KINETICS OF DAMAGE ACCUMULATION IN A MATERIAL AT HIGH STRAINS

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A new phenomenological model of damage accumulation has been proposed for metallic materials in static tension, which can also take into account the type of stress state. The coefficient of transverse strain at the stage of softening (on the descending portion of the strain curve) is taken as the main parameter of the current state of the material related to the degree of loosening.

INTRODUCTION

Within recent years, extensive investigations on the kinetics of fracture nucleation and propagation, in plastic materials in particular, have been carried out at the Institute for Problems of Strength of the National Academy of Sciences of Ukraine by testing specimens under conditions of equilibrium deformation. The experimentally obtained descending branches of complete diagrams turned out (1) to contain a great body of reliable information about physical processes occurring in a deformed material at different scale levels. Relying on this information, including that obtained by the metallographic analysis of the material structure at different stages of deformation, it is possible to construct physically reliable analytical models of the accumulation of non-localized damages and on their basis to describe structural transformations up to the initiation of a macrocrack.

The case of uniaxial tension. Let us consider the case of uniaxial tension of a body on the assumption of its macroscopic uniformity. Ignoring the elastic strain due to

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its smallness compared to the residual strain, i.e., assuming a rigid-plastic model of a body with hardening, we consider structural parameters $\alpha(\varepsilon)$ and $\beta(\varepsilon)$, which at the total strain

$$\varepsilon = \varepsilon_p + \varepsilon_l \tag{1}$$

(where ε, ε_p and ε_l are the total current strain, plastic strain, and loosening strain, respectively) are defined by the following relationships:

$$\alpha(\varepsilon) = \varepsilon_l / \varepsilon, \qquad \beta(\varepsilon) = \varepsilon_l / \left|\varepsilon_p\right| \tag{2}$$

Basing on relations (1) and (2), we obtain

$$\alpha(\varepsilon) = \beta(\varepsilon) / \left(1 + \beta(\varepsilon)\right). \tag{3}$$

The coefficient of transverse strain, which is one of important characteristics of the deformation processes in a material related to the variation of its density, can be formally put in correspondence with the parameter $\alpha(\varepsilon)$. Indeed, if ε' is the transverse strain, then

$$\mu = -\frac{\varepsilon'}{\varepsilon} = -\frac{\varepsilon'_p + \varepsilon'_l}{\varepsilon_p + \varepsilon_l}.$$

Considering that the growth of pores occurs mostly in the direction of acting stresses, i.e., in the axial direction, the transverse strain from loosening ε'_l can be neglected. Then

$$\mu = -\frac{\varepsilon'_p}{\varepsilon_p + \varepsilon_l} = \frac{0{,}5 \cdot \varepsilon_p}{\varepsilon_p + \varepsilon_l} = \frac{0{,}5}{1+\beta},$$

whence we find

$$\beta(\mu) = \frac{0{,}5 - \mu}{\mu} \tag{4}$$

and basing on expression (3) we have

$$\alpha(\mu) = 1 - 2 \cdot \mu . \tag{5}$$

Fig. 1 shows a general view of the stress-strain curve for a rigid-plastic body (curve 1), a typical form of the relationship coefficient of transverse strain versus the degree of deformation (curve 2), and a corresponding curve 3 calculated by eqn (5) with the account taken of curve 2. Curve 4 in this Figure illustrates the relation

$$\varepsilon_l^t = \alpha(\varepsilon) \times \varepsilon = \left[1 - 2 \cdot \mu(\varepsilon)\right] \cdot \varepsilon \tag{6}$$

at $\alpha(\varepsilon)$ varying in accordance with curve 3; $\mu(\varepsilon)$ is the current value of the coefficient of transverse strain.

