ENERGY ANALYSIS OF DAMAGEABILITY OF METALS DURING DEFORMATION AT ELEVATED TEMPERATURES

THEORY OF ELASTICITY

1966

SovietRxiv

Abstract

Full Text

UDC 620.178.38

THEORY OF ELASTICITY

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ENERGY ANALYSIS OF DAMAGEABILITY OF METALS DURING DEFORMATION AT ELEVATED TEMPERATURES

(Presented by Academician Yu. N. Rabotnov on 16 VIII 1965)

At the present time a number of dislocation mechanisms of fracture have been developed as applied to various conditions of static, quasi-static, and cyclic loading. Common to all these types of fracture is the fact that rupture of interatomic bonds, irrespective of the loading conditions, occurs at the moment when the metal lattice absorbs a specific energy of limiting magnitude, determined by the forces of interatomic bonding. In the case of plastic metals this is achieved as a result of the accumulation of a critical density of defects (dislocations, vacancies).

The magnitude of the limiting energy necessary for breaking interatomic bonds can be determined directly from data on thermodynamic constants, as was shown earlier in the works of I. A. Oding and co-workers ([1], [2]). In the present article a further development of the structural-energy theory of fracture is given ([2]).

In the general case, the magnitude of the specific energy A , absorbed by the lattice under mechanical loading, is composed of two components: the specific energy A , expended on the creation of limiting static distortions, and the specific energy A , expended on the breaking of interatomic bonds in the volumes of metal with limiting static distortions, i.e.

$$A = A + A .$$

The magnitude A depends on the initial state of the material, the loading conditions, and other external factors, while the values of A are determined, as was shown earlier ([2]), by the nature of the given metal and, first of all, by the forces of interatomic bonding.

To establish the general regularities of the weakening of metals with temperature, it seems expedient to consider the dependence of the structurally independent component of the specific energy A on temperature. This dependence can be

Figure 1

Figure 1: Figure 1

established on the basis of using the hypothesis of energetic similarity between mechanical fracture and melting ([2]). It is known that when a metal is heated to the melting temperature, limiting distortions are attained as a result of thermal vibrations of the atoms (dynamic distortions); in this case, at the melting temperature, to break the interatomic bond with limiting dynamic distortions, it is necessary to supply additional energy determined by the value of the latent heat of fusion L_{T_s}.

On the basis of the hypothesis of energetic similarity of mechanical fracture and melting, it may be assumed that under mechanical loading, for the breaking of interatomic bonds in volumes of metal with limiting static distortions at an arbitrary temperature T_x, such specific energy is required as would be needed if it were possible to transform the metal into the liquid state not at T_s, but at T_x, i.e. below the melting temperature.

Hereafter we shall denote this energy by L_{T_x}. The magnitude L_{T_x} can be calculated from Kirchhoff' s equation ([3]), describing the chan-

the change in the heat of a chemical reaction (the heat of a polymorphic transformation of the metal with temperature T_x).

For our case, Kirchhoff' s equation takes the form

$$L_{T_x} = L_{T_s} - \int_{T_x}^{T_s} \Delta c_p \, dT, \tag{1}$$

where L_{T_s} is the latent heat of melting; Δc_p is the algebraic difference between the specific heat capacity in the liquid and solid states; L_{T_x} is the "latent heat of melting" at T_x.

Fig. 1. Comparison of calculated and experimental values of the specific energy of limiting deformation.
a—Ta (99.9%); —Al (> 99.99%); —Cu (99.985%)

Since, under mechanical loading, the limiting static distortions are created as a result of the action of externally applied forces, in order to break interatomic bonds in the volumes of metal with limiting distortions, what is required is not L_{T_x}, but the specific energy

$$(A_p)_{T_x} = L_{T_x} - \int_0^{T_x} c_p \, dT \tag{2}$$

$$\left(\int_0^{T_x} c_p\,dT \text{ is the heat content of the metal at the given temperature}\right),$$

since the thermal vibrations of atoms in these volumes of metal will promote fracture.

Having determined L_{T_x} from equation (1) and calculated the values of $\int_0^{T_x} c_p\,dT$ at various temperatures, one can, in accordance with relation (2), determine the temperature dependence of the specific fracture energy A_p.

