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The military purpose two-circuit turbo-jet engine with an afterburner turbine working blades thermocycle durability experimental research methodology

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Abstract. The relevance of this article is due to the fact that it is extremely important to maintain the technical condition of the military aircraft engine fleet to ensure a high level of reliability and flight safety. This, in turn, requires experimental studies of the thermal cyclic durability of working blades, which limit the service life of an aircraft engine. The purpose of the study is to justify the further development of the experimental research methodology of the working blades` of turbojet two-circuit engines with an afterburner combustion chamber thermocycle durability, which have exhausted their resource, to assess their residual strength. The main research methods are methods of analysis and synthesis, deduction and induction, as well as methods of experimental research. Ten samples of the working blades of the RD-33 aircraft engine were chosen as the object of the experimental study. The experimental research was carried out on a special installation that allows samples` testing for stretching and creep in an air environment under isothermal and thermocycling conditions. To study the residual resource of working blades samples, the experimental research method was used, that involves the three stages (preparatory, main, final) of implementation. The further development of the methodology consists in a new working blades samples preparing procedure, thermocycling modes and mechanical loads for testing samples parameters determining, establishing the duration of their exposure at the maximum temperature, expanding modern tools for analytical results processing of the experimental studies. When conducting an experimental study, the parameters of the test modes were determined in such a way that it was possible to investigate the influence of the main load factors on the residual durability of the material, namely: the mechanical stresses magnitude; maximum and minimum temperature of the sample in the cycle; heating and cooling time; sample exposure time at the maximum temperature. Based on the analysis of the obtained experimental data, a conclusion was made concerning the significant dependence of the durability of the working blade samples on the level of temperatures, stresses and exposure time at the maximum temperature value in the cycle. The main results of the article are the proof of the working blades` resource potential according to the residual creep deformation and durability criteria, that creates grounds for forecasting and justified extension of the established resource during the military aircraft engines` operation according to the technical condition. The proposed further development of the experimental research methodology on the thermocycle durability of the turbojet two-circuit engines with an afterburner combustion chamber working blades meets the requirements of the Aviation Rules in terms of airworthiness standards for aircraft engines in relation to the aircraft engines resource`s management strategy. The materials of the article may be useful for developers, manufacturers and operators of power plants, as well as scientists and researchers in the field of aircraft engine construction.

Keywords: aircraft engine, thermocycle durability, damage, working blade, experiment.

Introduction

The engine park technical condition maintenance and a high level of their reliability and flights safety ensuring is based on the experimentally obtained performances of the thermocycle durability of the turbines working blades` heat-resistant alloys, those limit the aircraft engine`s life. In this context, it is relevant to carry out complex studies of the thermal and stress-strain states of the working blades (WB) material, that allow to determine the main factors that affect the damage mechanism.

Materials and Methods

The domestic scientific school, founded by Pisarenko G.S., Karpinos B.S., Serensen S.V., Tretyachenko H.M. has made a significant contribution to the basic provisions` development of the strength reliability of aircraft engines` materials and structural elements, including thermocycle creep and long-term strength of the material of the aviation gas turbine`s working blades after working the issue out. Thus, the works (Serensen, Dulnev, Bychkov, 1961; Pisarenko, 1980; Tretyachenko, Karpinos, 1990) provide the durability of operating under extreme conditions structural elements studies analysis. In work (Karpinos, 2022), the residual creep during the thermal cycle and the durability of the WB material of a high-pressure turbine are determined by tests. The work (Kulyk, Kucher, Koveshnikov, Dubrovskyi, Petruk, 2009) proposes a studying method for the asymmetry of the thermomechanical load cycle influence on the heat-resistant materials durability during thermocycle tests. The work (Pityak, Bilyavin, Mahotkin, Rovkov, 2005) presents the experiment`s methodology and results for deformation detecting and tension in structural elements under the influence of temperature gradients.

