Studying of accumulation damages regularities under low cycle loading and cycle variable parameters conditions

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Abstract. The aim of the work is to study the possibilities of predicting cyclic durability in low-cycle fatigue and variable cycle parameters conditions, which combination describes the change complex nature in the stress-strain state over time of aircraft engine parts, based on linear and nonlinear models of damage accumulation. To do this, low-cycle fatigue tests of cylindrical samples were carried out for various loading forms, consisting of several simple-shape cycles. On the results of the tests carried out, fatigue life was predicted based on the nonlinear hypothesis of the Marco-Starkey damage accumulation. An analysis of the mechanical hysteresis loops was carried out to estimate the reasons for the increase of life during tests with a large number of groups in blocks.

1. Introduction

Elements of the constructions and machine parts during operation undergo a cyclic loading with various stress amplitudes. Depending on the value of the applied load, the material is able to withstand a different number of cycles until destruction. The works [1-5] are devoted to the study of the mechanical response of materials during low-cycle deformation. The principles of low-cycle deformation and the influence of loading on damage probability are investigated in the work [5], where various steel types were considered. The study confirms that the resistance to deformation of materials decreases with increasing number of loading cycles and test temperatures. In the work [6] one considered the influence of the conditions of biaxial loading, the path of cyclic deformation, and the cycle types. The influence of overload on the fatigue life of alloy steel was studied in the work [7]. As a result, it was found that the residual stress, created by the initial overload, did not have much influence on the fatigue life of steel. The service life increase due to initial overload was minimal. The interdependency between inelastic deformation and fatigue failure due to the influence of the loading frequency was studied in the work [8]. The results showed that with an increase of the loading frequency, the limit stresses of the same cycle before failure increase in both high-cycle and low-cycle fatigue.

The influence of the loading rate on the fatigue properties of steel under low-cycle fatigue was studied in the work [9, 10]. The works showed that the fatigue life of steel decreases with a decrease of the Nowadays issues of damage accumulation and life estimation are relevant and are actively studied. The development of methods for predicting cyclic life has led to the occurrence of a large number of criteria for fatigue failure. Nowadays many studies are based on the deformation and energy criteria of the fatigue failure. When plastic deformation is the main cause of fatigue damage of the material, then the well-known traditional deformation method is used, developed by Manson and Coffin. In the work [11] the energy criteria of fatigue failure were studied, where the relationship between the total energy of plastic deformation and the number of cycles before failure was considered. rate and an increase of
amplitude. Nowadays issues of damage accumulation and life estimation are relevant and are actively studied. The development of methods for predicting cyclic life has led to the occurrence of a large number of criteria for fatigue failure. Nowadays many studies are based on the deformation and energy criteria of the fatigue failure. When plastic deformation is the main cause of fatigue damage of the material, then the well-known traditional deformation method is used, developed by Manson and Coffin. In the work [11] the energy criteria of fatigue failure were studied, where the relationship between the total energy of plastic deformation and the number of cycles before failure was considered. To estimate the degree of the material damage during low-cycle fatigue under the action of variable amplitudes of uniaxial or biaxial cyclic loading, various models of damage accumulation are used. The most widely used theory of damage summation is the linear theory of Palmgren, A., and Meiner, M.A., which suggests that the life at a given stress does not depend on previously applied loads, so the relative errors of the life linearly depend on the number of loading cycles. Nowadays, a large number of reliable constructions are working on low-cycle fatigue. In this regard, more studies are needed on this issue in order to predict the resource of such constructions more accurately. Figure 1 shows the dependence of the ratio of the relative intensity of elastic stresses to the yield limit of the material in the most loaded part of the web hub, illustrating the complex nature of the change of stresses in the cycle.

![Figure 1](image.png)

**Figure 1.** An example of time change of stress intensity in the most loaded part of the web hub.

The objective of the work is to study the possibilities of predicting a resource under conditions of low-cycle fatigue and variables of cycle parameters, a combination of which describes the complex nature of the change in the over-time stress-deformation state of aircraft engine parts, based on linear and nonlinear models of damage accumulation.

2. Experimental procedure

The tests were carried out on the basis of the Common Use Center "Center for Experimental Mechanics" of the Perm National Research Polytechnic University. The mechanical tests for low-cycle fatigue at normal temperature were carried out taking into account the requirements of ASTM E606-42 and GOST 25.505-85 standards on Instron 8801 servo-hydraulic system. As a control parameter for the test machine in low-cycle fatigue tests, one used the total amplitude of axial deformation, being controlled at room temperature using an Instron dynamic axial deformation sensor with a base of 12.5 mm. As the studied material, an aluminum alloy of the D16T type was used. For carrying out low-cycle fatigue tests with constant cycle parameters (Figure 2) at normal temperature, four groups of tests were used, each having its own cycling parameters. Three samples were tested in each group of test.
To analyze the common factors of damage accumulation under variable cycle parameters, several program loading blocks were chosen, which consisted of different cycles of a simple type. Figure 3 shows the cycle types of low-cycle block loading that were selected when combining the cycle types with constant parameters. During the test, the total number of cyclic deformation blocks before failure was calculated.

