ON THE “LOCAL APPROACH” TO THE BRITTLE FRACTURE OF STRUCTURAL MATERIALS

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We consider the principles and sources of an important scientific direction in fracture mechanics—the so-called “local approach” to the problem of fracture of materials. This approach provides a possibility to describe their crack resistance based on conventional mechanical properties and opens up a direct way to determining the limiting state of structural elements. As the first example of the application of this approach, we present the principal propositions of the two-parameter $K_μ$-model of fracture, which relates the “global” $K_Ic$ and “local” $ρ_c$ and $σ_c$ parameters via the yield condition on the contour of a small plastic zone near the tip of a crack. For the last decades, this direction was developed substantially and extended to the regions of quasi-brittle and ductile fracture. We also present the basic statements of this approach that were corroborated for the last decades.

The basic criteria of fracture mechanics (the theory of cracks) were developed and verified experimentally in the last half century [1, 2]. Such well-known parameters of the theory of cracks as the stress intensity factor, the rate of liberation of the energy of elastic strains, the opening of the tip of a crack, the $J$-integral, etc. have demonstrated their ability to describe unambiguously (for specified loads) the limiting state of a material near the tip of a crack in terms of their critical values. These parameters depend exclusively on the geometry of a cracked body and the load, whereas their critical values, according to the definition, have to be invariant under these factors, i.e., to be characteristics of the crack resistance of the material, which is often corroborated experimentally. For the practical application of the criteria of crack mechanics, it is necessary to establish experimentally the characteristics of the crack resistance of materials, and the corresponding procedure is regulated by the well-known standards [3–5].

The basic criteria of crack mechanics were established with the use of the model of a continuum (a structureless medium). As to the form of writing, they differ slightly from the classical fracture criteria (the theories of strength). For example, for a continuous body according to the first classical theory of strength (the theory of maximum tensile stress) and for a body with a normal tensile crack, the fracture criteria are written as

\[ \sigma_1 \geq σ_u, \]  
\[ K_1 \geq K_{lc}, \]

respectively. Here, $\sigma_1$ is the maximum principal stress, $σ_u$ is the ultimate strength of the material, $K_1$ is the stress intensity factor, and $K_{lc}$ is the fracture toughness of the material. In both cases, $σ_u$ and $K_{lc}$ are determined experimentally.

As to the site of location of the hearth of brittle fracture, the predictions of the criteria are different. The first asserts that it begins at the site where, according to the level of stresses, this criterion is satisfied earlier. For
example, in the case of uniaxial tension, a bar of constant cross section would disintegrate into the smallest fragments upon reaching the breaking stresses because the fracture condition is satisfied simultaneously at every point. However, in reality, the material has a great number of various defects, and its fracture begins at the weakest site. On the contrary, for a cracked body, it begins, as a rule, near the tip of the defect, where, owing to a strong stress concentration, both the first and second criteria are satisfied simultaneously in the form $\sigma_1 \geq \sigma_c$. Here, $\sigma_c$ is the local microspalling stress, which is most often greater than the ultimate strength. The necessity of satisfying both criteria simultaneously at the moment of beginning of the brittle fracture of a cracked body has resulted in attempts to construct theories of fracture where these criteria are interrelated by the law of stress distribution near the tip of a crack. Such a relationship represents the logical basis of theoretical search for the interdependence between the characteristics of crack resistance and conventional mechanical properties of materials.

In essence, the unity of criteria (1) and (2) is present explicitly or implicitly already in the first well-known theories of brittle fracture developed by Griffith [6], Barenblatt [7], and Leonov and Panasyuk [8]. Processes on the atomic or molecular levels in accordance with the “relay-race” mechanism of fracture precede it [9]. To derive the basic relations, these theories use such physical quantities as the true surface energy of the substance and the forces of interatomic or intermolecular cohesion.

As to the crack growth within the limits of a single crystallite (grain) of the material, undoubtedly, the mechanism of “relay-race” fracture is here determining. However, in the case of brittle fracture (spalling), as follows from the results of calculations and experiments [9–11], this mechanism can provide only a very low crack resistance, which is comparable with the true surface energy of the material but is very far from that necessary for structural materials. Fortunately, nature finds a way out of this situation, creating polycrystalline structures, where grain boundaries or other interfaces increase the crack resistance by an order of magnitude or even more. Hence, along with the plasticization of materials, polycrystallization is an important means of increasing their crack resistance. As is clear now, such an increase in the resistance of materials to brittle fracture is a result of the transport of the fracture hearth [i.e., the site where the criterion of the type (1) is satisfied first of all] far from the tip of a crack, to the domain of lower local stresses, situated at a significant distance from their peak. Naturally, a polycrystalline structure stimulates the “counter” mechanism of fracture, where a microcrack is initiated at a certain distance, great as compared with interatomic distances, before the tip, and a hindered main crack grows, absorbing the microcrack propagating towards it. There are numerous experimental facts corroborating that most structural materials fail exactly so [9–12].

In the first attempts to describe quantitatively this mechanism of fracture [13, 14], the location of the germ of a microcrack was connected with the peak of local stresses in front of the tip of a notch. According to the theory of slip lines, this peak coincides with the maximum of a logarithmic line going out from the tip of a concentrator. The fracture criterion based on these concepts can describe the mechanism of fracture only as much as the domain under study corresponds to the basic assumptions of calculations and the model of a continuous non-structurized medium. Such analysis [15, 16] is acceptable for fractures propagating from obtuse notches, where the stresses are concentrated in relatively great volumes of the material. At the same time, difficulties arise with passage to very acute notches and especially to cracks, where the domains of stress concentration are comparable with the volume of structural elements of the material. In other words, the first case corresponds to a continuum for which the local criterion of maximum tensile stress is satisfied in the domain of a “smeared” peak of stresses and envelops the entire spectrum of defects in the material. Then the local breaking stress is minimum and depends on the most dangerous defects. We connect such a location of the fracture hearth with the effective distance from its tip to the peak of stresses. Obviously, this distance depends on the geometry of the notch and body and on the load, and not only on the structure of the material (a structureless medium).

In the second case, the overstressed domain of the material is very small, and, therefore, fracture is initiated forcibly on the less efficient defects of the structure, for which higher local stresses are necessary. Exactly the average distance between such defects determines the distance from the tip of a crack where a microcrack is ini-