Approaches to experimental and calculation methods for assessing damage accumulation in aircraft engine parts are being investigated by foreign scientists. In particular, S.S. Manson (Manson S.) (Manson, 1974) calculated the low-cycle durability of the blade, the final service life according to the law of linear interaction of creep and fatigue. S. Majumdar (Majumdar S.) (Majumdar, 1975) investigated the creep of the turbine`s WB, the dependence between creep and fatigue for the durability calculation, proposed a low-cycle fatigue and creep failures predicting method. A thorough analysis of the phenomenon of creep and its calculation models for various components of aircraft engines is given in the Lin Yuan`s work (Lin Yuan, Wang Chenglong, Sun Yongchao, Sun Mingbo, Yuan Yu, Gao Zhan & Xiao Yiwen, 2023).

However, the previously researched problematic issues of the thermocycle durability evaluating the of WB material of the turbojet two-circuit engines with an afterburner combustion chamber (TJTCEACC) of military use, require further development of the scientific and methodological apparatus for the experimental studies conducting.

In accordance with the abovementioned, the purpose of the article is to substantiate the further experimental research methodology development of the TJTCEACC`s WB thermocycle durability, that have exhausted their resource, to assess their residual strength and present the results of its implementation.

The turbine`s WBs work at different engine operating modes, under the influence of high temperatures and in a wide range of power loads, while the damage accumulation in them occurs according to the mechanisms of both thermal fatigue and creep.

The WB`s destruction mechanism in operation is activated due to the nucleation of a fatigue crack, which increases its size under the action of acting stresses. The crack, acting as a stress concentrator, reduces the WB`s cross-sectional area, at a certain value of which it can no longer withstand the operating loads and is destroyed under the action of cyclic and static loads (Fig. 1).

The fatigue crack development and fracture zones at the alloy`s grain boundaries are observed on the destroyed WB. Of course, the destruction processes develop over time and, first of all, depend on the dominant influencing factors (temperature, load and time of their action).

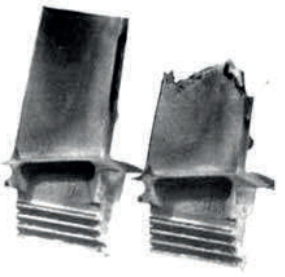


Figure 1. Destruction of the WB (Karpinos, Samuleev, Lyashenko, Lais'ke, Rutkovs'kyi, 2013)

Methods of the WB samples experimental research. The organization and conduct of experimental research requires the experiments planning based on the principles of a minimally sufficient number of factors to ensure the maximum possible impact on their result detection. To study the residual resource of WB samples, a method of experimental research is proposed (Fig. 2), which involves the implementation of three stages: preparatory, main, and final.

PREPARATORY STAGE: The experimental equipment preparation (E 1.1), test samples (E 1.2), determination of their test modes (Fig. 2), namely the required temperature and stress levels based on the results of modeling the thermal stress-strain state of WB turbines (E 1.3).

MAIN STAGE: The sample is heated to the specified temperature with the help of the special installation, using the method of high-temperature tests (E.2.1). Exposure of the sample at the specified (maximum) temperature during the specified time (E.2.2).

Then, the sample is cooled to the specified (minimum) temperature, and it is held on the sample for the specified time (according to the program) (E.2.3). The process of thermocycle loading according to the test program is repeated until the technical shutdown of the experimental installation for its maintenance.

Performing technical maintenance (replacing the graphite rod, quartz glass, seals, washing mirrors in the heating and cooling chambers, checking the functionality of the installation on a technological sample, etc.) (E.2.4). Continuation of tests of samples for thermocycle creep until sample failure.

FINAL STAGE: Analytical processing of the experimental studies results (E.3.1), those involves the calculation of the values of: operational factors damage accumulated from the "High Temperature Mode" (HTM); plasticity and strength of the WB material residual resource for unsteady and accelerated stages; steady stage (half-cycles of heating and cooling), as well as to obtain a regression full curve.

In contrast to existing methods, it is proposed to improve the quality of WB samples tests by introducing determining procedures for test modes and the duration of exposure setting, as well as the analytical processing of the results of experimental studies improving.

Thus, the determination of WB samples test modes (E 1.3) is performed with the help of mathematical models, those are meaningfully considered in the article [6]. Tensile stresses in the WB sample should have values that occur in the real WB under the action of centrifugal forces, namely, σ=(100...126) MPa. The temperature of the WB sample must correspond to the calculated maximum temperature of the WB in the elevated temperature mode (ETM) T=9650C and the cyclic temperature change T=9650C↔5000C over time. The time of heating and cooling of the blade in transient modes of operation of the engine corresponds to the values t=180 sec, t=90 sec.