Indirect confirmation of the S-shape of the damage accumulation curve (curve 4 in Fig. 1) is its correlation with some structure-sensitive parameters which characterize the process of acoustic signal passing through the deformed material.
The tests were performed on cylindrical small-scale specimens of steel 20 for the evaluation of damage accumulation in the process of deformation. Specimens were subjected to uniaxial tension to different strain levels followed by turning in order to remove the distortion of the geometry of the working section occurring due to deformation, including necking. The degree of the material damaging was defined by the changes in the parameters of the signals emitted by the generator, with the AE equipment "EMA" (2) operating in the regime of one-channel zone location.
The results of the processing of the experimental data revealed that with an increase in the specimen deformation the amplitude, A, of the acoustic signals received attenuates, whereas the time, R, of the signal enhancement up to the maximum value of the amplitude, i.e., the duration of the AE event, decreases. In this case, it is of essential importance that the shape (geometry) of curve $R(\varepsilon)$, corresponds to the shape of the $\varepsilon_l^t(\varepsilon)$ curve constructed using Eq.(6).
The investigations specially performed in the framework of the present work revealed that within the portion preceding the initiation of a macrocrack, the coefficient of transverse strain can decrease down to 0.15-0.10, and the level of loosening strain reaches 20% and more at the total strain of 25-30%.

The influence of the stress state type. Among the factors influencing the kinetics of damage accumulation in the process of static loading, the type of the stress state occupies one of the first places (3,4). This effect is most pronounced at the stage of fracture localization when microcracks and pores coalesce into a macrocrack which is evidenced, in particular, by the experimental data of the present authors (1).
If, by analogy with (5), the intensity of loosening strains is taken as a measure of damage accumulation, and the function $f(\sigma_{ij})$ is introduced in the model for taking into account the structure evolution due to the effect of the type of the stress state, then relationship (6) for an arbitrary system of stresses will take the following form:

$$\varepsilon_l^* = [1 - 2 \cdot \mu(\varepsilon_i)] \cdot \varepsilon_i \cdot f(\sigma_{ij}) \; . \qquad (7)$$

Comparing (6) and (7) we obtain

$$f(\sigma_{ij}) = \frac{\varepsilon_l^*}{\varepsilon_l^t} \qquad (8)$$

In order to specify the function $f(\sigma_{ij})$, we make a statistical analysis of the proposed model.

From the solution of the problem of the probability theory on the repeated sampling of the specified volume we have

$$f\left(\sigma_{ij}\right) = B^{3K_\sigma - 1}, \tag{9}$$

where B is a characteristic of the material structure related to sensitivity to the type of stress state, K_σ - Bridgman parameter.

Thus, comparing (8) and (9) we obtain a formula for determining the damage accumulated in the material at an arbitrary stress system:

$$\varepsilon_l^{*} = \varepsilon_l^{t} \cdot B^{3K_\sigma - 1} \quad . \tag{10}$$

For pure shear $\left(K_\sigma = 0\right)$ at any given strain

$$\varepsilon_l^{\tau} = \varepsilon_l^{t} \cdot B^{-1},$$

whence

$$B = \frac{\varepsilon_l^{t}}{\varepsilon_l^{\tau}}, \tag{11}$$

i.e., *B* is a characteristic of the material properties which is numerically equal to the ratio of the loosening strains in uniaxial tension and pure shear at the same or limiting strain intensity.

To verify the validity of the model described, special purpose experiments were carried out on specimens of steel 20.Smooth specimens 8 mm in diameter and specimens with circular concentrators were used.

Figure 2 presents the values (points) of the coefficients of transverse strain for the deformed steels at the stages which precede fracture of smooth specimens and specimens with concentrators R4 and R2, as well as their linear approximations and the curves of damage accumulation constructed after them using formula (6). Dark symbols on those curves correspond to the instant which is close to the coalescence of scattered damages and macrocrack initiation.

Thus, the data obtained on limiting damages of steel under conditions of different stress states indicate that with an increase in the rigidity of the stress state, the extent of these damages decreases. Using the first approximation of the experimental data in the form of a linear dependence of the extent of damages on the parameter K_σ, we find that $\varepsilon_l^{t} = 0.693$ in uniaxial tension $\left(K_\sigma = 1/3\right)$. The function of Eq. (10) was found to be in good agreement with the test results for specimens with concentrators. In calculations, *B* was taken to be 0.6.

