FRACTURE TOUGHNESS OF MATERIALS UNDER DYNAMIC LOADING

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In the process of the design and operation of structures and articles operating under dynamic loading, there arises the problem of determining the material properties as a function of the rate of loading or deformation. We note that the functional dependences of the deformation resistance characteristics on the deformation rate have been studied in more detail than these same dependences for the resistance to brittle fracture.

Moreover, in the latter case the question of the selection of the brittle fracture criterion has not been completely clarified. We generally use the critical stress intensity factors K_{Ic} and K_{IIc} that are defined in the framework of linear fracture mechanics, and also differing variants of the specific energy of separation per unit surface area $2\gamma(G_{Ic})$.

At the present time the nost complete studies under dynamic loading have been made of the critical stress intensity factor (fracture toughness) under conditions of normal separation based on crack movement K_{Id} up to loading rates $K_I \approx 4\cdot 10^7$ MPa$\cdot$m$^{0.5}\cdot$sec^{-1} [1, 2] and the specific work of material separation per unit surface area. For the determination of the latter we use various techniques, which yield similar results only in the region of cold brittleness [3].

There are practically no data on the crack resistance of materials under conditions of transverse shear K_{II} (even for static loading), although there is no question of the importance of this characteristic for many specific cases, for example, for structures and articles operating in compression or under conditions of hydrostatic pressure, and also those operating in processes associated with punching, piercing, and notching.

In addition, studies of back-surface spalling, arising in the case of high-velocity mutual impact of plates, have shown that for several metals longitudinal (relative to the direction of the shock wave) microshears initially form (during spallation surface formation) in a threshold fashion at the critical impact velocity. Then normal microcracks form independently upon interaction of the forward-traveling and backward-traveling unloading waves [4]. These microshears and microcracks have characteristic dimensions that do not exceed tens of microns, and thus they relate to the mesoscopic level of deformation [5], which is the governing level for the macroscopic strength and ductility properties. With account for initial microshear formation, it becomes evident that the importance of determining K_{II} increases significantly.

What causes the longitudinal microshears to form? It has been repeatedly shown in several studies (see, for example, [6]) that in the case of dynamic deformation of materials the elements of the medium displace in the form of an ensemble of microflows, having differing velocities relative to one another. In other words, for fixed loading conditions the material may be characterized by (in addition to all the other parameters) the dispersion of the medium particle velocities (the distribution width) Δu.

It is evident that microshearing takes place when the difference of the velocities at the boundaries of the microflows exceeds the critical value. We shall find the mathematical condition of initiation of this microshearing. To this end we assume that the material in the mesovolume is in the elastoviscoplastic state with zero coefficient of strain hardening. The equation of deformation of this material is

$$\sigma = \sigma_0(1 + \mu_1\dot{\varepsilon}), \quad (1)$$

where σ is the field stress; σ_0 is the static component of the stress; $\mu_1 = \mu/\sigma_0$; μ is the dynamic toughness; and $\dot{\varepsilon}$ is the strain rate. In the case when microshearing takes place the potential elastic energy of deformation of the medium E_1

$$E_1 = \frac{\sigma^2}{2E} = \frac{\sigma_0^2(1+\mu_1\dot{\varepsilon})^2}{2E}. \quad (2)$$

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(E is Young's modulus) will be equal to the difference of the kinetic energies of the medium elements within two neighboring microflows

$$E_2 = \rho u \Delta u \tag{3}$$

(ρ is the density of the material and u is the average velocity of the particles of the medium). Equating (2) and (3) and considering that $\mu \simeq \lambda\rho\Delta u\Delta h$ (λ is a constant multiplier, Δh is the distance between the microflows, and the deformation rate $\dot{\varepsilon} \simeq \Delta u/\Delta h$), we obtain

$$\sigma_0 = \frac{(2\rho E \Delta u u)^{0.5}}{\left(1 + \frac{\lambda\rho\Delta u^2}{\sigma_0}\right)}. \tag{4}$$

Elementary calculations using this formula for the steels show that for $\sigma_0 = 0.7\sigma_u$ (σ_u is the ultimate strength) longitudinal microshears form when the dispersion of the velocities of the particles is commensurate with their average velocity (i.e., $\Delta u \simeq u$), which has been verified experimentally many times [4]. The same calculations show that for the relation $\Delta u \simeq 0.1u$ the microshears propagate at an angle of 45°, since in this case we can take $\sigma_0 = \sigma_u/2$.