The introduction procedure for establishing the duration of WB samples exposure at the maximum temperature (E.2.2) is necessary to identify the impact of exposure time at different forms of cycles, that will indicate the degree of thermal fatigue and change in durability.

The results of the analytical processing experimental studies (E.3.1) involves expanding the use of modern data processing tools.

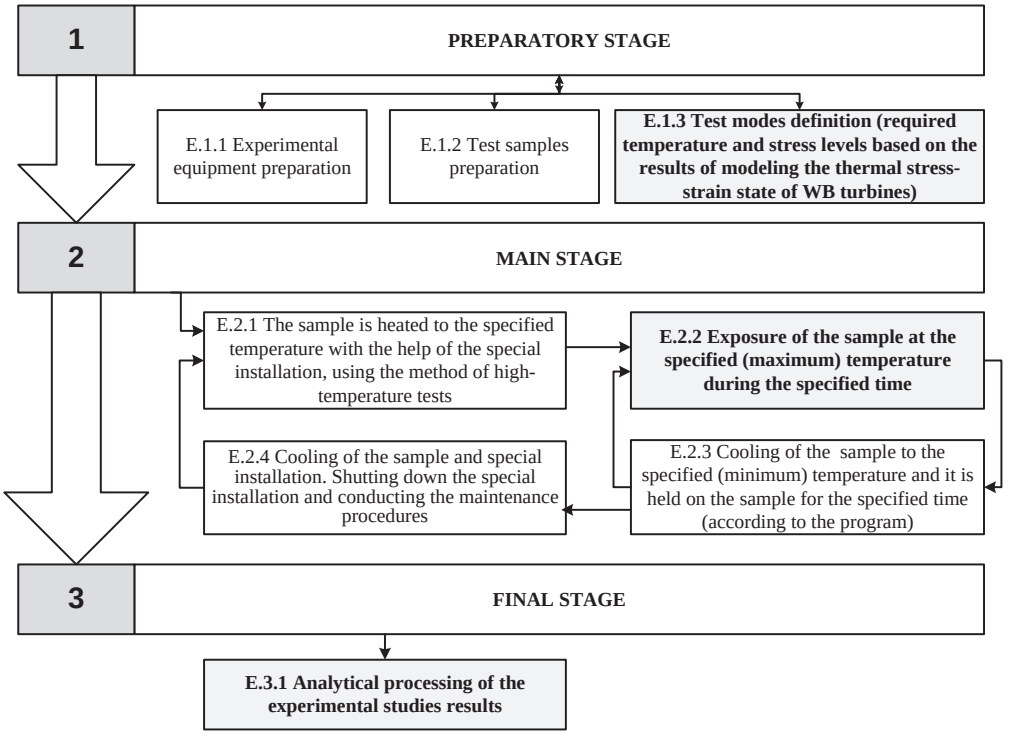


Figure 2. The experimental research methodology of WB samples for thermocycle durability block diagram

Results

The purpose of the experimental study is to assess the residual strength of the WB of the high-pressure gas turbine TJTCEACC RD-33 based on the study of changes in the mechanical properties/behavior of the material under external thermomechanical loading.

10 samples from the WB of the high-pressure gas turbine of the RD-33 engine were chosen as the object of the experimental study.

The experimental research was carried out at the special installation "Luskunchyk" of the Institute of Strength Problems named after H.S. Pisarenko of the National Academy of Sciences of Ukraine, which allows you to study samples for stretching and creep in an air environment under isothermal and thermocycle regimes.

When conducting an experimental study according to the proposed methodology, the parameters of the test modes were determined in such a way that it was possible to investigate the influence of the main load factors on the residual durability of the material, namely: the magnitude

of mechanical stresses; maximum and minimum temperature of the sample in the cycle; heating and cooling time; sample exposure time at the maximum temperature.

In accordance with this, a classic plan of a multifactorial experiment was adopted (Table 1).