To verify experimentally the data obtained on the limiting damages in steel at different stress states, an additional use was made of a direct method of weighing on a unique setup and of the technique of the authors. After determining the coefficient μ, the metal samples of similar weight (approximately 0.7 g) were cut from the central parts of all the specimens tested. Then, using the method described elsewhere , residual increment ΔV of the material volume due to the damage accumulated in the process of deformation was determined. The experimental data are similar to the results obtained by W.Dahl and colleagues (6).

Reducing ΔV and ε_l^* to the same scale gives the following relationship:

$$\varepsilon_l^* = 1.2 \cdot \Delta V$$

SYMBOLS USED

ε = total current strain

ε_p = plastic strain

ε_l = loosening strain

$\alpha(\varepsilon)$, $\beta(\varepsilon)$ = structural parameters

$\mu(\varepsilon)$ = current values of the transverse strain coefficient

$f(\sigma_{ij})$ = function of the effect of the stress state mode

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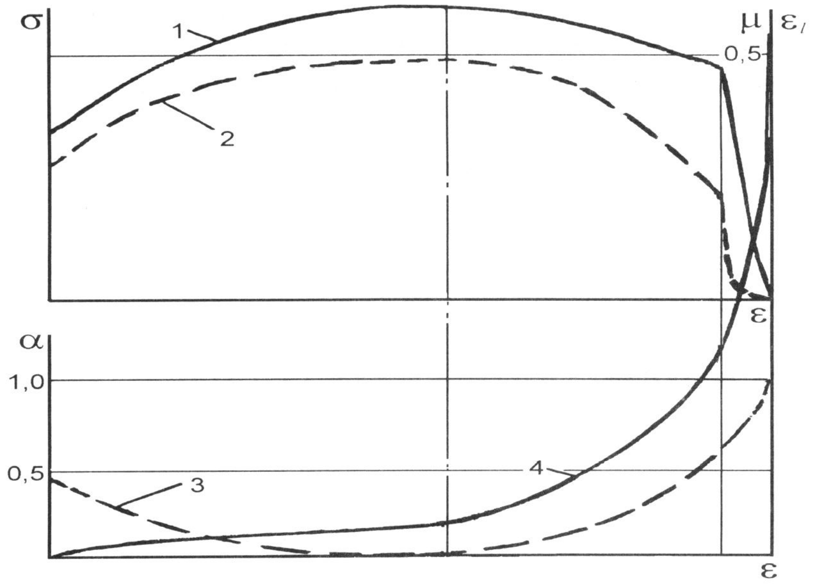

Figure 1. General view of the curves characterizing the processes of deformation and loosening of the material in tension.

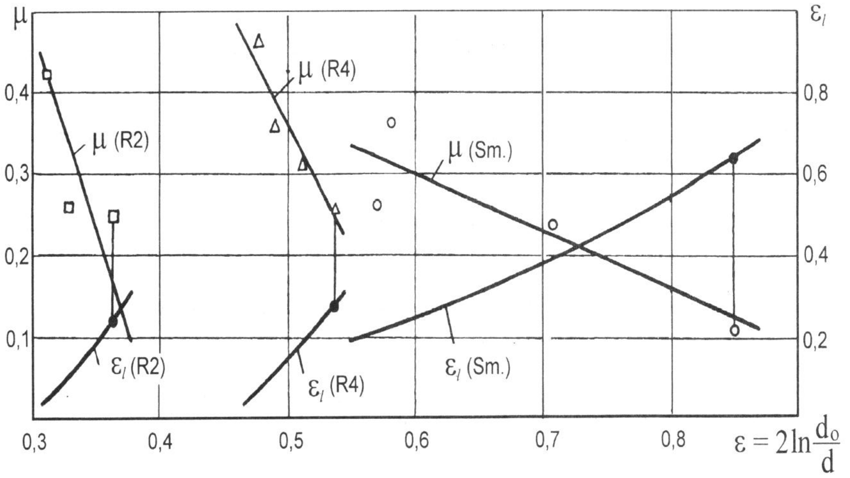

Figure 2. Magnitudes of the coefficients of transverse strain for steel 20 at the stages preceding failure.