Finally, there are two ranges of the relationships: $\Delta u < 0.1u$ and $0.1u < \Delta u < u$, for which other forms of plastic accommodation processes are possible: for example, for the first range by means of the rotational modes [7], for the second range with the aid of the oscillatory forms of motion [8].

We note that in the case of back-surface spalling the stress state in the material corresponds to the case of ideal one-dimensional deformation, which is not achievable in practice with the use of standard linear-fracture-mechanics specimens under conditions of either static or dynamic loading. This fact was the stimulus in [9] for the determination of K_{Ic} under spalling conditions for ductile materials. And with account for the fact that on the mesoscopic scale level the deformable medium is more elastoisotropic than in the macrovolume, the advantages of determining the fracture resistance characteristics (specifically, the fracture toughness) on this level become evident.

Since in the spallation case the problem is to determine the length of the microcracks and microshears after completion of the process, then of the three dynamic stress intensity factors (crack initiation K_d, propagation k_D, and arrestment K_a) only the last is amenable to determination.

Moreover, it was noted repeatedly in [10] that specimens of very large dimensions are required for the determination of K_d and k_D; however, it was also shown in [10] that $K_a = K_m$ – the minimal value of K_D.

We see from comparison of the data of direct interferometric measurements of the motion of the free surface of the specimens with the data of their subsequent metallographic studies that the maximal microshear length ℓ_2 is proportional to the loading impulse duration Δt and the particle velocity distribution width Δu:

$$l_2 \simeq \Delta u \Delta t. \tag{5}$$

In spite of the fact that a system of cracks of differing length forms in the specimen in the spallation zone, experimental and theoretical studies [11] show that the crack that first begins to move presents the greatest danger. Assuming that in our case the first crack to start moving is the crack having the maximal length ℓ_2, we use the well-known formula of linear fracture mechanics to evaluate the value of K_{IIa}:

$$K_{IIa} = \tau\sqrt{\pi l_2} = \frac{\rho c_p u}{4}\sqrt{\pi l_2}. \tag{6}$$

With account for (5) we rewrite (6) in the form

$$K_{IIa} = \frac{\rho c_p u}{4}\sqrt{\pi \Delta u \Delta t}, \tag{7}$$

where τ is the maximal tangential stress; c_p is the plastic wave velocity.

Since the formation of microshears and microcracks that are perpendicular to the direction of shock wave propagation takes place independently of one another, then on the basis of analogous arguments we can obtain the relation for determining the critical stress intensity factor in the case of normal separation based on crack arrestment K_{Ia}:

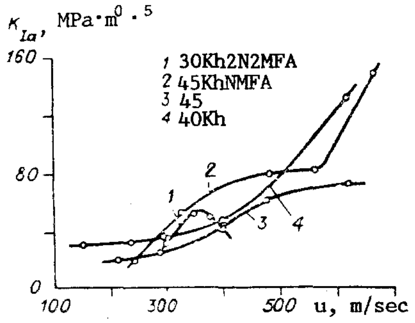

Fig. 1

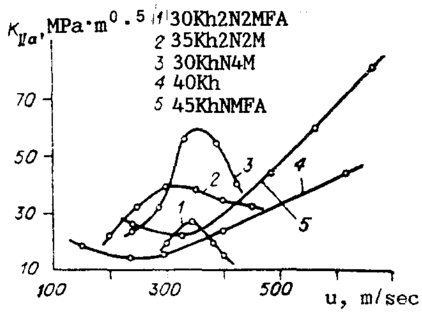

Fig. 2

$$K_{Ia} = \sigma \sqrt{\pi l_1} = \frac{\rho c_p u}{2} \sqrt{\pi l_1}. \tag{8}$$

Here σ is the maximal normal stress; and ℓ_1 is the maximal microcrack length (determined on the basis of metallographic analysis of fractured specimens).