Table 1. The plan of the multivariate experiment by modes

Regime	Test temperature, Tmax	Average holding time, τvytr.sr	Load, σ	Deformation, ε	Time to destruction of the sample τruyn.	Number of cycles, N cycle
Mode 1	const	180 p	var	var	var	var
Mode 2	const	3 hours	const	var	var	var
Mode 3	const	90 p	const	var	var	var

Each mode of the multifactorial experiment has its own character of test cycles of WB samples for durability (Fig. 3).

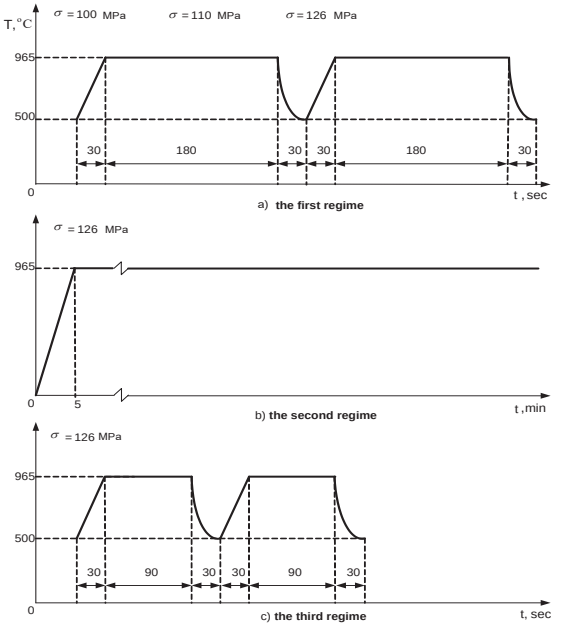


Figure 3. Modes of WB samples testing for durability

When conducting an experimental study, it was supposed to test the following hypotheses regarding confirmation/refutation:

Hypothesis 1: the existence of a linear dependence of the thermocycle damage of the WB turbine on stress and the number of cycles;

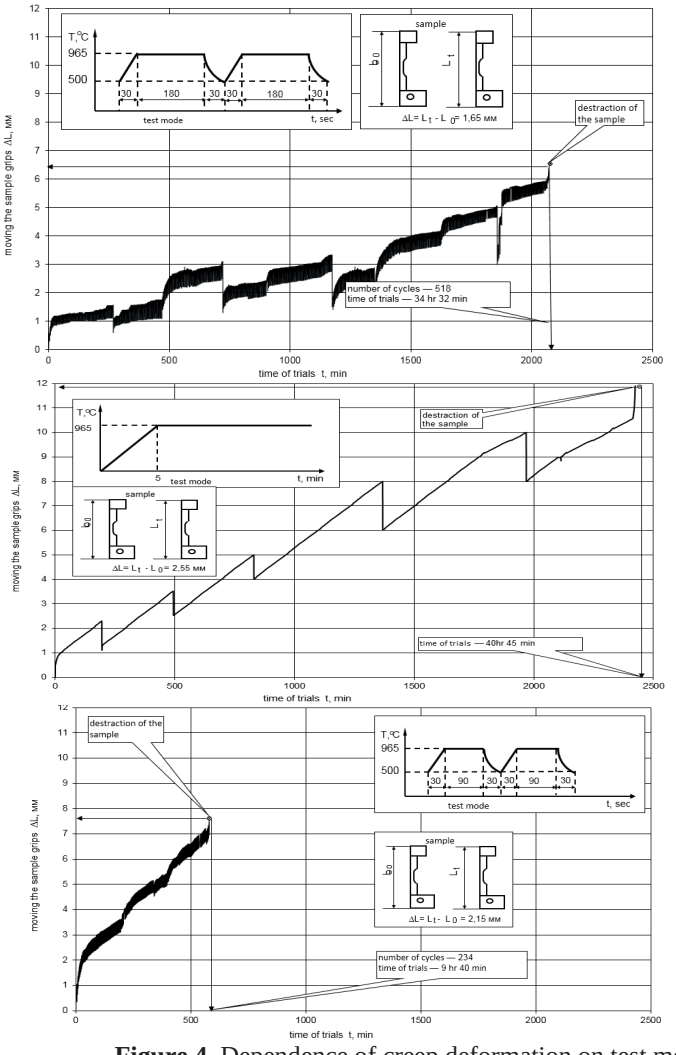
Hypothesis 2: the influence of the form of the cycle and the exposure time at the maximum temperature regime on the time and number of cycles to destruction.

