Failure features of laminated materials under static and cyclic loading

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Abstract. The paper discusses the behavior of a hot-rolled laminated metal material under cyclic loading according to the three-point bend and uniaxial static tension scheme. It is shown that the creation of a gradient structure provides increased resistance to the fatigue cracks growth while the propagation of a fatigue crack does not cause interlayer delamination, and the effect of retardation is realized until the crack tip reaches the interface of the layers. Under the conditions of static tension, the laminated material obtained by hot batch rolling has an increased ductility, and delamination along the interfaces occurs as a result of the formation of a neck and, as a result, a change in the stress state in the plastic deformation zone.

1. Introduction
Laminated metal materials are a multicomponent structure consisting of a set of alternating metal layers and zones of their connection. Depending on the obtaining method structure of the connection layers boundaries has its own characteristics [1]. Thus, the layers connection zone consist of directly the surface boundaries and the welded areas, the formation of which also creates favorable opportunities for increasing the ability of the material to resist fracture. The gradient structure of layered materials has a significant impact on the characteristics of their failure under various types of loading [2]. Thus, in a number of works, it is noted that, on the one hand, the layered structure of the material makes it possible to increase the characteristics of crack resistance, on the other hand, due to the formation of border zones it is necessary to to analyze the effect of their structure on the material properties when calculating structural elements in which they can be used [3].

To assess the reliability and durability of structural elements, it is necessary to study the mechanical behavior of materials under the influence of both static and cyclic types of loading [4, 5, 6]. However, today the main attention is focuses on studying the fracture features of multicomponent materials which contain fibers or dispersed particles [7, 8]. It is known that there are several approaches to the determination of the limiting state of the structural element materials. In particular, in aviation systems two approaches are considered: “fail-safe” and “safe-life” [9]. Those, it is understood that the construction can work until one of two critical states occurs — catastrophic failure occurring after the design life, and until the critical defect such as crack length size is reached. According to this approach, the work considers the fracture features of a laminated material obtained by the method of hot batch rolling under the influence of a static load and under conditions of fatigue crack propagation.
2. Materials and methods

Laminated materials "09G2S - EP678" were obtained by the method of hot batch rolling without vacuum on a rolling mill DUO/Quarto 200. The main structural elements of the obtained layered materials are the interlayer surface boundaries and alternating layers of low carbon EP678 and 09G2S steels in a 30/70 volume ratio. The choice of materials is due to the low carbon content in both 09G2S and EP678 steels, which ensured their good deformability in a wide range of temperatures, as well as the possibility of implementing such heat treatment in which layers of maraging steel are maximally hardened, and layers of low-carbon low-alloyed steel retain their original ductility.

Preparation of the original plates for rolling was carried out as follows. Plates with different thickness were subjected to planing until a height difference was obtained over the cross section of ± 0.15 mm and the complete removal of corrosion products. The surfaces of the blanks activated in this way were degreased and put together in a batch. The assembled batch was welded around the perimeter in a semi-automatic mode by a direct current of welding copper coated wire of the SG2 brand according to DIN8559 in a protective CO2 environment. Before the final welding of the ends, the joint zone was blew with CO2 gas. The assembled multilayer batches were placed in an electric furnace and heated to a temperature of 1050 °C. The initial heating was 30 minutes and the intermediate heating between passes 10 minutes. Hot rolling was carried out at the DUO-200 mill with a roll diameter of 250 mm at a rolling speed of 40 mm/s. The total batch deformation during rolling after three passes was ~ 50%. The obtained layered composites were subjected to additional heat treatment at 500 °C for 3 hours. The purpose of heat treatment of layered composites is to achieve the maximum level of strength properties of steel EP678 while maintaining the ductility of steel 09G2S.

From the obtained multilayer sheets, as well as their base materials, flat samples were cut that corresponded to type 4 according to GOST 25.506-85 for cyclic and type I according to GOST 1497-84 for static tests. To compare the mechanical strength of the laminated material and its components, monolithic billets of steels 09G2S and EP 678 were subjected to deformation and heat treatment according to the modes identical to the production of a laminate. Static loading of flat proportional samples was carried out on the servo-hydraulic testing machine INSTRON8801. Cyclic loading of a prismatic specimen with a concentrator made of a multilayer material was implemented according to the three-point bending scheme on a MIKROTRON RUMUL high-frequency resonant testing machine with a loading frequency of ≈100 Hz.

3. Experiment and discussion

During cyclic tests a fatigue crack was grown in the samples in the direction perpendicular to the layer orientation. The incision initiating the crack was made from the condition that its tip remained within the first outer layer of steel 09G2S. According to the results of laminated material cyclic testing the crack growth rate da/dN dependence on the stress intensity factor of the cycle ∆K was carried out. A fragment of the kinetic diagram corresponding to the propagation of a fatigue crack in the layers 09G2S → EP678 is shown in Figure 1.

