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Planning an Experiment for Low-Cycle Fatigue under Conditions Deep Cooling

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Abstract. In the elements of structures with a limited resource during operation, significant cyclic stresses can occur, reaching and exceeding the yield strength; the results of an experimental study of the effect of the magnitude of preliminary plastic deformations on the strength and durability of structural alloys under low-cycle loading can be of undoubted interest for practice. The use of experimental planning methods in the study of the influence of the maximum cycle stresses and the magnitude of the preliminary permanent deformation on the low-cycle fatigue of 03Kh13AG19 chromium-manganese steel at T = 4.2 K under pulsating tension showed that these methods can be successfully used.

Introduction

The assessment of the bearing capacity of structural elements, the material of which was plastically deformed as a result of previous loading, should be based on the results of studying the effect of preliminary plastic deformation on the strength and durability of the material [1]. Most of the known experimental data are obtained from research in the field of high-cycle fatigue.

Due to the fact that significant cyclic stresses, reaching and exceeding the yield point, can arise in the elements of structures with a limited resource during operation, the results of an experimental study of the effect of the magnitude of preliminary plastic deformations on the strength and durability of structural alloys under low-cycle loading may be of undoubted interest for practice [2].

For planning any experiments, the question arises about the adequacy of the obtained mathematical model. When setting up an experiment on simplex - lattice designs have no degrees of freedom to test the adequacy of the equation, since these designs are saturated. To check the adequacy put experiments in additional, so-called control points. Number control points and their coordinates are associated with the problem statement and the features of the experiment. At the same time, they try to provide for the possibility of using control points to improve the model in case of inadequacy [3].

When constructing a regression dependence of properties on content of components, problems arise with the assessment coefficients of this model due to the normalization of the sum of independent variables. In this case, the regression model can be built with respect to an incomplete number of components, which is of course undesirable.

One of the variants of another approach to solving the problem is associated with the use of the Scheffe experiment planning method. The essence of this approach is reduced to using relation 1 to lower the order of the polynomial describing the desired dependence, and, as a result, to estimate the coefficients of the equation by the method of simple substitution.

The article discusses Scheffe's simplex-lattice planning method using the example of describing the dependence of the properties of a mixture by a second-order polynomial [4].

Analysis of Publications

The complexity and laboriousness of experimental studies in liquid helium (T = 4.2 K) determines the limited information on this issue. As a rule, the research results refer to one-factor experiments, in which only the level of the maximum cycle stresses changes [5].

Aim of Paper

Investigate low-cycle fatigue of cryogenic steel using mathematical experimental design methods.

Materials and Methods

Such data for chrome-manganese steel 03Kh13AG19 were obtained in this work. As a study, we used standard five-fold cylindrical samples with a diameter of the working part of 5 mm. The tests were carried out with a triangular shape of the load change cycle with a frequency close to 2 cycles/min. In order to reduce the complexity of the research and increase the accuracy of the results, the methods of mathematical planning were used.

The work investigated the effect of the magnitude of the preliminary permanent deformation x_1^H, set at a single axial tension of the samples at the temperature of subsequent low-cycle tests, and the level of maximum cycle stresses x_2^H for low-cycle fatigue of steel 03Kh13AG19 at a temperature of 4.2 K. The effect of preliminary deformation was estimated by the change in the value of the logarithm of durability (response function) y = log (Np), where Np is the number of cycles before failure.

Research Results

To construct an incomplete quadratic model based on the results of the experiment

$$y = \beta_0 + \beta_1 x_1^H + \beta_2 x_2^H + \beta_{12} x_1^H x_2^H \quad (1)$$

Table 1. Factors and levels of their variation

i	Factors	x_i^H	x_i
1	The amount of preliminary residual deformations ε_H, [%]	1	-1
		3	1
2	Maximum cycle voltage σ_{max}, [MPa]	1080	-1
		1280	1

The value of the preliminary residual deformation xin was set according to the deformation diagram P – Δl with a scale of 1: 80 (Fig. 1).