Hypothesis 3: the decrease in long-term strength is associated with the exhaustion of the WB resource at the stage of engine operation.

Hypothesis 4: presence of dependence of creep deformation on cyclic temperature changes.

Hypothesis 5: there is a margin of safety in the WB for further operation of the engine.

The specified hypotheses verification is carried out during tests of WB samples for the purpose of characterizing the material behavior under the loads action under conditions of high temperatures with the special experimental equipment application. According to the experiment results, the dependences of the deformation of the sample were obtained (Fig. 4).



a) the first regime

b) the second regime

c) the third regime

Figure 4. Dependence of creep deformation on test modes

It was established that the creep curves for all test regimes have three stages: unstable creep, stable creep and intense avalanche deformation. The main part of the deformation accumulated in the stable stage. Unsettled and established stages took place after a test break. The results of experimental studies according to test modes are shown in Fig. 5.

To evaluate the residual strength, the deformation index of the WB material (half cycles and full) is used:

$$\varepsilon_n = a + bt - ct^2 + dt^3, \quad (1)$$

where ε_n – complete deformation.

t – time

Based on statistical processing of the experimental data, the kinetic equations for the complete curve of the WB sample were obtained, according to

the first mode is sample WB No. 1:

$$\varepsilon_n = 0{,}738 + 1{,}2 \cdot 10^{-3} t - 3 \cdot 10^{-6} t^2 + 1{,}1 \cdot 10^{-9} t^3, R^2 = 0{,}935 \quad (2)$$

the second mode, sample WB No. 3:

$$\varepsilon_n = 2{,}26 + 3{,}7 \cdot 10^{-3} t - 3{,}9 \cdot 10^{-6} t^2 + 3{,}5 \cdot 10^{-9} t^3, R^2 = 0{,}962 \quad (3)$$

the third mode is sample WB No. 8:

$$\varepsilon_n = 1{,}11 + 2{,}6 \cdot 10^{-3} t - 3{,}8 \cdot 10^{-6} t^2 + 2{,}3 \cdot 10^{-9} t^3, R^2 = 0{,}962 \quad (4)$$

Adequacy of the proposed dependencies was confirmed with reliability $R^2 \geq 0{,}93$. The results of the experiments were within the constructed 95% confidence intervals. The spread of the values of the limit characteristics of the materials is insignificant and amounts to an average of 5%.

