STUDY OF THE LAWS GOVERNING THE CHANGE IN THE PLASTIC ZONE AT THE CRACK TIP AND CHARACTERISTICS OF THE FRACTURE TOUGHNESS OF METALLIC MATERIALS IN RELATION TO THEIR STRUCTURE (SURVEY)

A. A. Kaminskii and S. B. Nizhnik

INTRODUCTION

Progress in fracture mechanics has recently centered on the development of new models and criteria of the fracture of physically different bodies with more complex (than elastic) laws of deformation. This applies in particular to the study of the failure of strain-hardening metallic materials.

In examining the theoretical solutions presented in the works of D. S. Dugdale [81], G. P. Cherepanov [68], V. Z. Parton and E. M. Morozov [50], J. Rice [54], and others for problems concerning the distribution of stresses and strains near cracks, it becomes evident that the development of plastic deformation is accompanied by a change in the gradients of the plastic strains near the crack tip and the shape of the plastic zones.

In order to further refine existing models and construct new models to describe the fracture of elastoplastic strain-hardening materials, it will be necessary to obtain direct quantitative data on the laws that govern the evolution of the stress—strain state and the form of the tip region of the crack as a function of the loading conditions and the mechanical properties of the material. The latter can be realized either on the basis of numerical solutions — especially those obtained by the finite-element method [36, 50] — or through experimental studies [23, 24, 25, 36, 70].

In the static and low-cycle loading of elastoplastic metallic materials, large strains are typically seen at distances amounting to hundredths of the crack length. Limitingly large strain gradients are also characteristic of these materials, the gradients increasing disproportionately to the nominal stresses. Both of these factors make it necessary to tighten the requirements established for the methods used in experimental studies of the strain fields near the crack tip. It will be necessary to improve their resolution and the accuracy of measurement of the strains for small test bases. Most commonly, these goals are being achieved at present through the use of special resistance gages, interferometric methods, optically active coatings, moiré fringes, and precision dividing grids [36].

Here, we should point out that there are serious limitations to the use of direct structural methods to analyze the stress—strain state of the plastic zone at the crack tip in fracture mechanics. However, it is known that the kinetics of the propagation of cracks are determined to a significant extent by the structural state of the material in this zone. This makes it necessary to address the problem of the fracture toughness of the given material, together with fracture mechanics and current approaches to the physics of fracture.

Studies in this area have led to the development of several dislocation models of fracture, the most well-known being those of A. N. Stroh [99], A. H. Kottrell [78], and V. I. Vladimirov [5]. These models, differing in the dislocation mechanism responsible for the formation of plastic zones and submicrocracks, make it possible to represent the fracture process during static and low-cycle loading as a discrete, multistage process involving the growth of a macrocrack. Each model allows determination of the role of the initial structure in its development.

The discrete location of cracks in static and cyclic loading is also examined in the works of G. P. Cherepanov [67, 69] within the framework of quantum fracture mechanics. These investigations were carried out as part of the construction of a mathematical model of the fracture of ideal crystals with allowance for the interaction between the crack front and specified periodic chains of edge dislocations.
In regard to actual structural metals, characterized by different dislocation distributions, multiple phases, and metastability, the construction of models of fracture requires using results of experimental studies of the structural state of the plastic zone at the crack tip. The systematic use of metallographic analysis, electron microscopy, and x-ray diffraction makes it possible to study the kinetics of the change in the phase composition and structure of the plastic zone [26, 45, 46, 53], establish the causes of catastrophic failure, and determine the structural conditions for improving the resistance of the material to crack propagation. The latter entails increasing the energy content of the fracture process by increasing the mobility of the structural elements with the development of structural and phase transformations.

The fact that medium- and high-strength structural metals with a pronounced plastic zone at the crack tip are widely used in industry and construction makes it necessary to develop new fracture models that can eliminate the need for complex experiments on large specimens to evaluate and predict the critical stress-intensity factor $K_{ic}$. Of particular scientific and practical interest in this regard are the approaches proposed by J. M. Krafft [30], G. T. Hahn and A. R. Rosenfield [82], J. R. Rice and M. A. Johnson [95], V. V. Panasyuk [48] and others. Here, the fracture-toughness characteristic $K_{ic}$ is evaluated from the results of uniaxial tension of standard specimens without cracks with allowance for the structural parameters of the material. The formulas obtained in these investigations were constructed using strain-based fracture criteria applicable to medium-strength structural metals with high values of $K_{ic}$ [55, 92].

The authors use a power strain-hardening law for structural metals, postulate that the local strains at the crack tip are identical to the strains in the neck of tensioned specimens without cracks, and replace the dimensional plastic-zone parameter that goes into the theoretical formulas with various structural characteristics of the material. However, no allowance is made for the initial structure of the metal (which controls the size of the plastic zone), the complexity of the structure, and the effect of the representation of the tip region on the fracture-toughness characteristics of the material. Attempts to formally use several of the formulas without substantiation of the initial premises have been unsuccessful in numerous instances [16, 55, 58].

This article examines the laws governing the formation of the structural state of the tip region of a crack and its effect on the fracture toughness of strain-hardening metallic materials. We will also survey and systematize current approaches to evaluating fracture-toughness characteristics based on data from the uniaxial tension of crack-free specimens with allowance for their structural parameters.