3. Results and discussion

3.1. Mechanical test results
Table 1 provides the limit number of cycles before failure with constant cycle parameters.
Table 1. Test results on low-cycle fatigue with constant parameters

| № group | Strain range in cycle, $\varepsilon_r$, % | Asymmetry coefficient, R | The number of cycles to failure, N |
|---------|----------------------------------------|-------------------------|----------------------------------|
| 1 group | 1,38                                   | 0                       | 522                              |
| 2 group | 1,18                                   | 0                       | 3361                             |
| 3 group | 0,72                                   | 0                       | 44443                            |
| 4 group | 0,73                                   | 0,5                     | 21100                            |

Table 2 shows the test results for low-cycle loading with variable cycle parameters according to block loading schemes. Figure 4 shows the dependences of the normal stress on the axial deformation recorded at the beginning, in the middle, and at the end (before failure) of the test for one sample from each loading block.

Table 2. Test results of cylindrical samples made of D16T aluminum alloy under low-cycle loading according to block schemes

| № blok | Maximum strain in the block, $\varepsilon_{max}$, % | Minimum strain in the block, $\varepsilon_{min}$, % | Range of deformation in the block, $\varepsilon_r$, % | Asymmetry coefficient, R | The average number of cycles to failure, N |
|---------|----------------------------------------------------|-----------------------------------------------|-------------------------------------------------|-------------------------|----------------------------------------|
| 1 blok  | 1.38                                               | 0.01                                          | 1.37                                             | 0.007                   | 120                                     |
| 2 blok  | 1.38                                               | 0.02                                          | 1.36                                             | 0.014                   | 468                                     |
| 3 blok  | 1.38                                               | 0.02                                          | 1.36                                             | 0.007                   | 630                                     |

4 cycles из 1 group, 4 cycles из 4 groups
3 cycles из 2 group, 1 cycle из 1 group, 4 cycles из 4 group
4 cycles из 3 group, 1 cycle из 1 group, 4 cycles из 4 group

Figure 4. Typical dependences of normal stress on axial deformation for different types of the block loading cycle: 1 block (a), 2 block (b), 3 block (c).
3.2. Processing of results

As a result, experimental data on low-cycle fatigue with complex cycle parameters of the D16T aluminum alloy were obtained, and common factors of damage accumulation processes were analyzed on the basis of the linear damage summation model [12]. Although, the experimental data of both domestic and foreign researchers mostly do not confirm the linear theory. A great influence on the life during subsequent loading is exerted by the earlier loading, which is not taken into account by the linear hypothesis of damage summation. Therefore, it is reasonable to use non-linear models of damage accumulation.

One of the first nonlinear hypotheses of damage accumulation is the hypothesis proposed by Marco and Starkey [12]. In our work [13], one considered the possibility of using this nonlinear model of damage accumulation for the case of loading upon complex M-shaped cycle type. The calculation of the total damage was carried out taking into account the damage accumulated on the previous steps [14]:

$$\sum_{k=1}^{i} D_k = \left[ \frac{n_i}{N_i} + \left( \sum_{k=0}^{i-1} D_k \right)^{1-m_i} \right]^{m_i}$$

For different deformation amplitudes, such coefficients $m_i$ were selected that allowed to predict the life of the material under a complex (M-shaped) type of loading. However, the question arises of the solution unicity.

Consequently, the possibility of using this model for three loading blocks consisting of different groups is considered. The scheme for calculating the damage accumulation of complex type according to this model is presented in Figure 5, where $\Delta D$ - the damage for one test group, $n'$ - the number of cycles passed for one test group. Each curve in the figure shows the change of the damage degree from the amount of operating time for each type of a simple cycle.

![Figure 5. Scheme for calculating damage accumulation for a block of three simple cycles.](image-url)
Figure 6. The dependence of the width of hysteresis loop on the number of cycles to failure for 1 group and 3 test block.

This hypothesis allowed to predict the life of the first loading block, which consists of two test groups. Comparison of the obtained calculated values of the life with the values of experimental data gave good convergence. However, the hypothesis does not allow predicting cyclic life, where the block comprises cycles from three different test groups (blocks 2 and 3). So, the Marco-Starkey hypothesis cannot be used to calculate the damage accumulation in blocks with three test groups. According to the test results, one observes a significant increase of life in blocks 2 and 3 relative to the tests with 1 group with the same deformation range. Answering the question, what way an increase of life can occur, the analysis of the characteristics of the mechanical hysteresis loops is performed. Figure 6 compares the widths of the hysteresis loops for 1 test group (blue color) and 3 blocks (red color) with the same deformation range.

Comparing three blocks, in each of which there is a group with a maximum deformation range, one observes that the width of the hysteresis loop in 1 block is larger than in other blocks, but the life is minimal.

Figure 7. The dependence of the width of hysteresis loop on the number of cycles to failure at different loading cycles: 1 block (green), 2 block (red) and 3 block (blue).

Because the initial cycling in blocks 2 and 3 is carried out in groups with a smaller deformation range, a significant cyclic hardening of the material occurs (Figure 7). As a result, one can conclude that a different sequence of cycles in block causes different values of cyclic life.
4. Conclusions
According to the results of carried out tests for low-cycle fatigue with cycle constants and variables, the prediction of cyclic life was performed on the basis of the nonlinear hypothesis of the damage accumulation by Marco-Starkey. As a result, it was found that this hypothesis cannot be used to calculate the damage accumulation in blocks that comprise three test groups. The analysis of mechanical hysteresis loops was carried out to estimate the causes of the life increase during tests with a large number of groups in blocks. The work demonstrates that a different sequence of cycles in a block results in different values of cyclic life.

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