Fatigue Fracture of Steel with a Ferrite-Martensite Composite Structure

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Abstract—In this paper, we present results of fatigue tests of a natural steel composite material for cyclic bending by a zero-loading cycle. Natural ferrite-martensitic composite (NFMC) has a structure of alternating layers of ductile ferrite and strong martensite, which causes a special mechanism of crack retardation under loading. The zero-loading cycle assumes the presence of tensile forces directed only in one direction, which makes it possible to avoid hardening of the crack edges during its growth. Using the obtained data on the kinetics of the development of a fatigue crack and the rate of its growth, a diagram of fatigue failure was constructed depending on the number of vibration cycles. Test results of samples from steel of one chemical composition are compared. In one case, a traditional heat treatment was carried out on the structure of tempering sorbitol. In the other case, a layered structure of the ferrite-martensite composite was obtained by quenching the initial line ferrite-pearlite structure from the intercritical temperature range. These materials had the same hardness, but the difference in structural organization determined the advantage of steel with the NFMC structure in terms of fracture resistance under cyclic loading. When a crack approaches the martensite-ferrite interface, delamination occurs in the ferrite due to tensile stresses parallel to the crack plane. The crack growth stops until additional energy for the formation of a new crack under conditions close to the uniaxial stress state is supplied. A technique for determining the characteristics of crack growth kinetics under fatigue loading, which is recommended for testing steels and alloys under conditions of cyclic load changes, is presented.

Keywords: composite, steel, delamination, zero loading, ferrite, martensite, fracture, crack
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INTRODUCTION

The possibility of creating steel with the structure of a natural ferrite-martensitic composite (NFMC) based on the use of hypoeutectoid steels with a line ferrite-pearlite structure was substantiated in [1, 2]. Hardening of such steel from the intercritical temperature range \((A_1-A_3)\) makes it possible to obtain a layered structure of the ferrite-martensite composite (Fig. 1).

A study of the properties of the considered steels upon static tension and impact bending [2–6] suggests that such a structure is characterized by a special mechanism of inhibition of crack development. This study is aimed at obtaining information about the development of fracture upon fatigue loading of steels with the structure of a ferrite-martensitic composite.

RESEARCH METHODOLOGY

The prismatic samples passed the fatigue tests for cyclic bending [7–9] in order to study the kinetics of the development of a fatigue crack and the rate of its growth depending on the number of vibration cycles, and fatigue failure diagrams were constructed based on these data. Samples with a size of \(10 \times 10 \times 100\) mm were tested for cyclic bending according to a zero-loading cycle [10], i.e., a bending scheme, in which the bending moment led only to tensile stresses in the ferrite and martensite layers while the compressive stresses were equal to zero, was used. This was achieved by adjusting the vibration stand: the tensile force of the sample was directed only in one direction (Fig. 2). This scheme excludes the possibility of work hardening of the crack edges during its growth. The dimensional parameters of the vibration stand and samples had constant values \((a = 10\) mm, \(b = 10\) mm, \(L = 540\) mm, and \(L_{cr} = 160\) mm). The \(A\) oscillation amplitude was 5 mm. Based on this, the parameters necessary to determine the stress at the site of crack development were calculated according to the method from [11]. The force is \(P = 3EJA/L^3\) (where \(J = ab^3/12\) is the inertia moment, and \(E\) is the elasticity modulus).
During testing, the $b$ value with allowance for the notch (1.25 mm) and crack growth will decrease and, accordingly, the inertia moment will change. The initial value is $b = 8.75$ mm and $P = 10.7$ N while the bending moment at the crack development site is $M = P(L - L_{cr}) = 4.07$ N m and stress is $\sigma = M/W$ (where $W = ab^2/6$ is the moment of resistance for a rectangular section).

**RESULTS AND DISCUSSION**

The crack development process was recorded by the method of electric potentials [8–10] in the potential difference–time coordinates. This dependence was deciphered according to the calibration chart for plotting the curves crack length—number of loading cycles (Fig. 3). These dependences illustrate the significantly different character of the crack growth in steel after quenching and tempering (curve 1) and in steel with a NFMC structure (curve 2). As can be seen, the crack “starts” earlier in steel with the NFMC structure. This is not a rule and is due to the fact in which the notch bottom is located on the structural component of the NFMC: if it is located on a brittle artensitic plate, then the crack “starts” earlier; if the bottom of the notch is located on a viscous ferrite plate, then the crack can start moving in the same way as in a sample with a tempered troostite structure.

The main difference is expressed in different crack growth rates and a significantly larger number of cycles to fracture in steel with a composite structure. This situation is due to a special mechanism of crack propagation in steel, the structure of which is organized in the form of parallel layers of plastic and ductile ferrite and strong martensite. In a sample with an initial notch ending in one layer (according to the “crack retardation” type [11]), when a crack approaches the martensite-ferrite interface, delamination in ferrite occurs on it (or near it) due to the presence of tensile stresses parallel to the crack plane [12–16]. In this case, a part of the energy supplied from outside is spent on the for-
mation of a delamination surface in the ferrite. The exit of a crack into a delamination leads to a change in its trajectory, a stop of propagation, and relaxation of tensile stresses at its tip. In order to destroy the next layer of the composite (martensite layer), a new crack must form in it, but already under conditions close to the uniaxial stress state, which will require additional energy. Figure 4 shows illustrations showing the occurrence of delaminations in composites.

