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EVOLUTION OF FRACTURE OF STEELS AT A TEMPERATURE OF 4.2 K AND UNDER THE ACTION OF ELECTRIC CURRENT PULSES

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ABSTRACT

The authors studied specific features of the formation of a plastic zone at the crack tip at a temperature of 4.2 K and under the action of electric current pulses (ECP) of high density using steel 03Kh20N16AG6 with a stable austenite as an example. Employing the method of stereofractographic analysis, the results of investigations into specimen fracture surface microrelief, and analytical solutions, they demonstrate the formation of the plastic zone at the crack tip at a temperature of 4.2 K to follow the mechanism of discontinuous yielding. The influence of electric current pulses stimulates the process of the formation of the plastic zone to step up causing the plastic zone to reach its critical size at lower load levels. In the calculation of the stress intensity factor of materials characterized by non-monotonic development of elasto-plastic deformation at a temperature of 4.2 K it is recommended to choose the design load P_Q by the method of 5% secants.

KEYWORDS:

fracture, plastic zone, discontinuous yielding, electric current pulses

INTRODUCTION

The reason for the majority of unexpected fractures of high-stressed elements of structures is various design and manufacturing stress concentrators such as discontinuities, notches, recesses, holes, cracks, etc. The presence of such concentrators in the units of superconducting electromagnetic equipment operating at the temperature above 4.2 K and subject to powerful electromagnetic actions is responsible for significant nonuniformities of both mechanical and electromagnetic stress fields. These nonuniformities may result in the accumulation of energy in local regions of a material, where a crack is most likely to initiate and propagate. A rather strong electromagnetic action may give rise to deformation of the crack profile, which causes either its blunting or healing up, local thermal treatment and hardening through deformation due to electrodynamic loads, stimulation of the crack propagation as a result of the exhaustion of plasticity in the overstressed zone, etc. Electric current pulses passing through the loaded material plasticize it. In so doing at cryogenic temperatures and certain parameters of electric current pulses this plasticization is a consequence of the electron-dislocation interaction and occurs within the period of the electric current pulse action. At the instant the plasticity of the material increases, an abrupt reduction in the metal resistance to deformation is observed that manifests itself as a sharp change of load on tensile diagrams [1]. The effect of the ECP on the metal with non-conducting defects of the crack type would have shown up most vividly at a temperature of 4.2 K since in the zone adjacent to the crack tip the concentration of electromagnetic, thermal, and force fields reaches its maximum.

Under conditions of subzero cooling (< 20 K) most metallic materials exhibit instability of plastic yielding that manifests itself in jump-like deformation (discontinuous yielding). The latter is recorded in the form of saw-tooth tensile diagrams. The initiation of the low-temperature discontinuous yielding and its character depend on a number of factors. One of the main factors is the volume of the material deformed. Strain constraint in the region of the material adjacent to the crack tip and nonmonotonic evolution of the plastic flow at cryogenic temperatures are responsible for specific features of the formation of the plastic deformation zone and the conditions of the evolution of fracture.

It is the foregoing that determined the objective of the present investigation – to establish specific features of the evolution of plastic deformation at the crack tip related to the action of the ECP and cooling down to 4.2 K.

EXPERIMENTAL RESULTS AND DISCUSSION

For the investigation we have chosen steel 03Kh20N16AG6, which exhibits stability of the phase composition in the temperature range from 293 to 4.2 K. Compact tension (CT) specimens of 12 mm thickness were fabricated from sheet billets of that steel. Analysis of fracture diagrams of CT specimens obtained at the temperature of liquid helium revealed the appearance of local load maxima to the left of the 5 % secant. In this case, we face the uncertainty in the determination of the design load P_Q [2, 3] because these local maxima can be indicative of both crack growth onset and discontinuous yielding of the material that is characteristic of the steels considered at 4.2 K in the process of plastic zone formation at the crack tip preceding its growth onset.

To verify this assumption, an experiment was performed according to the following scheme. Compact-tension specimens of steel 03Kh20N16AG6 were loaded at a temperature of 4.2 K until several local maxima appeared located to the left of the point of intersection of the load displacement (P –V) diagram with the 5 % secant. Then the specimens were unloaded. A possible crack extension increment was controlled by thermal painting. Ten specimens were tested in this way and no crack extension was observed. It is only after the maximum that coincided with the point of intersection of the 5 % secant with the P – V diagram or immediately following it that the crack growth onset was noted. Thus, the presence of a number of local maxima on the P – V diagrams to the left of the 5 % secant in testing CT specimens of the above steel is a result of the formation of a plastic zone prior to the crack growth onset that, under these temperature conditions, occurs by the mechanism of discontinuous yielding. The formation of a plastic zone due to discontinuous yielding is also confirmed by the fact that the stress values corresponding to the beginning of discontinuous yielding and determined on smooth specimens coincide with the values of nominal stresses in the weakened section of the CT specimen, σ_0, under the load corresponding to the first local maximum P_{D1}. The value of σ_0 is calculated by the following formula [3]:

$$\sigma_0 = \frac{P_{D1}}{(b-l)t}\left[1+\frac{3(b+l)}{b-l}\right], \tag{1}$$

where t is the specimen thickness, $b = 2t$ is the distance from the line of load application to the specimen edge; l is the distance from the line of load application to the crack tip.

