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Low Cycle Fatigue of Structural Alloys

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Abstract. Metallurgy, mechanical engineering, energy, agriculture, food industry, energy, electronics, rocket and space technology – this is a far from complete list of areas of the national economy in which liquid cryogenic products (cryoproducts). The production volumes of such products and the scale of their use are constantly increasing. This is due to the fact that cryogenic temperatures (below 120 K) provide unique opportunities for the implementation of such physical phenomena and processes that do not manifest themselves under normal conditions, but are used very effectively in science and technology.

The solution of fundamental scientific problems and applied problems of both promising and current importance is determined by the level of development of cryogenic technology and the degree of its practical application.

The continuous expansion of the scale of production of liquid cryogenic products has led in recent years to a significant increase in the volume of production of systems for their storage and transportation. These systems, as a rule, are welded shell structures in execution, they are operated in difficult conditions of temperature and force effects. The share of their production in the total output of cryogenic engineering products is very significant, and the operating conditions are the most stressful in comparison with other types of cryogenic structures.

For the manufacture of cryogenic shell structures, expensive non-ferrous alloys and special steels are used, the degree of consumption of which, taking into account the sufficient material consumption of such structures and the expanding scale of their production, is constantly increasing. Therefore, one of the most urgent for cryogenic mechanical engineering at present is the problem of reducing the material consumption of shell structures and increasing their reliability and durability. It is obvious that a solution to this problem for cryogenic engineering products can be achieved by improving the methods of their strength calculations based on taking into account the specific hardening effect of low temperature on structural alloys.

The phenomenon of low-cycle fatigue of metals is associated with elastoplastic deformation of their macrovolumes. The kinetics of elastoplastic deformation processes under cyclic loading depends on the loading conditions and material properties, and the nature of these processes and their intensity have a decisive influence on the features of material destruction.

If the accumulation of deformation is small, then the destruction, as a rule, is of a fatigue nature; quasi-static fracture (similar in appearance to fracture during static tests for short-term strength) occurs after the realization of the ultimate plasticity of the material. The task of assessing the bearing capacity and durability under cyclic loading conditions is extremely important. Under cyclic loading, a number of specific phenomena and factors that are difficult to take into account analytically arise, which are primarily associated with the development of fatigue damage, with the

need to assess the cyclic and structural instability of materials. Since such studies are very laborious and expensive, the problem of minimizing such experiments is currently urgent. In this paper, we investigate the possibility of using mathematical planning methods for experimental studies at cryogenic temperatures. Experiment planning is usually understood as the procedure for choosing the volume and conditions of testing necessary and sufficient to solve the problem with the required accuracy.

Introduction

The task of assessing the bearing capacity and durability under cyclic loading conditions is extremely important [1, 2]. Under cyclic loading, a number of specific phenomena and factors that are difficult to take into account analytically arise, which are primarily associated with the development of fatigue damage, with the need to assess the cyclic and structural instability of materials [3, 4]. Since such studies are very laborious and expensive, the problem of minimizing such experiments is currently urgent. In this paper, we investigate the possibility of using mathematical planning methods for experimental studies at cryogenic temperatures. Experiment planning is usually understood as the procedure for choosing the volume and conditions of testing necessary and sufficient to solve the problem with the required accuracy.

The conditions of the experiment are set by a set of factors, which are independent variables, the change of which can be controlled during the experiment. The number of possible values of a factor, which it takes in various experiments, is usually called its levels.

When planning an experiment, it is assumed that each set of levels of factors, that is, each experience, corresponds to a well-defined behavior of the object under study and the corresponding value of the dependent variable (response), up to the experimental error.

The type of analytical dependence of the response function on the factors included in the experiment is determined by the nature of the phenomenon under study, while recording in a certain sequence of the conditions for conducting the experiment, necessary and sufficient to obtain estimates of the unknown parameters of the response function, is called the experimental plan.

Analysis of Publications

Analysis of the latest achievements and publications. The strength problems of structural alloys in a wide temperature range are being dealt with by a group of scientists led by Professor V. A. Strizhalo. The complexity and laboriousness of experimental studies determines the limited information on this issue [5].

Materials and Methods

In this work, it was supposed to determine the degree and nature of the influence of the level of maximum cycle stresses (X_1^i), preliminary plastic deformation (X_2^i) and test temperature (X_3^i) on the low-cycle fatigue of the PT-3B titanium alloy. 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.

Research Results

The value (number of cycles before failure) was taken as a response function. The regional average value of the variance of the experiment was. No direct research has been conducted. Therefore, it was advisable to assume a non-linear model.

To ensure the maximum possible accuracy in setting the levels of the factor (X_3^i), preliminary deformation was carried out in the media of liquid refrigerants: nitrogen and helium, as well as in air at temperatures of 77, 4.2 and 293 K [6, 7].