According to the kinetic diagram in the laminated material obtained by hot batch rolling the presence of interlayer boundaries significantly affects the kinetics of fatigue crack growth. The crack retardation effect is intensely manifested until its tip reaches the interface of the layers in the range of values ∆K = 18-20 MPa × m1/2. During subsequent cyclic loading the rate of crack growth in the steel layer of EP678 increases to the initial level and as its tip grows to the next layer of 09G2S steel it decreases again, but manifests itself to a much lesser extent.

According to the results of determining the mechanical properties of the 7-layer material obtained by hot rolling, ensuring the deformation of the layers at 50%, followed by heat treatment, it was found that it’s tensile strength σв = 870 MPa and the yield strength σ0.2 = 495 MPa (fig. 2). An interesting revealed feature is the increased plastic properties of the layered material compared to the base materials. The ratio σ0.2/σв = 0.57 for the laminated material obtained by hot rolling indicates a possible reserve of strain hardening and a reserve of plasticity for subsequent technological operations.
Direct observation of the failure process under static loading conditions showed that the delamination of material layers along the surface boundaries occurred at the stage of intense plastic deformation after the formation of the neck. Further loading led to the successive propagation of the crack and the failure of individual layers of the study material. The fracture surface is characterized by a characteristic for layered materials type with numerous stratifications and the formation of individual centers of fracture in separate layers (Fig. 3, a).

Figure 1. Fatigue crack growth kinetic diagram in layered material «09G2S-EP678»

Figure 2. Mechanical properties of layered material «09G2S-EP678» (♦), steel 09G2S (■) and EP678 (▲)

Figure 3, a. Fracture surface of layered specimens after static loading.

Figure 3, b. Fracture surface of layered specimens after fatigue crack propagation trajectory
At the same time under conditions of cyclic loading the crack propagated through 4 layers while characteristic of layered materials effect of the crack trajectory deviation from the main direction was observed only when crossing one boundary of the layers located in the neutral section of the sample (Fig. 3, b). The propagation of fatigue cracks in the remaining areas at the macro level was of a “monolithic” type and was not accompanied by a change in the relief of the fracture surface and the appearance of layering characteristic of laminates. It is important to note that some deviation of the trajectory did not occur along the interface of the layers, but at some distance from them. The reasons for this behavior may be associated with lower rates of mechanical strength of steel 09G2S layer in combination with high strength of the weld boundary of layers, as well as the influence of the material gradient structure on the process zone formation at the propagating crack tip. Model experiments on static loading by Mode I of a laminated material with a sharp notch showed that the process of fracture by delamination is not occurring in its pure form, and the deformation of material occurs through the layer of steel 09G2S as the least durable, which confirms our conclusions [10]. And the formation of a complex gradient structure made it possible to limit the propagation of a crack-like defect into subsequent layers of material which is an important indicator in the design of structural elements consist of this class materials the possibility of the occurrence of through-defects in which is critical.

A detailed analysis of the fatigue cracks behavior at the interface of the layers and the identification of mechanisms for its retardation were performed using the laser dynamic speckle interferometry technique. So, when approaching the fatigue crack tip to the interface of the layers the main mechanism reducing the propagation rate of a fatigue crack is the change in the stress-strain state at its tip until the crack reaches the new layer, which is confirmed by the analysis of speckle images patterns shown in Fig. 4.

![Figure 4. Distribution of the speckle images correlation field during crack propagation in layered material "09G2S-EP678".](image)

According to the obtained distribution fields of the speckle images correlation during the fatigue crack growth it was established that at its top forms a characteristic zone of plastic deformation - the “process zone”. While the crack grows fixed by the speckle interferometry method the plastic zone approaching the layers interface substantially changes its shape. As the boundary between the layers passes the plastic zone is re-formed and advances in each subsequent layer of the layered material. Thus, based on the results of cyclic crack resistance tests and the use of fracture mechanics approaches, it has been established that the effect of retardation fatigue cracks in laminated materials accompanied by the appearance of minima on the kinetic diagrams of fatigue failure is determined by the integral action of a number of factors. These include slowing down the cracks growth rate approaching the interface of the layers as a result of a change in the stress state, a relay transition of the plastic zone at the tip of the stress concentrator and the need to re-form the initiating microcrack during the passage of the main crack of each subsequent layer.

4. Conclusion

According to the results of studying the failure features of the laminated material “09G2S-EP678” it was shown that the structure of the interface of the layers makes a significant contribution to the propagation kinetics of fatigue crack in the crack-arrester direction (across the layers) under cyclic
loading. According to the obtained experimental results it was shown that the kinetics of laminated materials failure substantially depends on the type and loading scheme. Due to its gradient structure laminates exhibit both monolithic and composite type of fracture. The revealed features in the crack behavior in particular the type of fracture are an important parameter in modeling the material behavior. This is important for choosing design schemes and selecting methods for diagnosing damage. Calculating and modeling the behavior of real structural elements of such materials it is important to understand the stages of development of a crack-like defect as the most dangerous one. At the same time further studies related to determining the quantitative measure of the stress-strain state at the fatigue crack tip within the localized zone of plastic deformations are of interest, in order to allow mathematical modeling of the layered materials fracture taking into account the influence of structural features of the structure of the joint boundaries.

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