CRACK RESISTANCE AND MICROMECHANISMS OF FRACTURE OF THERMOMECHANICALLY TREATED HIGH-STRENGTH STEEL

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We study the influence of thermomechanical treatment with deformation by the method of hydrostatic extrusion on the parameters of crack resistance of 45KhN2MFSh high-strength steel and plot the dependences of the critical stress intensity factor $K_{IC}$ and critical crack opening displacements $\delta_c$ on temperature. It is shown that these curves have the threshold character. The results of microfractographic analysis demonstrate that changes in crack resistance observed as temperature decreases are accompanied by changes in the micromechanisms of fracture in the regions of the onset of crack propagation, which may take place under the condition of changes in the second-order stress-strain state. We show that the temperature curves of the parameters of crack resistance can be efficiently used in determining the temperature of brittle-ductile transition. In the considered case, this temperature does not depend on the size of the specimen and the loading mode and characterizes the structural state of the cracked material. As compared to conventional modes of thermal treatment, thermomechanical treatment guarantees much higher values of crack resistance, especially at low temperatures, and decreases the threshold of cold brittleness for 45KhN2MFSh steel by 20°C. The indicated increase in crack resistance is explained by the hereditary influence of the deformational substructure on the structural and morphological parameters of martensite.

Thermomechanical treatment is one of the most efficient methods used to increase the resistance of steel to brittle fracture. The major part of research works performed in this field deal with high-temperature thermomechanical treatment [1]. The analysis of structural factors contributing to the increase in the resistance of steel to brittle fracture in the process of high-temperature thermomechanical treatment was carried out by Bernshtein and his colleagues [2]. They explained the positive effect of this type of treatment by the hereditary influence of the substructure of hot-strained austenite on the morphological and structural parameters martensite. In using cold plastic deformation in the process of thermomechanical treatment, the inheritance of strain hardening is, to a great extent, complicated by the double transformation, which requires a special approach to the formation of the substructure of steel prior to heating for the final thermal treatment. We developed special principles for the choice of basic parameters of the process of treatment guaranteeing the efficient substructural hardening of low-tempered steels [3]. By using these principles, one can significantly improve not only the strength properties of steel but also its characteristics of plasticity and ductility, which enables us to expect that the structural strength of treated products would also increase.

In the present work, we analyze the temperature dependences of the critical stress intensity factor $K_{IC}$ and critical crack opening displacements $\delta_c$.

Check specimens of 45KhN2MFSh steel were subjected to thermal treatment (hardening from 870°C followed by low-temperature tempering). The other specimens of the same type of steel were subjected to thermomechanical treatment with cold plastic deformation (cold straining by the method of hydrostatic extrusion followed by stabilizing tempering and final thermal treatment in the same mode as for check specimens). The quantity $K_{IC}$ was determined by testing specimens with a cross section of $10 \times 20$ mm, lateral notch, and an induced fatigue crack by three-point bending. The cross section of the specimens and the sizes of the notches and induced cracks were chosen to form the two-dimensional strained state at the tip of the crack. To evaluate the parameter $\delta_c$, we tested specimens with two concentrators (Kanazawa's specimens [4]) by impact bending.

The crack resistance of steel subjected to thermomechanical treatment is higher than the crack resistance of check specimens subjected to thermal treatment in the entire temperature range (Fig. 1).
Fig. 1. Temperature dependences of the critical stress intensity factor \( K_{lc} \) (a) and critical crack tip opening displacements \( \delta_c \) (b) for specimens of 45KhN2MFSh steel subjected to thermomechanical treatment (1) and to thermal treatment (2).

The serial curves of the investigated parameters are characterized by the well-pronounced threshold behavior. Thus, in the temperature range from +20°C to -40°C, the values of \( K_{lc} \) for steel subjected to thermomechanical treatment with cold plastic deformation remain practically constant (curve 1 in Fig. 1a) and suffer an abrupt drop as temperature decreases further. For check specimens, the threshold temperature is much higher (-20°C) and, in the subthreshold region, the quantity \( K_{lc} \) monotonically decreases in the process of cooling. It is worth noting that the influence of the substructural factor becomes more pronounced as temperature decreases. Thus, at +20°C, the increment of \( K_{lc} \) is approximately equal to 10%. At the same time, at -20°C, it becomes equal to 25% and, at -80°C, can be as high as 50%.

The threshold temperatures determined according to the serial curves of the parameter \( \delta_c \) are the same as in the first case.

The behavior of the parameters of crack resistance recorded as testing temperature decreases is similar to the behavior of serial curves of impact toughness used for the evaluation of the threshold of cold brittleness. However, it is known that the temperature of ductile-brittle transition determined according to these curves is not a material constant because it depends on the loading mode, sizes of the specimen, and the shape of the notch. The application of severer loading schemes and larger specimens, as a rule, increases the temperature of ductile-brittle transition. In this sense, the application of the parameters of crack resistance to the evaluation of the threshold of cold brittleness seems to be preferable because even the procedure of their determination is based on the formation of the conditions of constrained plastic deformation as happens in the case where the cross sections of impact specimens increase or we apply severer testing procedures. On the other hand, abrupt changes in crack resistance observed as temperature decreases cannot be interpreted as the transition from macroscopic ductile to macroscopic brittle fracture or as the transition from the plane stressed state to the plane strained state. As shown in [5], this type of behavior of the curves of crack resistance cannot be explained by the violation of the conditions of tensile fracture in the plane strained state. Most likely, the causes of changes in the parameters of crack resistance can be found on the micro-level, by analyzing the micromechanisms of fracture of steel.