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COMPOUND-FAILURE POLAR-FAN DIAGRAMS

Yu. I. Fadeenko

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The kinetic theory of failure gives a relationship between the lifespan τ and the applied stress σ as a formula typical of a thermally activated process:

$$\tau = \tau_0 \exp\left[(u - \gamma\sigma)/kT\right], \tag{1}$$

where τ_0 is the period of the relevant mode of thermal vibrations, and the exponential factor is a quantity reciprocal to the probability of an elementary act of failure (overcoming the activation barrier) in one period of oscillations, while u is activation energy, and γ is the activation volume.

Here we wish to point out that one can use the shape of the observed $\tau(\sigma)$ to judge how many elementary failure mechanisms make a substantial contribution to the lifespan. Here the polar-fan diagram technique is used.

It follows from (1) that the family of $\tau(\sigma)$ isotherms forms a fan of rectilinear rays in the (σ, ln τ) plane emerging from the pole with coordinates (u/γ, ln τ_0). If two different failure mechanisms are active together, there will be two different isotherm fans, and the resultant isotherms will have the form of kinked lines, as shown in Fig. 1. The experimental isotherms in fact sometimes have these kinks [1, 2]. In [1], it was assumed that the lifespan is determined always by a single universal failure mechanism, namely by the stage of initiation and growth of microscopically small cracks. The growth rates of these nuclear cracks increase rapidly with the lengths, and the total time for them to reach the critical Griffiths size is determined by the time required to reach a size of a few times the interatomic distance. Then τ_0 is of the order of the atomic vibration period, u is the energy of an elementary atomic bond intersected by the plane of the crack, and γ is the product of the effective stress concentration and the volume occupied by an atom. According to [1], the kink in $\tau(\sigma)$ corresponds to a stepwise change in the structure of the solid, and also in the structure-sensitive parameter γ (and evidently also in τ_0). The values of u should remain unchanged.

It may be that the concepts of [1] describe some particular cases of kinks on isotherms correctly, but in the general case one naturally assumes that the rectilinear parts of the kinked isotherms may be related to different physical mechanisms acting simultaneously. That

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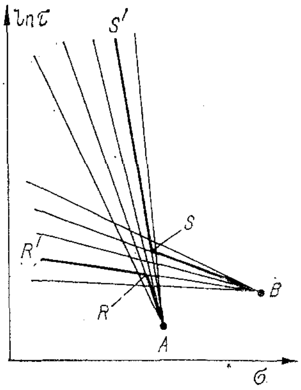

Fig. 1

point of view is taken in particular in [2], where the kinks were compared with changes in the failure mechanisms accompanied by changes in all the parameters of (1), including u.

If two different mechanisms are involved, Fig. 1 shows that two different situations can occur.

Firstly, two competing mechanisms may operate independently, and then the lifespan will be determined by the mechanism that leads more rapidly to failure in the given state (σ, T), and the resultant isotherms will be distinct lines ARR'.

Secondly, the two mechanisms may operate in sequence at different stages, and then the lifespan will be determined by the mechanism that occurs more slowly, while the resultant isotherms will be BSS'.

We note that the lines ARR' resemble the observed τ(σ) curves found in viscous—brittle transition [3], while BSS' represent the data on spalling failure when a strong compression wave emerges on the free surface of a solid [4, 5].

To identify situations of ARR' and BSS' type, one needs at least three isotherms determined with adequate accuracy, since this enables one to establish whether their continuations intersect at a single point forming a fan. As regards spalling, data exist indicating that temperature may affect the lifespan in very rapid failure [5], but these data are at present insufficient to yield polar-fan diagrams or any definite judgement on the two-stage character of spalling failure. Additional complications may arise if the rays of the fan are curved because the parameters of (1) are dependent on the parameters (σ, T). Curvature occurs also in polymer failure, where the stress-concentration coefficient and therefore γ vary as the cracks grow [6]. Also the strain occurring in shock spalling is accompanied by appreciable heating, and the lines corresponding to fixed initial temperatures may additionally be curved because the process is not isothermal at short lifetimes.

This case with two fans is readily generalized to that of several. Obvious geometrical arguments show that then the number of mechanisms identified from the diagram may be less than the actual value, which is particularly important in the general case of competition between several multistage processes.

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