The value of the preliminary static permanent deformation was recorded according to the diagram (P-Δl) with a scale of 1:200, and the levels of the factor $X_1^н$ – according to the ultimate strength curve for the samples in the initial state (Table 1).

Table 1. The importance of factors in the experiment

Factor Number	Factor Name	F_i	Natural value, $X_i^н$
1	Maximum relative cycle voltage, $\frac{\sigma_{max}}{\sigma_{\hat{a}}}$	0	0.76
		1	0.85
		2	0.94
2	The amount of preliminary permanent deformation, ε_i, [%]	0	0
		1	1
		2	3
3	Pre-deformed temperature, $T_н$, [K]	0	4
		1	77
		2	300

The design of a full factorial experiment requires 3^3 experiments, and the model itself contains a large number of interaction effects, which are not always statistically significant. Therefore, it was decided on the basis of the results of the fractional factorial experiment 3^{3-1} to build a model of the main effects with the generating ratio $F_3 = F_1 \cdot F_2^2$. Test conditions for replica 3^{3-1} are shown in Table 2.

Table 2. Experimental conditions

Experience number	F_1	F_2	F_3	X_1^i	X_2^i	X_3^i
1	0	0	0	0.76	0	4
2	1	0	1	0.85	0	77
3	2	0	2	0.94	0	300
4	0	1	2	0.76	1	300
5	1	1	0	0.85	1	4
6	2	1	1	0.94	1	77
7	0	2	1	0.76	3	77
8	1	2	2	0.85	3	300
9	2	2	0	0.94	3	4

To obtain estimates of the parameters of the model and to carry out statistical processing and interpretation of the experimental results, it is convenient to normalize the levels of factors. The normalized matrix of the design of the fractional factorial experiment 3^{3-1} and the results of the experiments are presented in table 3.

Table 3. Normalized plan matrix

Experience number	X_0	X_1	X_2	X_3	Z_1	Z_2	Z_3	$\lg N_p$
1	1	-1	-4	-2.5	1	2	3	4.5750
2	1	0	-4	-1.0	-2	2	-4	3.9500
3	1	1	-4	3.5	1	2	1	2.4500
4	1	-1	-1	3.5	1	-3	1	4.3876
5	1	0	-1	-2.5	-2	-3	3	3.7552
6	1	1	-1	-1.0	1	-3	-4	2.0899
7	1	-1	5	-1.0	1	1	-4	4.2739
8	1	0	5	3.5	-2	1	1	3.6068
9	1	1	5	-2.5	1	1	3	2.0864

As a result of the experiments, estimates of the model parameters were obtained:

$$y = \beta_0 + \beta_1 \cdot X_1 + \beta_2 \cdot X_2 + \beta_3 \cdot X_3 + + \beta_{11} \cdot Z_1 + \beta_{22} \cdot Z_2 + \beta_{33} \cdot Z_3, \quad (1)$$

where: X_1, X_2, X_3- normalized values of linear members of the model;
Z_1, Z_2, Z_3- normalized values of the quadratic terms of the model.

For parameters β_i the estimates are the values of b_i. Thus, the coefficients of the model are equal: $b_0 = 3.4639$, $b_1 = -1.1017$, $b_2 = -0.0341$, $b_3 = -0.0034$, $b_{11} = -0.1534$, $b_{22} = 0.0290$, $b_{33} = 0.0056$. Checking their statistical significance showed that the estimates b_3 and b_{33} are statistically insignificant. Since the design matrix is orthogonal, the factors corresponding to them can be excluded from the model without recalculating the remaining ones. Then the refined model will look like:

$$y = 3.4639 - 1.1017 \cdot X_1 - 0.0341 \cdot X_2 - 0.1534 \cdot Z_1 + 0.0290 \cdot Z_2 \quad (2)$$

The hypothesis about the adequacy of the resulting model was tested by F-Fisher's test. At the significance level $\alpha = 0.05$ the refined model quite accurately describes the low-cycle fatigue of the PT-3B alloy.

To interpret the results obtained, one should go to the natural values of the factors under study. In this case, the model will look like:

$$\lg N_p = -26.6783 + 84.3436 \cdot X_1^н - 0.3130 \cdot X_2^н - 56.8147 \cdot (X_1^н)^2 + 0.0677 \cdot (X_2^н)^2 \quad (3)$$

This work also provides experimental data on the effect of deep cooling on the cyclic creep of the PT-3B alloy. The studies were carried out in air and in environments of liquid refrigerants (nitrogen and helium) at temperatures of 293, 77 and 4.2K, respectively.

Analysis of the obtained experimental data showed that at a test temperature of 293K, directional plastic deformation takes place in the range of durability 0.5-10^4 cycles.

In the PT-3B alloy, the processes of cyclic creep occur most intensively in the region of stresses corresponding to quasi-static fracture. The curves characterizing the kinetics of changes in plastic deformation versus the number of loading cycles in this stress region have three characteristic sections: unsteady decaying, steady-state, and unsteady accelerated creep. In this case, the main part of plastic deformation is realized in the last two stages (Fig. 1).

