PREDICTION OF THE EFFECT OF THE ASYMMETRY OF THE LOAD CYCLE ON THE CYCLIC FRACTURE TOUGHNESS OF STRUCTURAL ALLOYS

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In most cases, failure of structures consists of the process of initiation and development of cracks to critical dimensions under the effect of cyclic loading. Therefore, to predict the life of structures, in addition to the characteristics of the resistance of the material to the initiation and propagation of fatigue cracks, it is essential to have the characteristics of the resistance to brittle fracture in cyclic loading since the use of the fracture toughness in static loading $K_{IC}$, determined by standard methods, is not always justified. This is especially important in the case of materials in which fatigue cracks propagate in an unstable manner and the fracture toughness of these materials in cyclic loading is considerably lower than $K_{IC}$ [1, 2].

Recently, a number of investigations were carried out into the prediction of the resistance of structural alloys to brittle fracture in the conditions of cyclic loading [3, 4]; however, the problems of the effect of the loading conditions, especially the asymmetry of the load cycle, in fracture toughness in cyclic loading remain unexplained.

The present work is concerned with the examination of the effect of the asymmetry of the load cycle ($R = 0.05-0.95$) on the relationships governing the propagation of fatigue cracks, the threshold coefficient of stress intensity $K_{th}$ and fracture toughness of 15Kh2MFA steel with two different structures in cyclic loading.

The chemical composition, heat treatment conditions, and also the mechanical properties of the steel in the two conditions are given in Table I. In the rest of the article, we shall use the notations of the steel given in Table I.

The rate of fatigue crack propagation (FCP) and fracture toughness characteristic of the 15Kh2MFA (I) and 15Kh2MFA (II) steels in static and cyclic loading were examined in the conditions of off-center tensile loading compact specimen 25 mm thick in laboratory air. The tests were conducted in a Gidropul's 400-kN servohydraulic testing machine at a loading frequency of 25 Hz. The threshold stress intensity factors were determined at a loading frequency of 60-80 Hz.

The stress intensity factor (SIF) of the crack-containing specimens subjected to off-center tensile loading was calculated from the equations derived in [5].

Figure 1 shows the kinetic diagrams of fatigue failure of the 15Kh2MFA (I) and 15Kh2MFA (II) steels at various load cycle asymmetries at a room temperature. The points with arrows correspond to the start of unstable (jumplike) fatigue crack propagation.

It may be seen that in the case in which the rate of FCP is represented in relation to the stress intensity factor $K_{max}$, the increase of the cycle asymmetry coefficient $R = K_{min}/K_{max}$ from 0.1 to 0.95 (0.89) leads to a large reduction of the rate FCP in the 15Kh2MFA (I)

### TABLE I. Mechanical Characteristics of 15Kh2MFA (I) and 15Kh2MFA (II) Steels at 293°K

<table>
<thead>
<tr>
<th>Steel and its chemical composition, %</th>
<th>Heat treatment conditions</th>
<th>$\sigma_0$, MPa</th>
<th>$\sigma_0$, MPa</th>
<th>$\Delta \sigma$, %</th>
<th>$\nu$, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>15Kh2MFA (I), 0.18 C, 0.62 Mn, 0.27 Si, 0.30 V, 0.48 Mo, 2.58 Cr; 0.019 S, 0.16 Ni, 0.01; P: 0.011 Ti</td>
<td>Quenching from 1273°K, 13 h, oil; tempering at 973°K, 14 h, air; additional annealing at 923-943°K, 70 h, air. Quenching from 1270°K, 4 h, oil; tempering at 893°K, 6 h</td>
<td>550</td>
<td>674</td>
<td>16.1</td>
<td>67.2</td>
</tr>
</tbody>
</table>
Fig. 1. Dependence of the rate of FCP on $K_{\text{max}}$ in 15Kh2MFA (I) (a) and 15Kh2MFA (II) (b) at a temperature of 293°K and various coefficients of the load cycle asymmetry.

Fig. 2. Diagram of loading the specimen containing a crack in determination of the critical coefficient of load cycle asymmetry.

and 15Kh2MFA (II) steels. For example, an increase of $R$ from 0.1 to 0.75 reduces the rate of FCP in 15Kh2MFA (I) steel by a factor of 15-20. When the cycle asymmetry is increased from 0.1 to 0.6, the rate of FCP in 15Kh2MFA (II) steel decreases by a factor of 8-15, depending on the level of $K_{\text{max}}$. To describe the common trend for both steels, it should be mentioned that an increase of the coefficient of the load cycle asymmetry is accompanied by a reduction of the rate of crack propagation corresponding to the inflection point of the diagram (the transition from the region of crack propagation in the vicinity of the threshold to the Paris region). For example, for 15Kh2MFA (I) steel, the increase of $R$ from 0.1 to 0.95 reduces the rate of FCP from $5 \times 10^{-9}$ to $2 \times 10^{-10}$ m/cycle.

In 15Kh2MFA (II) steel at room temperature at $K_{\text{max}} \geq 28$ MPa$\cdot$vm$^{-1}$ the fatigue crack propagates in an unstable (jump-like) manner. Final fracture of the specimen is preceded by several brittle jumps of the crack which alternate with sections of stable of FCP. Failure of the specimens of 15Kh2MFA (I) steel in cyclic loading takes place in a single jump. In certain cases the specimen fails by quasibrittle failure, whereas in other cases by plastic opening of the specimen.

In 15Kh2MFA (I) steel at $R = 0.89$, crack jumps were already detected at a rate of $8 \times 10^{-11}$ m/cycle and the diagram of stable crack growth in these conditions has the form of a single point. Thus, in 15Kh2MFA (II) steel at high cycle symmetry coefficients, jump-like crack propagation is detected in area around the threshold. It is evident that a further increase of the coefficient of the load cycle asymmetry will be accompanied by an increase of critical SIF ($K_{\text{fc}}^{-1})_{\text{min}}$ [2].

To determine the value of the cycle asymmetry coefficient $R_c$ at which ($K_{\text{fc}}^{-1})_{\text{min}}$ starts to increase, we carried out the tests in accordance with the scheme shown in Fig. 2. In stage 1 (initial $R = 0.1$), the tests were conducted at a constant value of $K_{\text{max}}$ and the range of SIF $\Delta K = K_{\text{max}} - K_{\text{min}}$ decreasing in steps (by no more than 5%) and, consequently, with an increasing coefficient of load cycle asymmetry.

At the end of stage 1 $\Delta K = \Delta K_1 = \Delta K_{\text{th1}}$, where $\Delta K_{\text{th1}}$ is the range of threshold SIF at cycle asymmetry $R_1$ corresponding to the last loading step in stage 1. Subsequently, the value of $K_{\text{max}}$ was increased to the level $K_{\text{max}1}$ and the tests in stage 2 were carried out at $K_{\text{max}} = K_{\text{max}1}$ = const and the $\Delta K$ range decreasing from $\Delta K_2 = \Delta K_{\text{th2}}$ to $\Delta K_2 = \Delta K_{\text{th2}}$, where