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PROCESSING OF LOW-CYCLE FATIGUE TESTS DATA ON A BASE OF KINETIC FATIGUE THEORY

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ABSTRACT

To describe the results of tests of samples destruction in a field of low-cycle deforming authors use mathematical model developed in the kinetic theory of mechanical fatigue. Two additional parameters were included in developed model. First parameter characterizes the initial damage of part material, which exists before cyclic deforming of part. Second parameter describes the part resistance against the growth of fatigue cracks. Proposed earlier methods of experimental determination of these parameters values in real operational tests of parts do not allow to obtain required information. The paper considers the task of calculation of these parameters based on results of sample's longevity tests and developed mathematical model. Described task is leaded to two transcendental equations solving. Developed mathematical model allowed to create the method of statistic data processing for samples low-cycle fatigue tests. The method is illustrated on a example of low-cyclic fatigue curve description for the samples made of HS80 pipe steel, tested in conditions of cyclic deforming to its breakage at constant displacement amplitude. The fatigue curve corresponding to 50% of samples destruction probability and also several fatigue curves characterized by different values of accumulated fatigue damage.

Keywords: tensile strength, cyclic deforming, low-cycle fatigue, damages accumulation

1. INTRODUCTION

For the description of results of fatigue tests the linear regression dependences [1] considering, within statistical models, dispersion of mechanical and fatigue properties of a material, but not having any physical filling now are widely used. Ensuring demanded durability and reliability of cyclically loaded products with the set probability of non-destruction is connected with need of use of more difficult models [2, 3, 4] reflecting process of accumulation of fatigue damages to products. Such models are developed in the kinetic theory of mechanical fatigue [5]. The most important practical value of this theory is possibility of curve plotting of the fatigue, corresponding to the various size of damage of a material (D): from $D = D_0 \geq 0$, characterizing initial damage of a material of a detail which takes place even prior to its cyclic deformation, up to the limit size corresponding to destruction of a detail (sample) owing to saved-up fatigue damages.

The purpose of this work is creation of algorithms of data processing of low-cyclic tests ($i = \overline{1,n}$ set of values of tension σ_i and number of cycles N_i before destruction of samples) on the basis of the semi-empirical models developed within the kinetic theory of fatigue, and also a method of calculation of borders of confidential intervals of curve low-cyclic fatigue.

2. MATHEMATICAL MODEL OF LOW-CYCLIC FATIGUE CURVE

In work [5] for the description of multi-cycle fatigue curve formula is received:

$$N = \frac{Q}{\sigma}\ln\left\{\left[\exp\left(\frac{\sigma-\sigma_r}{\sigma_r-\sigma_{rT}}\right)-1\right]^{-1}\right\}, \qquad (1)$$

where: N - is the number of loading cycles; σ - is maximum tension of a cycle; Q – is fatigue ratio; σ_r – is the limit of detail endurance at coefficient of cycle asymmetry r; σ_{rT} – cyclic limit of yielding (below its level traces of plastic deformation even after several million cycles of loading are absent).

Determination of parameters values σ_r, σ_{rT} and Q dependences (1) on the basis of an available data set of destruction of samples $\sigma_i, N_i, i=\overline{1,n}$ it is carried out by function [6, 7] minimization:

$$\Phi(Q,\sigma_r,\sigma_{rT}) = \sum_{i=1}^{n}\left\{N_i - \frac{Q}{\sigma_i}\ln\left\{1+ \right.\right. \qquad (2)$$

$$\left.\left. + \left[\exp\left(\frac{\sigma_i-\sigma_r}{\sigma_r-\sigma_{rT}}\right)-1\right]^{-1}\right\}\right\}^2 \xrightarrow[Q,\sigma_r,\sigma_{rT}]{} \min$$

constructed according to a least squares method.
The mathematical description of curve fatigue in low-cyclic area $(N \le 10^5)$ is presented in work as [5] formula:

$$\sigma = \sigma_B + \vartheta\lg\left(\frac{N}{H}+1\right), \qquad (3)$$

where σ_B - is the yield material value; ϑ - is the slope of a fatigue curve in system of coordinates $\lg N - \sigma$; H - is number of deformation cycles to the top point of an excess of the curve low-cyclic fatigue, counted on dependence (1) for $\sigma = \sigma_B$:

$$H = \frac{Q}{\sigma_B}\ln\left\{1+\left[\exp\left(\frac{\sigma_B-\sigma_r}{\sigma_r-\sigma_{rT}}\right)-1\right]^{-1}\right\}. \qquad (4)$$

In work [5] for coefficient the following formula is received:

$$Q = -Q_T\ln\left[1-\exp\left(-\frac{D_0}{1-D_0}\cdot\frac{\sigma}{(\sigma_r-\sigma_{rT})}\cdot\frac{\sigma_B}{(\sigma_B-\sigma_r)}\right)\right], \qquad (5)$$

where Q_T - is the coefficient characterizing resistance to a detail to growth of fatigue cracks.

Values D_0 and Q_T can be defined on a basis: recorded lengths of fatigue cracks, measurement of the damaged areas of tested details, calculation of the moments of inertia of the damaged sections of details [5]. However in real practice tests obtaining such information is often very complicated, and in many cases it is impossible. However in real practice tests obtaining such information is often very complicated, and in many cases it is impossible. Nevertheless, the knowledge of initial D_0 and limit value of parameter D_k allows at the set value of the operating tension σ and number of loading cycles N to estimate the reached level of the current damage of a material D and, finally, to realize procedure of calculation of residual detail strength (sample).
Let's use the law (5) which we will transform as follows:

$$\exp(-Q/Q_T) + \exp\left[-\frac{D_0}{1-D_0}\cdot\frac{\sigma}{(\sigma_r-\sigma_{rT})}\cdot\frac{\sigma_B}{(\sigma_B-\sigma_r)}\right] = 1. \qquad (6)$$

After the solution of a problem (2), the parameters values σ_r, σ_{rT} and Q on the basis of an available data set of fatigue tests $\sigma_i, N_i, i=\overline{1,n}$ are determined: σ_r^*, σ_{rT}^* and Q^*. In this case formula (6) is as follows:

$$\exp(-Q^*/Q_T) + \exp\left[-\frac{D_0}{1-D_0}\cdot\frac{\sigma}{(\sigma_r^*-\sigma_{rT}^*)}\cdot\frac{\sigma_B}{(\sigma_B-\sigma_r^*)}\right] = 1. \qquad (7)$$

We will be set by average value of strength $\sigma_B = \overline{\sigma_B}$. Then in the equation (7) indeterminate are only two parameters: D_0 and Q_T. For their definition we will use the following mode. As value D_0 characterizes damage of a material in an initial condition, its value (σ) at deformation of a sample doesn't depend on the value of the operating tension. D_0 is a constant for all range of tension change σ. If, in addition to noted to assume, as coefficient Q_T, in the range of tension change $\sigma_r^* \le \sigma \le \overline{\sigma_B}$ also is constant value, for calculation D_0 and Q_T let's enter into the equation (7) twice: at a tension $\sigma = \overline{\sigma_B}$ and $\sigma = \sigma_r^*$. As a result we will obtain:

$$\left.\begin{aligned}
&\exp\left(-Q^*/Q_T\right) + \exp\left[-\frac{D_0}{1-D_0}\cdot\frac{\overline{\sigma_B}}{\left(\sigma_r^*-\sigma_{rT}^*\right)}\cdot\frac{\overline{\sigma_B}}{\left(\overline{\sigma_B}-\sigma_r^*\right)}\right] = 1;\\
&\exp\left(-Q^*/Q_T\right) + \exp\left[-\frac{D_0}{1-D_0}\cdot\frac{\sigma_r^*}{\left(\sigma_r^*-\sigma_{rT}^*\right)}\cdot\frac{\overline{\sigma_B}}{\left(\overline{\sigma_B}-\sigma_r^*\right)}\right] = 1.
\end{aligned}\right\} \qquad (8)$$