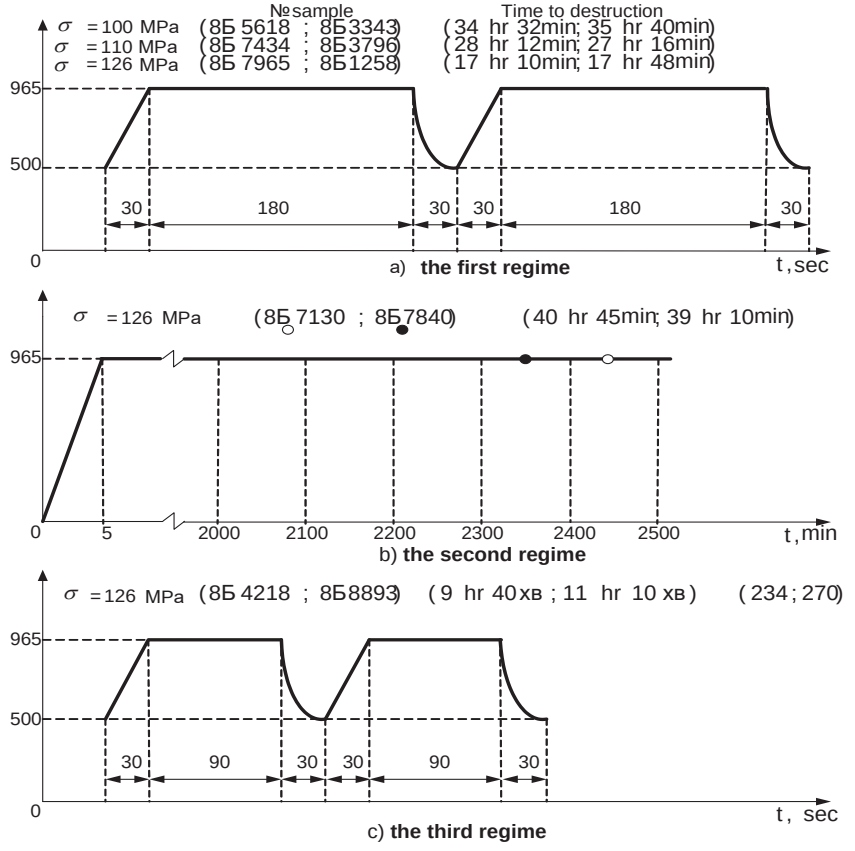


Figure 5. Results of experimental studies by test modes

Therefore, the form of the test cycle, the amount of stress, the value of the maximum temperature significantly affect the time and number of cycles to failure:

an increase in the stress level in the cycle, under other equal conditions of the experiment, leads to a decrease in durability by almost two times, while the ultimate deformation does not change significantly (hypotheses 1-4 are confirmed for regime 1);

at a constant maximum temperature, the maximum number of cycles and time to failure is ensured (according to mode 2, hypotheses 2 and 3 are confirmed);

reducing the length of exposure time in the cycle at the maximum temperature sharply reduces the durability (according to mode 3, hypotheses 3-5 are confirmed).

Discussions

The conducted experimental study has been performed for one of the six resource-limiting modes of operation of a military aircraft engine, namely, the mode of elevated temperatures, which has a significant impact on the level of the residual resource of the engine. Conducting further research under other regimes with a potential reserve of residual resource from 20% to 90% raises the issue of developing a scientific and methodological apparatus for mutual calculation of resource indicators. It is quite possible to adopt a single resource indicator taking into account the damage of resource-limiting parts of the engine, when the resource will be presented in two dimensions: static and thermocycle. Calculating damage for all resource-limiting elements would make it possible to set individual resources to engine modules and, if their replacement in military units is provided, to operate the engines practically without removing them from service. However, the transition to a new resource indicator is debatable and requires additional resource tests of aircraft engines with simulation of resource-limiting modes of operation in flight conditions on the stand.

Conclusion

Thus, the method of experimental research on the thermocycle durability of the WB of the high-pressure TJTCEACC`s turbine received further development, the feature of that, unlike the existing ones, is the thermocycle regimes and mechanical loads parameters determination, taking into account the duration of WB samples exposure at the maximum temperature, expanding the toolkit of the results` analytical processing, which allows to evaluate the thermocycle creep, long-term strength of the material and the residual resource of the WB turbine samples.

The residual creep deformation and durability of the WB calculation proved the resource potential existence, based on the margin of safety and creates grounds for forecasting and a reasonable extension of the established resource when operating the engines according to the technical condition.

The further development of the methodology for experimental research on the thermocycle durability of the TJTCEACC high-pressure turbine WB meets the requirements of the Aviation Rules in terms of airworthiness standards for aircraft engines regarding the resource management strategy of aircraft engines, namely the establishment and increase of the designated resource of the main engine parts based on the use of experimentally substantiated calculation methods and databases given curves of low-cycle fatigue and operation of the engine without mandatory removal for repair before reaching the designated resource of any of the main parts (Aviation regulations, 2004).

The materials of the article may be useful for developers, manufacturers and power plants operators, as well as scientists and researchers in the field of aircraft engine construction.

Recommendations

The proposed method for experimental research of the turbine`s WB thermocycle durability was tested on the RD-33 engine of the MiG-29 aircraft and can be recommended for other types of TJTCEACC of fighter aircraft. Such a technique may serve as a basis for the technique of resource management improving for the military aircraft engines fleet, that will allow to carry out a

comprehensive analysis of TJTCEACC operational parameters, the technical condition monitoring and residual resource control for managing the aircraft engines life cycle.\

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