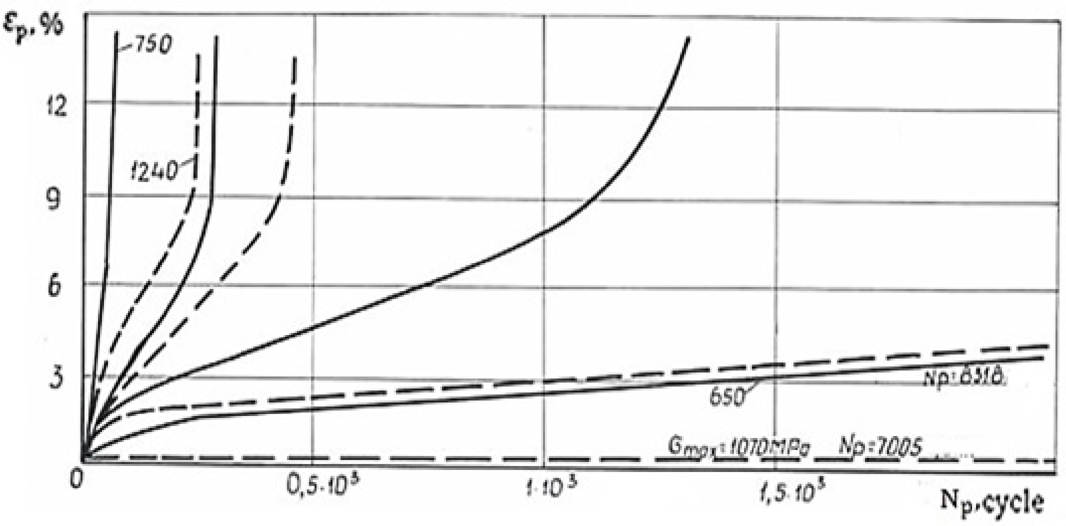

Fig. 1. Cyclic creep curves of PT-3V titanium alloy: — - 293 K; ---- - 77 K

A decrease in the test temperature to 77 K does not qualitatively change the nature of deformation and fracture of the studied materials, however, there is a sharp deceleration of the processes of directional plastic deformation, which is characterized by a change in the angle of inclination of the steady-state creep sections on curves plotted for the same values of reduced stresses at test temperatures of 293 and 77 K. respectively.

Thus, taking into account this fact that in the temperature range of 293-77 K on the cyclic creep curves the stage of accelerated creep is very limited in terms of durability, it can be said with confidence that the number of cycles before the destruction of the PT-3B alloy in the low-cycle region will be determined by its ability to resist deformation at a steady state.

In this case, the kinetics of directional plastic deformation of the PT-3B alloy at temperatures of 293 and 77 K with a sufficient degree of accuracy can be described from the standpoint of the theory of hardening.

Significant changes in the behavior of structural materials occur when they are tested under deep cooling conditions (T = 4.2K). The deformation mechanism changes, and the plasticity decreases sharply. All deformation accumulated before failure is realized in the first half-cycle of loading as a result of acts of intermittent flow, the number of which is uniquely determined by the level of maximum cycle stresses.

With further cyclic loading, no plastic deformation of the alloy was found. This indicates that the process of directional plastic deformation at T = 4.2 K is completely suppressed and the destruction of the samples occurs as a result of the formation and development of a fatigue crack to a critical value. At the same time, it should be noted that an intermittent flow was experimentally recorded for a number of structural materials at the initial stage of cyclic loading. Consequently, the absence of cyclic creep in structural steels and alloys at T = 4.2 K cannot be considered an absolutely established fact. For a deeper study of this phenomenon, additional experimental studies are required.

Conclusions

A mathematical model has been obtained that determines the degree and nature of the influence of the level of maximum cycle stresses, preliminary plastic deformation of the test temperature on low-cycle fatigue of the PT-3B titanium alloy. Analysis of the obtained mathematical model shows that the assumption of the nonlinear effect of the maximum cycle stress and preliminary deformation was confirmed. The statistical insignificance of the b_3, b_{33} estimates can be interpreted as the absence of the effect of the preliminary deformation temperature on the durability of the PT-3B titanium alloy. In addition, to solve this problem, the volume of tests was reduced by about 15 times.

At a test temperature of 293 K in the range of fatigue life of $0.5\text{-}10^4$ cycles, specimens of the PT-3B alloy exhibit directional plastic deformation. Lowering the test temperature to 77 K does not qualitatively change the nature of deformation and fracture of the alloy.

The process of directional plastic deformation of structural steels at T = 4.2 K turns out to be completely suppressed and the fracture of the samples occurs as a result of the formation and development of a fatigue crack to a critical value.

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