It is of interest to compare the calculated values of the limiting work of fracture with experimental values. Figure 1 gives such a comparison for high-purity Ta, Al, and Cu. The experimental values of A_p were determined by the Shvining method, described in work (4), or by the Gilman method (5), as the energy of limiting deformation referred to the neck. A satisfactory agreement between the calculated and experimental data can be seen (5-7). Consequently, the structurally independent part of the specific fracture energy can be calculated or determined experimentally by the Shvining or Gilman method.

The use of the specific fracture energy makes it possible to solve a number of important practical problems associated with the problem of the behavior of metals and alloys at low and elevated temperatures.

In the present article, the use of the energy of limiting deformation is considered for establishing the regularity of accumulation of damage in metals under conditions of long-term fracture.

Let us denote by $(A_p)_0$ the value of the specific fracture energy for the metal in its initial state at room temperature, and by $(A_p)_i$ the specific fracture energy at room temperature after prior deformation under arbitrary conditions. Then the degree of damage to the material as a result of the preceding deformation can be expressed as

$$\Pi = \frac{(A_p)_0 - (A_p)_i}{(A_p)_0} \cdot 100\%. \tag{3}$$

We studied the accumulation of damage in steel 1Kh18N9T as a function of the degree of preliminary deformation during deformation under tensile conditions at 700°. The results of processing the experimental data are presented in Fig. 2.

Extrapolation of the straight line after the break to $P = 100\%$ gives a limiting deformation (relative elongation) equal to 31%, which coincides with the experimental value of elongation at the moment of rupture of the steel at a temperature of 700°.

Fig. 2

Figure 2: Fig. 2

Fig. 3

Figure 3: Fig. 3

Attention is drawn to the fact that at a deformation equal to 4% (or a yield stress of 20 kg/mm^2), a break is observed in the rectilinear dependence $P-\varepsilon$ (Fig. 2); moreover, as follows from the data presented in Fig. 2, the intensity of damage (determined by the tangent of the angle of inclination of the straight line $P-\varepsilon$ to the ordinate axis) at deformations greater than 4% is higher than at lower deformations; therefore, the stress corresponding to the deformation above which an increased intensity of damage is observed may be called the stress of intense damage σ . At stresses $\sigma > \sigma$, it is natural to expect the absence of an established creep stage and the presence of a break in the rectilinear dependence of long-term strength $\sigma - \lg t$ (t is the time to failure), since, beginning with stresses

Fig. 2. Dependence of damage on the magnitude of preliminary deformation, steel 1Kh18N9T, temperature 700°

Fig. 3

Fig. 4

Fig. 3. Long-term strength curve of steel 1Kh18N9T at 700°

Fig. 4. Change in the specific energy of limiting deformation of steel at 20° during creep at 700°, $\sigma = 12.5$ kg/mm^2

σ , already at the moment of loading the plastic deformation that arises leads to intense damage. Experiments to study the character of creep curves and long-term strength curves did indeed confirm the assumptions stated. Figure 3 gives the long-term strength curve of steel 1Kh18N9T at a temperature of 700°. It can be seen that the break in the dependence of the long-term strength curve $\sigma - \lg t$ is observed at a stress close to the stress of intense damage, equal in this case to 20 kg/mm^2.

Further analysis showed that, from the character of the change in the specific energy of fracture as a function of the time during which the metal remains under load, one may also judge the duration of stages I and II of creep and the time to failure. As an example, Fig. 4 shows the change in the specific energy of fracture as a function of time at 700°. It can be seen that the onset of the

Fig. 4

Figure 4: Fig. 4

accelerated stage of creep corresponds to the onset of intense damage, while extrapolation of the curve $(A_p)_i - t$ to the value

$(A_p)_i = 0$ gives the time to failure t_p of the specimen at a given stress; moreover, the agreement of the values of t_p determined experimentally and from extrapolation of the work to failure is sufficiently close (Fig. 4).

Thus, the results of the study indicate the expediency of using energy concepts to assess the behavior of metals under load at elevated temperatures.

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Received
3 VIII 1965

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