In the case of microshear propagation at an angle of 45°, we obtain [12]

$$K_{Ia} = K_{IIa} = \sigma \sin^2\beta \sqrt{\pi l} = \sigma \cos\beta \sin\beta \sqrt{\pi l} = \frac{1}{2}\sigma \sqrt{\pi l}$$

(β = 45°, ℓ is the maximal length of the inclined microshear).

The values of K_{Ia} and K_{IIa} that are calculated using (7) and (8) for several steels are shown in Figs. 1 and 2. The agreement of these results with those of other authors was discussed in [13].

We see from the functional curves of the variation of K_{Ia} in Fig. 1 that for the three steel grades with low ductilities there is a tendency toward increase of the values of K_I with increase of the impact velocity and therefore the deformation rate, which varied in the experiments from $4 \cdot 10^4$ to $2 \cdot 10^5$ sec^{-1}, while for the more ductile steel 30Kh2N2MFA the curve of K_{Ia} variation has an extremum; these qualitative results on the whole correlate well with the data on K_{Id} variation from [1].

The K_{IIa} variation curves (presented in Fig. 2) indicate the presence for all the steel grades of an extremum of the relation $K_{IIa} = f(u)$, lying in the range of impact velocities from 200 to 350 m/sec.

We shall examine the nature of the manifestation of this extremum. It was assumed earlier that the material in the mesovolume is in the elastoviscoplastic state with zero strain hardening coefficient and dynamic toughness that is proportional to the microflow velocity distribution width Δu. We rewrite (7):

$$K_{IIa} = \frac{\rho c_p u \Delta u \Delta t \pi^{0,5}}{(\Delta u \Delta t)^{0,5}}. \tag{9}$$

Since $c_p \Delta t \varphi = \Delta h$ ($\varphi < 1$ is a constant multiplier), then (9) can be written in the form

$$K_{IIa} = \frac{\alpha \mu u}{(\Delta u \Delta t)^{0,5}}, \quad \alpha = \text{const}. \tag{10}$$

We note that in [1] the dynamic stress intensity factor in the case of normal separation based on crack movement is proportional to the square root of the dynamic toughness.

It is well known that the dynamic toughness decreases with increase of the strain rate, and this means in our case with increase of the impact velocity ($\dot{\varepsilon} = u/2c_p\Delta t$). This decrease is quite intense for practically all types of materials, including the steels [14, 15], i.e., with increase of the impact velocity u and corresponding reduction of the dynamic toughness μ, as follows from (10), an extremum of the function $K_{IIa}(u)$ will appear.

If there exists an extremum (maximum) of the function $\Delta u = f(u)$, coinciding (or nearly so) with the extremum of the function $K_{IIa} = f(u)$, then the extremal point of K_{IIa} will be a minimum; if there is no extremum of Δu as a function of u, the extremal point of K_{IIa} will be a maximum.

In conclusion, we shall examine the relationship between the average velocities of the normal-opening crack and the transverse-shear crack. As is well known, there are several relations for the maximal crack velocity, obtained by Mott, Ioffe, and others [16]:

$$v_{cr} = 0.38\ c_l \quad \text{or} \quad v_{cr} = 0.57\ c_l, \text{ and so on}$$

(c_ℓ is the longitudinal sound wave velocity and c_t is the transverse sound wave velocity).

The recorded maximal crack velocities for the steels range from 0.17 to 0.9 c_ℓ, i.e., in the absolute value range from 1000 to 5000 m/sec [16].

In our case the maximal normal-opening crack velocities, calculated using the formula $v_{cr} \approx \ell_I/\Delta t$, range from 500 to 1000 m/sec, which on the whole agrees with the results obtained by other investigators.

It follows from (5) that the transverse-shear crack velocity is equal to the particle velocity distribution width Δu; its maximal value ($\approx$310 m/sec) was recorded for steel 30KhN4M with σ_u = 1400 MPa and impact velocity 330 m/sec, for all the other steels this velocity is in the range from 100 to 300 m/sec, which is considerably less than the normal-opening crack velocity [$v_{cr\,sh} \approx (0.2 \text{ to } 0.3) v_{cr\,op}$].

On the basis of the foregoing we note that the proposed method for determining the critical dynamic stress intensity factors in the case of normal opening and transverse shear based on crack arrestment and for determining the crack velocities makes it possible to significantly expand the range of materials that can be tested and reduce the specimen dimensions.

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