The condition for the occurrence of a bundle can be written in the following form [13]:

\[ \sigma \geq \frac{K_D}{\phi \sqrt{c}} \]

where \( K_D \) is some critical value of the stress intensity factor, \( \phi = \frac{3 + \nu}{1 + \nu} \) is the constant, \( \nu \) is the Poisson’s ratio, and \( c \) is the thickness of the brittle layer (martensite).

It is shown that for the occurrence of delamination ahead of the martensitic crack (before the destruction of the next brittle layer), it is necessary that \( \sigma_d < \sigma < \sigma_{0.2} \). Therefore, the condition for the occurrence of delamination, which retards the destruction of the layered sample, has the form:

\[ K_D \leq \phi \sqrt{\frac{E\sigma_{0.2}h\nu}{\alpha \beta}} \]

where \( E \) is the elastic modulus of the composite, \( \nu \) is the Poisson’s ratio, \( \sigma_{0.2} \) is the yield stress, \( h \) is the thickness of the plastic layer, \( \nu \) is the Poisson’s ratio, \( \alpha = 1 + \nu(3 - \nu) \) is the constant, and \( \beta = 4/(3 - \nu) \) is the constant.

The value of \( K_D \) is \( \sqrt{\gamma_{\pi}l^2} \), then condition (2) will take the following form:

\[ \sqrt{\gamma_{\pi}l^2} < \theta \sqrt{\sigma_0} \]

where \( \gamma_{\pi} \) is the ultimate shear strain in the ferrite plate, \( n_s \) is the shear hardening index, and \( \theta = \frac{\phi}{\sqrt{\alpha \beta}} \) is the constant.

If the thickness of the ferrite plastic layer in a multilayer sample is sufficient to fulfill condition (3), then a delamination prevents further propagation of the main crack is formed. For steel 14G2, at values of \( \gamma_{\pi} \) of \( \sim 1000 \) MPa and \( n_s = 0.43 \), delamination occurs at a ratio of \( \frac{h}{c} \geq 3 \). This relation takes place during hardening of steel 14G2 from 730–740°C in the intercritical range [17, 18].

Fracture diagrams and kinetic characteristics obtained upon cyclic loading (Fig. 3) depend on the stress level, the frequency and asymmetry of the cycle, and the sample geometry. At the same time, the durability of a sample is practically determined by the growth rate of a macrocrack, which is a function of the force driving the crack or stress intensity factor \( K \) at its tip. As was shown in [19–23], the dependence of the fatigue crack growth rate on the stress intensity factor at the crack tip of the current length within a cycle of \( \Delta K = K_{\text{max}} - K_{\text{min}} \). This dependence is shown in Fig. 5 that is built using the data in Fig. 3 and determination of the \( K = \sigma \sqrt{l} \) value (where \( \sigma \) is the nominal stress in the sample section, which changes with the crack growth, and \( l \) is the crack length). The \( \sigma \) value is determined by the difference between the maximal and minimal values of stresses arising in the sample during cyclic bending tests. In this study, we used a zero-loading cycle, at which the minimal stress is zero, and therefore, only positive tensile stresses appeared in the sample section during crack growth.
The dependence of the crack length on the number of cycles is valid only for a specified cycle stress, changing which may change the behavior of materials. However, the dependence of $dl/dK$ on $\Delta K$ is universal in terms of its application at various cycle stresses and constants included in the equation relating $dl/dK$ and $\Delta K$ and can be used as a characteristic of materials [24]. In the P. Paris equation of $dl/dK = CK^n$, the $n$ and $C$ values are important comparative parameters of the material, which make it possible to evaluate its behavior in a wide range of crack lengths and acting stresses [25–30]. In particular, the $n$ value is equal to the tangent of the slope of the straight line of $dl/dK - \ln\Delta K$ to the $\ln\Delta K$ axis. The smaller the $n$ value, the lower the sensitivity of the material to increasing stresses (to overloads). For steel with the NFMC structure, the $n$ value is significantly lower ($n = 2.14$) than that for the same steel with the tempered sorbite structure ($n = 8.14$). This is due to crack growth stops due to delaminations. The $C$ value is determined by the value of the crack growth rate at $\Delta K = 0.3$ MPa m$^{1/2}$ (1 kgf/mm$^{3/2}$). The smaller the $C$ value, the relatively higher the ability of the material to inhibit fracture at any stress level.

**CONCLUSIONS**

The presented results of the study prove the advantages of steel with the structure of a layered NFMC in terms of fracture resistance upon cyclic loading compared to steel of the same composition after traditional heat treatment on the sorbite tempering structure. The suggested methodology for determining the characteristics of crack growth kinetics upon fatigue loading can be recommended for studying the conditions of failure of steels and alloys under cyclic load changes.

**CONFLICT OF INTEREST**

The authors declare that they have no conflicts of interest.

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