On the scale paper of the diagrammatic drum of the test setup on the scale of absolute elongations at P = 0, the value of Δln was plotted, corresponding to the relative residual deformation of the sample 1 and 3%.

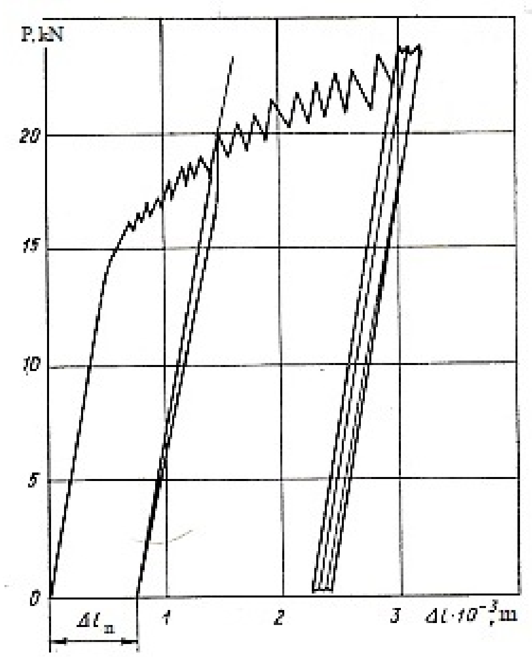

Fig. 1. Deformation diagram of chrome-manganese steel 03Kh13AG19 at T = 4.2 K

Through the points obtained, lines were drawn parallel to the linear section of the tensile diagram of 03X13AG19 steel at the test temperature. To give the sample the required permanent deformation, it was loaded until the recorder crossed the line corresponding to the selected level of permanent deformation. After that, the sample was unloaded and then loaded cyclically at the values of σ_{max} determined by the experimental design. In this case, deviations from the selected level of preliminary deformation did not exceed 0.06%.

Levels x_2^{H} was selected according to the curve of low-cycle fatigue of the material in the initial state so that the expected durability of the samples did not go beyond the region corresponding to low-cycle fatigue.

Dispersion of experience s_y^2 was evaluated according to the results of a series of parallel tests of non-deformed samples, with the number of degrees of freedom $f_1 = 2$, it was 0.1407.

The closest plan in terms of the number of experiments required to determine all unknown parameters of model (1) is the plan of the full factorial experiment 2^2 (Table 2), including all possible combinations of levels of factors x_1^{H} and x_2^{H}.

Table 2. Conditions for a full factorial experiment 2^2

Experience number	x_1	x_2	x_1^{H}, [%]	x_2^{H}, [MPa]
1	-1	-1	1	1080
2	1	-1	3	1080
3	-1	1	1	1280
4	1	1	3	1280

Each line in the table. 2 defines the conditions for carrying out one experiment, for example, the first line - the conditions of the experiment in which a sample with a preliminary deformation of 1% must be tested at a maximum cycle stress of 1080 MPa, etc. For the convenience of processing and interpretation of the experimental results from the natural values of the factors xin we went over to the dimensionless xi, while for the factors with equally spaced levels, the coefficients of the orthogonal Chebyshev polynomials were taken [6].

An extended normalized design for a full factorial experiment 2^2 is presented in Table 3.

Table 3. Expanded normalized full factorial experiment design 2^2

Experience number	Procedure realization	x_0	x_1	x_2	x_1x_2	y
1	2	1	-1	-1	1	2.251
2	3	1	1	-1	-1	3.111
3	1	1	-1	1	-1	1.778
4	4	1	1	1	1	0.700

In addition to the columns x_1 and x_2, which determine the conditions of the experiment, there are also auxiliary columns x_0, x_1x_2, which are used only for calculating sample estimates of the parameters of the model (1); x_0 is a dummy variable, in all experiments $x_0 = 1$. The values of the pairwise interaction effect x_1x_2 can be obtained by multiplying the corresponding main effects x_1 and x_2. As a result of the experiments, determined by the experimental plan, we found the number of cycles until the destruction of the samples, calculated the logarithms of the longevity, and based on the data obtained, we filled in the column y (Table 3).

