

Comparing the lateral strain of the strips in the stage A_2 we obtain the strain concentration factor

$$f = \frac{\varepsilon_{a_1}}{\varepsilon_{a_2}} = \frac{a_2}{a_1}, \tag{3}$$

since lateral strain in the strips of the width a_2 is defined as $\varepsilon_{a_2} = -(a_2 - a_2')/a_2 = -\Delta L/a_2$, and similarly $\varepsilon_1 = -(a_1 - a_1')/a_1 = -\Delta L/a_1$. Formula (3) is valid for intermediate stages of deformation before the separation of the central strip.

Comparing the lateral strain in the central strip wih that for the model without cracks (Fig. $1B_2$) we obtain another definition of the strain concentration factor for the intermediate stages of deformation

(4) $$f = \frac{\varepsilon_{a_1}}{\varepsilon_c} = \frac{c}{a_1}.$$

The reduction of the cross-sectional area for the stage shown in Fig. $1A_3$ is $(a_1+2\Delta L)$ and the relative reduction of this area, which may be interpreted as the damage parameter, is equal to

(5) $$\omega = \frac{a_1+2\Delta L}{c}.$$

Let us consider now a similar model with a number of slits in one cross-section. Let the strips between slits have various widths $a_i (i = 1, 2, ..., m)$ with $a_i < a_{i+1}$ and let the number of strips of the same widths a_i be n_i. The equation of evolution of the damage parameter with increasing elongation may be written in the form

(6) $$\omega = \frac{1}{c}\left(\sum_{1}^{k} a_i n_i + \Delta L \sum_{k+1}^{m} n_i\right) \quad \text{for} \quad a_k < \Delta L < a_{k+1}.$$

The first term in brackets is connected with the separation of the narrow strips and the second term corresponds to the reduction of the width of the wider strips due to necking.

Since during the tension test the actual length of the model L exposed to creep is a function of the time t, the length increment ΔL may be calculated as $\Delta L = \frac{dL}{dt}\Delta t$. Then the parameter ω given by Eq. (6) may be represented as the function of time.

Although the theoretical analysis presented above is based on the rigid-plastic time-independent model of the material, one can expect that the mechanism of internal micronecking plays certain role in the evolution of damage in the final stage of the processes of creep. In order to verify that the micronecking process is qualitatively similar for the final stage of the standard tensile test and for the tertiary period of creep, a simple experiment described below has been performed. The specimen of an AlMg2 aluminium alloy with two prepared slits presented in the upper part of Fig. 2 has been exposed to the creep test at the temperature 300°C. In the lower part of the figure is presented the specimen after 500 hours of creep under constant load. It is clearly visible that the necking process is only

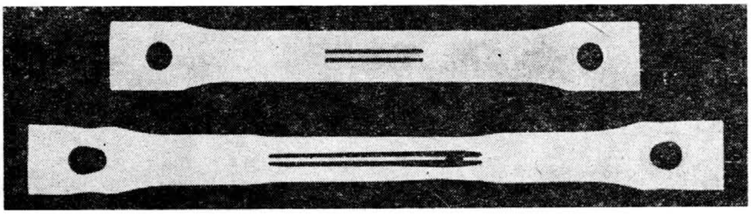

FIG. 2.

slightly advanced in the two wide strips while the narrow central strip has been ruptured. Cental part of the specimen before and after the test is shown in Fig. 3.

This simple experiment shows that the internal micronecking should be considered as one of the factors responsible for the behaviour of metals during the tertiary creep and as a factor taking part in the evolution of the damage parameter in the theory of creep.

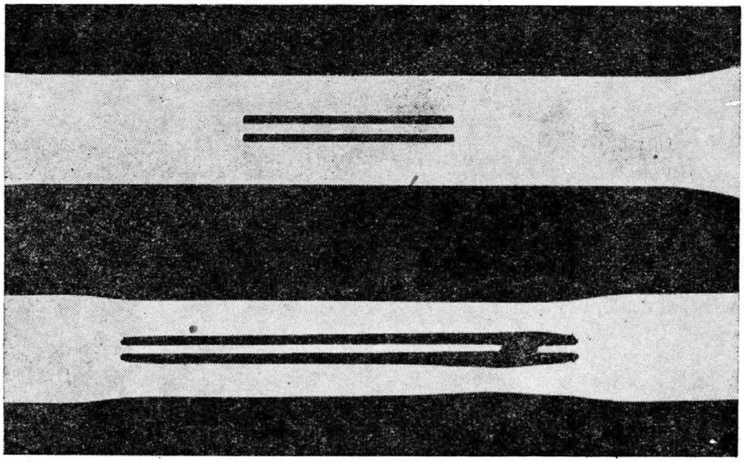

FIG. 3.

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