Experimental and numerical determination of the barrier layer effect in the composite on the crack propagation

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Abstract. Cyclic crack resistance tests of samples from a seven-layer metallic material obtained by the method of hot rolling were carried out. Identified features of fatigue cracks propagation. Mathematical finite element models describe the stress state at various stages of the experiment are constructed. The features of a finite thickness barrier layer effect in modeling the fatigue crack behavior are revealed.

1. Introduction
Modern conditions of design, production and operation of structures in a wide range of influence set the trend for using materials with high strength properties. One of the ways to achieve the specified characteristics is the creation of materials with pre-predicted unique properties caused, among other things, by high intense structural heterogeneity, for example, layered metal composite materials (LMCM) from dissimilar metals, obtained by batch rolling as well as other methods. However, introducing components from such materials into the design, it is necessary to reliably describe their properties and the structure of layered materials makes it very difficult to analyze its behavior under various types of loading. It should be noted that the gradient structure of the LMCM is caused both by the presence of separate layers of metals and alloys with different mechanical properties and the zone with special physic-mechanical properties that is being formed in the process of obtaining them [1]. The authors [2] analyzed the deformation process and evaluated changes in the properties of the welded boundary during gradual plastic deformation during the rolling of a bimetallic strip and showed that the weld of a bimetallic strip largely determines the level of its mechanical properties. In the framework of this work a numerical-experimental approach is presented. Such approach allows, in the first approximation, to predict the work of a material with a gradient structure under cyclic loading conditions, where the presence of a transition zone between the layers, the “barrier layer”, also influences on the fracture kinetics.

2. Materials and methods
As part of the research, analysis of the fracture processes under the conditions of cyclic loading of the 7-layer LMCM steel-steel system obtained by hot batch rolling was carried out. Laminated composite materials “09G2S - EP-678” were obtained by the method of hot batch rolling without vacuum at the DUO / Quarto 200 rolling mill with subsequent heat treatment involving water hardening from 1050 °C and subsequent exposure in a furnace for 30 minutes at a temperature of 500 °C. The volume fraction of the most durable EP678 steel in layered composites was 30%. Experimental studies of the
fatigue cracks growth kinetics were carried out on prismatic specimens with a Charpy type sharp notch cut from a LMCM. The orientation of the notch is made according to the type of crack arrester orientation. Cyclic loading is implemented on a high-frequency resonant machine MIKROTRON (Rumul) at a loading frequency of 100 Hz. A finite-element modeling of the fatigue crack propagation was carried out using CAE FIDESYS with boundary conditions specified taking into account the experimental conditions for the application of loads. To carry out a numerical modeling of the failure process of the studied LMCM the experimental results of the composite mechanical properties and its individual components with uniaxial static tension on the universal servo-hydraulic testing machine INSTRON 8801 were used as input parameters for the material properties.

The structure of the obtained 7-layered composite “09G2S-EP678” is shown in fig. 1.

Using diffraction electron microscopy and micro X-ray spectral analysis diffusion zones were registered at the interlayer boundaries of hot rolled 7-layer composites 09G2S-EP678 which were formed as a result of mutual diffusion of the main alloying elements of 09G2S steel layers (Mn, Si) and EP678 (Cr, Ni). The width of the diffusion zone in hot-rolled composites amounting to about 20 μm (Fig. 1, b), confirms the need to take into account the barrier layer. To analyze the conditions of crack propagation in a layered material and allowance for the barrier layer some characteristic volume was introduced into the finite element model and the analysis of the failure of a layered material was carried out with its account. The impact of the barrier layer presence was estimated by comparing the two solutions. In the first case, the barrier layer was not introduced, i.e. only the integral influence of the layered structure and the mutual influence of individual layers on the stress-strain state at the crack tip was taken into account. In the second case a barrier layer was introduced.