The stress of the beginning of discontinuous yielding determined on smooth specimens at a temperature of 4.2 K corresponds to the yield strength of the steel studied and is equal to 1440 MPa. The magnitudes of nominal stresses calculated by formula (1) for a batch of CT specimens are within 1400 – 1470 MPa. It is obvious that due to stress concentration in some region in the vicinity of the crack tip the stresses not only reach the level of the stresses corresponding to the beginning of discontinuous yielding, but exceed it.

When studying the influence of the ECP on the kinetics of plastic zone formation at the crack tip, electric current pulses were applied so that the current flew about the crack tip. This direction of the current causes local concentration of the electric and thermal fields [1] and also contributes to elasto-plastic deformation of the largest region of the material at the crack tip. The maximum value of the current density with the consideration of its concentration at the crack tip with its pulse amplitude being equal to 2800 A reached $18.5 \cdot 10^8$ A/m^2. The load levels, at which the specimens were exposed to the action of the ECP, produced nominal stresses equal to $0.6\sigma_{0.2}$, $\sigma_{0.2}$, and $1.2\sigma_{0.2}$.

Passing through the material at the nominal stress equal to $0.6\sigma_{0.2}$, the ECP does not change the run of the P-V diagram and the character of crack propagation as compared to the initial state. The influence of the ECP at the nominal stresses $\sigma_{0.2}$ and $1.25\sigma_{0.2}$ causes some deviation from the linear portion of the P-V diagram appearing as horizontal steps. However, the crack propagation is therewith not observed. At the same time, the first local maximum after the action of the ECP corresponds to the crack growth onset.

The estimation of the plastic zone radius r_n was performed on the basis of the Irvin approach [4] according to which $r_{p.stress} = \frac{1}{2\pi}\left(\frac{K}{\sigma_{0.2}}\right)^2$ in the case of the plane stress state, and $r_{p.strain} = \frac{1}{6\pi}\left(\frac{K}{\sigma_{0.2}}\right)^2$ in the case of the plane strain state. The estimation showed that on the exposure to the ECP at the instant of the crack growth onset $r^{ECP}_{p.stress} = 2.18...2.33$ mm and ($r^{ECP}_{p.strain} = 0.75...0.78$ mm). Also the values $r^{ECP}_{p.stress}$ ($r^{ECP}_{p.strain}$) are matched by the values of the plastic zone radii $r_{p.stress}$ ($r_{p.strain}$) calculated for the local maximum corresponding to the crack growth onset in the absence of the ECP action. Meanwhile, in the latter case for the first local maximum the size of the plastic zone radius is equal to $r_{p.stress} = 1.05...1.15$ mm and $r_{p.strain} = 0.35...0.40$ mm, i.e., under this load the plastic deformation zone at the crack tip does not reach its critical size.

The fracture kinetics of steels at the initial stage at a temperature of 4.2 K and under the action of the ECP has also been studied by the method of stereofractographic analysis following the procedure described in [5]. Two batches of specimens were loaded in the medium of liquid helium. One part of the specimens of the first batch was loaded until the first clear-cut local maximum appears on the P-V diagram and then unloaded. The second part of the specimens was loaded until the appearance of two local maxima.

The next batch of the specimens, which was divided into two parts, was exposed to the ECP and also loaded until the appearance of two maxima. The specimens of the second batch were unloaded as soon as the load reached the values corresponding to those attained in testing the first batch of the specimens. In this case, the only local maximum was observed at the load value corresponding to the appearance of the second local maximum for the specimens not exposed to the ECP. After unloading a possible crack extension increment was recorded and the specimens were fractured. Stereo pairs were photographed on the halves of the fractured specimen using a scanning electron microscope 'Stereoscan' at the convergent angle $\Theta = 5^0$ and magnification M=400. The stereo pairs were processed by a stereocomparator "Stecomoter".

The height difference between two points of the object was determined for the case of orthogonal projection by the formula $\Delta h = \frac{\Delta F}{2M \sin \Theta}$, where ΔF is the difference of distances between the images of two points of the object on two microfractograms of the stereo pair. In view of an appreciable nonuniformity of the stretch zone height along the crack front its size was obtained by averaging the results of measurement of no less than four profiles of fracture surfaces for each specimen.

It was established that even the appearance of two maxima recorded on the load vs displacement diagram does not imply the crack propagation since in this case the height of the stretch zone is 5×10^{-2} mm and no crack propagation is observed on the fractograms of fracture surfaces. After the appearance of the first local maximum, the height of the relief does not change at all as compared to the initial fatigue crack.

The action of the ECP results in an appreciable (1.4 fold) increase in the height of the stretch zone. The fact that there are no local maxima on the P-V diagram is likely to point to the change in the mechanism of its formation.

CONCLUSION

The investigations performed allow us to conclude that, when calculating the stress intensity factor in the case of discontinuous yielding of the material at a temperature of 4.2 K, the magnitude of the design load P_Q should be determined either from the load maximum, which coincides with the 5% secant, or from that immediately following the latter. On exposure to the action of the ECP, this should be done from the first maximum. The ECP contributes to the intensification of the process of the plastic zone formation at the crack tip. This makes the plastic zone reach its critical size at lower levels of the load, i.e., the ECP acts as an embrittling factor.

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