Relation of threshold levels fatigue crack development in low-alloy steel under harmonic and operational loading

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Abstract. The results of experimental studies of the patterns fatigue crack development in samples made of 20GFL steel cut from the cargo over-spring beam are analyzed. The relation of the threshold stress intensity coefficient \( K_{th} \), determined from the kinetic diagram of fatigue failure, and the parameters of the threshold level and the operational loading process is estimated.

Introduction

The task of improving estimation accuracy of the resource of railway structures \([1, 2]\) resource is of paramount importance for cast parts. It is known that in the process of their manufacture, occurrence of casting defects is inevitable, resulting in formation of stress concentrators further leading to the development of fatigue cracks. This way, the resource of a freight car bogie is largely determined by the duration of development of fatigue cracks to critical values. As studies \([3-5]\) show the main factors affecting the development of cracks at low, pre-threshold loading levels are the effect of cyclic hysteresis of stresses and deformations at the apex of a crack, and their interaction with residual stresses. At the same time, with the reduction of fatigue crack growth rate, the impact of the environment on the fracture process rises significantly. This indicates the complexity of forecasting of damage accumulation processes when reducing operational loads, especially considering their stochastic nature.

As a rule, calculations of fatigue cracks development, influenced by operational loads are carried out using parameters of the kinetic diagram of the fatigue failure of the material, which are obtained experimentally under harmonic loading. And since one of the most important parameters is the threshold level of the stress intensity factor \( K_{th} \), it is important to establish the relation of this value with the corresponding average parameters of the operational loading process. Then, the \( K_{th} \) determined on the fatigue failure kinetic diagram (FFKD) of 20GFL steel \([6]\) and the parameters of stress intensity factor (SIF) variation process, corresponding to the condition of the crack arrest on the same steel grade specimen were compared, when simulating the operational loading process. During the above comparison procedure, analysis of the work \([7]\) is concurrently carried on. This paper presents a method for determining the crack development rate variation pattern under operational loading reduction. The method consists in controlling the loading level reduction in accordance with specimen stiffness decrease (increase in compliance) while the crack grows. During the first stage of experiment, the loading block recorded in operation is reproduced, and the corresponding process of crack edges opening is recorded (figure1). In the second stage, this recording is activated on the test bench as a control signal for reproducing the operational load block.
Figure 1. Sequence of formation of the control signal for hard (on the opening) loading at the second stage, (a) - the loading process, (b) - corresponding process of crack edges displacement.

Figure 2. Reduction in the operational level of loading with an increase in the specimen compliance from crack growth from the 1st level to the 2nd - (a), while maintaining the similarity, (b) - the corresponding shift in the distribution of extremes of processes 1 and 2.

With the development of the crack and reduction of the specimen stiffness, the loading level drops. Analysis of the regularity of changes in the parameters of the simulated loading process with concurrent crack growth and its level corresponding reduction, shows that the ratio of maximum and minimum values of cycles (extremes) in the loading block remains constant. Process of reduction of average, general loading level is under way. This allows us to consider the loading process with crack growth similar to changing processes, with a similarity coefficient matching the reduction level (figure 2).

Applying extrapolation to the results of such tests, a method for calculating and experimentally predicting the rate of development of fatigue cracks in the studied steels at a low level of operational loading, while maintaining the constant ratio between the minimum and maximum values of the cyclic variable loading, was developed [7].
Figure 3. (a) - block of operational loading in the SIF units that meets the conditions for cracks arrest in 20GFL steel [7] and 95% confidence limits of the process; (b) - process of the skewness coefficient R change in accordance with the SIF change (figure 1). The average value of R=0.364 and 95% confidence limits of the SIF.

Test results

In the experiment [7], the relationship of fatigue crack development rate reduction and the number of repeating blocks of operational loading, and the corresponding load decrease under the fixed process of crack edges opening. Extrapolation of the load reduction value ∆P to the level of the zero velocity value (the crack arrest condition) was performed using regression dependencies. The similarity coefficient predicted for the zero speed level allows us to build a model of the threshold loading process, expressed as a cyclic SIF change. The process obtained from the results of work [7] for a compact specimen of C(T) type is shown in figure 3 (a). The following parameters of the resulting process are determined. The average SIF value of the process is 1.978 MPa m$^{0.5}$, in the range of 0.2036 - 5.458 MPa m$^{0.5}$, with a standard deviation of 1.235. Figure 3 (a) shows 95% confidence limits of the SIF (dotted lines), assuming a lognormal distribution. Similar calculations were carried out for the sequence of values of the skewness coefficients R, defined as the ratio of successive SIF extremes (figure 3 (b)). The mean value of R=0.364, in the variation range 0.047 – 0.96 with a standard deviation of 0.215. For comparison with the threshold value of the operational process, experimental results on the crack development under harmonic loading in the form of fatigue failure kinetic diagram (FFKD) for the same steel grade were taken from [6]. Figure 4 (a) shows a diagram of 20GFL steel for the skewness coefficient R=0.5, as the closest value to the average value of the skewness coefficient of the operational loading process under consideration R=0.364 (figure 3 (b)). The values of the skewness coefficient were calculated to determine the crack development rate variation pattern at the low level.
The calculation was performed using the parameters defined in [6] for $R \leq 0.5$. This is $K_{th}=12.34$ MPa$\cdot$m$^{-0.5}$ at $R=0$ (zero cycle) and $\alpha=0.846-0.37R$. On the FFKD graph (figure 4 (a)), the calculated dependence at $R=0.364$ is shown as a dotted line and corresponds to the threshold value of the SIF amplitude $\Delta K=8.949$ MPa$\cdot$m$^{-0.5}$. For the operational threshold process, the same calculation of the SIF threshold amplitude, carried out on the average level of the maximum values of 2.807 MPa$\cdot$m$^{0.5}$ and the average value of $R=0.364$ determines the value of 2.13 MPa$\cdot$m$^{0.5}$. Figure 4 (b) shows the enlarged lower part of figure 4 (a). It can be seen that threshold value of the SIF amplitude determined by extrapolation of the FFKD is significantly greater than those found from the average values of the operational threshold process (this value is shown by the arrow). Even for the maximum value, process values of 5.458 MPa$\cdot$m$^{0.5}$, the threshold amplitude will be 3.96 MPa$\cdot$m$^{0.5}$, which is almost half the threshold level defined by the FFKD (8.949). It shows that this type of operational process, such as [7], causes much more damage compared to simple harmonic loading.

**Conclusions**

The above analysis shows that the threshold level of development of fatigue cracks in low-alloy steel of 20GFL grade (specimens from the cast bolster of a freight car), obtained by extrapolating the fatigue failure diagram, is significantly higher than determined by the forecasting of the threshold level of the operational loading process. Thus, as per average value of maxima of the process 2.807 MPa$\cdot$m$^{0.5}$ and the average skewness factor $R=0.364$, the threshold SIF amplitude is equal to 2.13 MPa$\cdot$m$^{0.5}$, and as per FFKD obtained under harmonic loading, this parameter is equal to 8.95 MPa$\cdot$m$^{0.5}$. In other words, the use of operational process model [7] results in greater damage compared to harmonic loading. This should be taken into account in the calculations of such critical structural elements as the bolster and the side frame of a freight car, made of this steel grade.
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