3. Experiment and discussion

According to the results of cyclic tests of the “09G2S-EP678” LMCM a fatigue crack growth kinetic diagram has been constructed (Fig. 2). It has been established that the effect of retardation crack propagating during cyclic loading is realized before its tip reaches the boundary of the layer interfaces.

Thus, it has been experimentally shown that the gradient structure of the LMCM consisting of different layers of material as well as of a certain barrier layer significantly affects the character of the fatigue crack growth kinetic.
For the numerical experiment formulation models of a seven-layer material with a Charpy-like cut were constructed. For the case of modeling without the influence of the barrier layer the top of the concentrator was located directly on the border of a more durable layer of steel EP678, to take into account the effect of the barrier effect the top of the concentrator was located at a distance from the interface between the layers. The contact problem for a three-point bend with two fixed supports and a movable pusher in a cyclic formulation was solved. Contact zones were set to non-slip. The crack propagation was carried out by removing a group of elements and removing the boundaries between the nodes connecting them. The criterion of crack propagation was taken as the data of a full-scale experiment. The criteria for achieving the limiting state was the achievement of the limit of temporary resistance to fracture or the transfer of stresses to the plastic zone of an individual layer [3]. It is believed that the fatigue failure of a material occurs when the tensile strength decreases to the level of stress intensity at a given point corresponding to the maximum value of the cyclic load. That is, the stress in the above scheme should be understood as the stress intensity. In the force approach the ultimate strength is taken as a representative parameter of the fatigue process the available ductility in the deformation approach, and the area under the full deformation diagram in the energy approach. These parameters as functions of the maximum level of stress and number of cycles are set in the basic experiment. In a number of works the power dependence was used to approximate the experimental curves of a change in one parameter or another [4, 5] and the change in the stress level was associated with a transition from one kinetic curve to another. The order of transition was determined from the equivalence condition of two cyclic states of a material with a different loading history in terms of equality of the values of the controlling parameter [6].

According to the results of numerical modeling in the case of disregarding the barrier layer a characteristic zone is visible at the tip of the fatigue crack. In this area the stress intensity distribution characteristic of the monolithic material is traced (fig. 3, a). Gradient structure is actually not visible. Of greatest interest is the second case (fig. 3, b). As can be seen from the stages of fatigue crack propagation we can notice a significant complication of the stress distribution. Also the mutual influences of the individual components of the layered material were clearly observed. The presence of the barrier layer has the effect of the appearance of so-called zones of localized plastic deformations characteristic of the distribution of stresses between the individual components of the sample. Thus, when modeling fracture with regard to the barrier layer the stress state is redistributed to the point where the top of the concentrator goes directly to the interface of the layers which is in good agreement with the experimental data. It should be noted that the package used characterizes the dimensionless formulation of the problem and in order to get the values in SI it is necessary to divide the result by 10.
4. Conclusions
According to the results of experimental tests and numerical modeling in the first approximation a model with a volumetric trapezoidal concentrator was constructed to solve the problem of a multilayer sample fracture. The transition criterion is the moment when the maximum stress is reached at the top of the stress concentrator for a given layer. The further solution was divided into a series of successive procedures and upon reaching a given level according to the selected criterion a transition was made to the next loading stage. According to the modeling results it was found that at certain stages of crack propagation arises the stress-strain state characteristic of the visible effect of the barrier effect, which has a significant impact on the kinetics of the propagation of the main crack. It is shown that experimentally determined staging of fracture can be analyzed using FEM. Thus, comparing the experiment data and numerical analysis proved the effectiveness of applying mathematical modeling approaches to studying the staging of the initiation and propagation of a main crack in structurally inhomogeneous materials taking into account the nonlinearity of properties of both individual layers of the composite and the introduction of a barrier layer.

The data obtained allow us to modeling the process of LMCM fracture as well as to predict the behavior of the main crack at the interface between the layers. A special feature of the modeling is taking into account the barrier layer of finite thickness and analysis of its influence on the characteristics of resistance to fatigue failure of layered composites of the steel-steel system.

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