Solving the received system of two transcendental equations, we will define required values D_0^* and Q_T^*.
In view of that the current damage of a material, following the work [5], is described by formula (5) when replacing D_0 on D, we will receive the specified law for low-cyclic fatigue curve:

$$N = \left(1 - 10^{\frac{\sigma - \bar{\sigma}_B}{\vartheta}}\right) \cdot Q_T^* \cdot B_0 \cdot$$

$$\cdot \ln\left[1 - \exp\left(-\frac{D \cdot \bar{\sigma}_B}{(1-D)(\sigma_r^* - \sigma_{rT}^*)(\bar{\sigma}_B - \sigma_r^*)} \cdot \sigma\right)\right] \quad ,(9)$$

where
$$B_0 = \frac{\ln\left\{1 + \left[\exp\left(\frac{\bar{\sigma}_B - \sigma_r^*}{\sigma_r^* - \sigma_{rT}^*}\right) - 1\right]^{-1}\right\}}{\bar{\sigma}_B}.$$

3. PROCESSING OF DATE OF LOW-CYCLIC TESTS OF SAMPLES

The stated technique is used at data processing of low-cyclic tests of samples of pipe HS80 steel. In a result of tension of flexible pipe samples on tensile-testing machine before destruction (Figure 1) we determined value: $\bar{\sigma}_B$ =602,1MPa. Process of low-cyclic deforming of pipe rectangular samples on experimental stand (Figure 2) at constant displacement amplitude allows to obtain model (9) parameters: $\vartheta = -12{,}81$; $Q_T^* = 1{,}531\cdot 10^{6}$; σ_r^* =263,621 MPa; σ_{rT}^* =201,914 MPa. In fig. 3 in coordinates $\lg N - \sigma$ experimental points and a number of curves of fatigue with damage value: $D = D_0^* = 0{,}0016$ (thick line) $1\cdot10^{-7}; 1\cdot10^{-5}; 1\cdot10^{-4}; 1\cdot10^{-2}$ are presented.

Figure 1. Destroyed samples of pipes

Figure 2. Experimental stand

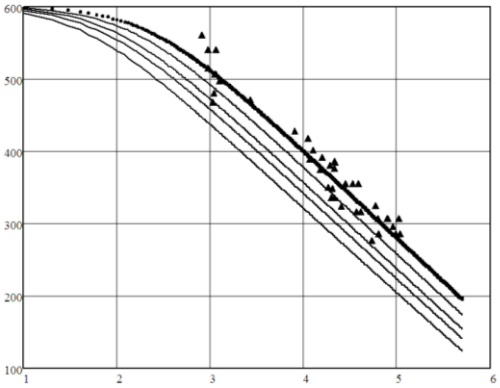

Figure 3. Curve of low-cyclic fatigue with the various value of material damage (HS80 steel)

Analyzing Figure 3 it is easy to see that at $D = D_0$ and $\sigma_B = \bar{\sigma}_B$ formula (9) describes the curve of fatigue corresponding to 50% for probability of samples destruction.
Mathematical model of low-cyclic fatigue curve in kind of (9) allows to determine the decreasing of number of deforming cycles before samples destruction in dependence of accumulated fatigue damage, and also to decide the task of calculation of equivalent damaging stress at given load variation block. The method of this task solving developed on base of mathematical model (9) is presented in paper [7].

4. CONCLUSION

For data processing of low-cyclic tests the mathematical description of fatigue curve considering process of accumulation of damages at cyclic deformation of samples is executed. Algorithms of calculation of parameters of model on the basis of a data set of tests of samples on fatigue are developed. The developed techniques and computing algorithms are illustrated on the example of data processing of low-cyclic fatigue tests of samples from HS80 steel.

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