The full factorial experiment design 2^2 is D-, G-, A-, and E-optimal. Moreover, it is orthogonal and rotatable [6, 7]. The last two properties make it possible to obtain selective estimates of the unknown parameters of the model (1) with the same variance (in this case, the determination accuracy is four times higher than the accuracy of a single test) and independently of each other. With the orthogonal design of the experiment, the calculation of the estimates of the unknown parameters of the model by the formula [6].

$$b_i = \frac{\sum_{u=1}^{N} x_{iu} \cdot y_u}{\sum_{u=1}^{N} x_{iu}^2}, \tag{2}$$

where: u is the number of the experiment; N is the total number of experiments on the plan; i is the index of the coefficient in the model (1).

In accordance with expression (2), the following values were obtained for the parameters of model (1); $b_0 = 2.210$; $b_1 = -0.305$; $b_2 = -0.971$; $b_{12} = -0.235$. An estimate is considered statistically significant if the condition is met for it [4]:

$$|b_i| > t_{\propto, f_1} \cdot s_{b_i,} \tag{3}$$

where: $t_{\propto, f_1}$ is the Student's coefficient: $s_{b_i}^2 = \frac{s_y^2}{\sum_{u=1}^{N} x_{iu}^2}$- variance in determining the estimate of the i-th parameter.

At a 5% significance level α and $f_1 = 2$, only the coefficients b0 and b_2 can be considered statistically significant, and since the design matrix is orthogonal, the exclusion of statistically insignificant estimates does not affect the value of the coefficients remaining in the model. Then we get

$$y = 2.210 - 0.978 \cdot x_2 \tag{4}$$

The hypothesis of the adequacy of the model (4) was tested by the Fisher's F-criterion, in accordance with which the model is considered adequate if the condition is met [6, 7]:

$$F_{\text{calc}} < F_{\text{tabl}}, \quad (5)$$

where: $F_{\text{calc}} = \frac{1}{s_y^2} \cdot (ss_{nead}/f_2)$ - the calculated value of the criterion;

f_2 = N-k - the number of degrees of freedom in determining the variance of inadequacy;

k- is the number of coefficients left in the model, including b_0;

$ss_{nead} = \sum_{u=1}^{N} (y_u^{calc} - y_u^{exp})^2$.

With the tabular value of Fisher's criterion $F_{tabl} = 19$, its value, obtained by calculation, $F_{calc} = 2.1$. Consequently, using expression (4), it is possible to accurately describe the phenomenon under study.

When passing from normalized values of factors to natural values, one can obtain an analytical expression for the low-cycle fatigue curve in the coordinates σ_{max} – logNp:

$$y = \lg N_p = -13{,}668 - 0{,}0097 \cdot \sigma_{max}. \quad (6)$$

Analysis of expression (4) showed that the preliminary residual deformation of 1 and 3%, obtained by the sample as a result of a single loading by the axial tensile force, does not have a noticeable (in a statistical sense) effect on the durability of 03Kh13AG19 chromium-manganese steel during low-cycle tests under deep cooling conditions in the voltage range. Therefore, when the condition of the adequacy of the model is fulfilled, the need to complete the plan (Table 2) automatically disappears to a compositional plan of a higher order.

Conclusions

The use of experimental planning methods in studying the effect of maximum cycle stresses and the magnitude of preliminary residual deformation on low-cycle fatigue of chromium-manganese steel 03Kh13AG19 at T = 4.2 K under pulsating tension showed that these methods can be successfully used to solve problems related to mechanical - tests of structural materials.

The use of planning methods made it possible to significantly reduce the volume of tests, which is especially important when conducting technically complex and expensive research [8].

The durability of 03Kh13AG19 steel in the area of low-cycle fatigue at T = 4.2 K does not depend on the value of the preliminary permanent deformation of 1-3% and is determined only by the level of the maximum cycle stresses.

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