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Gulnara Pukhalska — PhD, Associate Professor, Associate Professor of the Department of Machinery Engineering Technology, National University Zaporizhzhia Polytechnic, Zaporizhzhia, Ukraine, *e-mail: puhalska66@gmail.com*, ORCID 0000-0001-8118-4179

Sergey Subbotin — Dr. Sc., Professor, Head of the Department of Software Tools, National University Zaporizhzhia Polytechnic, Zaporizhzhia, Ukraine, *e-mail: subbotin@zp.edu.ua*, ORCID 0000-0001-5814-8268

Serhii Leoshchenko — PhD, Associate Professor, Associate Professor of the Department of Software Tools, National University Zaporizhzhia Polytechnic, Zaporizhzhia, Ukraine, *e-mail: sergleo.zntu@gmail.com*, ORCID 0000-0001-5099-5518

Dmytro Bezkhlibnyi — Post-graduate student of the Department of Mechanical Engineering Technology, National University Zaporizhzhia Polytechnic, Zaporizhzhia, Ukraine, *e-mail: dmitriym713@gmail.com*, ORCID 0009-0002-3403-4615

RESEARCH ON THE INFLUENCE OF BALL TREATMENT IN THE MAGNETIC FIELD OF THE BLADES WITH OPERATIONAL DAMAGES ON FATIGUE STRENGTH

Purpose. *Research the effect of ball treatment in a magnetic field on the blade tips, which have varying degrees of blade tip damage in operation, on their endurance limit.*

Research methods. *Mechanical method for studying residual stresses, experimental method for determining blade endurance, stepwise regression methods for building regression models.*

Results. *On engine blades that operated under different conditions and had different service life, the greatest wear was observed in the peripheral part of the blade (cross sections A7-A7 and A8-A8). Processing blades from various engines with operational damage with balls in a magnetic field significantly increases the resistance of the blades to fatigue, the endurance limit of the blades increases from 14 to 22 %. Regression models of natural oscillation frequencies and blade life were constructed. The obtained regression models showed that the greatest influence on the natural oscillation frequency of blades is not only the operating conditions and blade geometry, but also the amount of life, the hardness of the initial blade and the ultimate strength of the blades. Operation of helicopter engines in conditions of increased dustiness and abrasive wear requires the application of protective coatings with high erosion resistance to the upper section of the blade back. Additional application of surface hardening methods provides increased reliability, fatigue strength and extended service life of the gas turbine engine.*

Scientific novelty. *A method has been proposed that allows for effective processing of blade back with damage that occurred during operation, which ensures an increase in their durability and reliability. As a result, endurance indicators increase and the service life of parts is extended.*

Practical value *. The obtained experimental data provide grounds to recommend the method of treating blade tips with steel balls in a magnetic field as a technological operation for repairing compressor blades that have undergone operational damage such as potholes on the leading edges.*

Key words: *blade, erosion, damage, balls, magnetic field, endurance, performance, regression model.*

Introduction

The extension of the service life of aircraft gas turbine engines is largely determined by the durability and operational reliability of the compressor and fan blades. A significant factor in this process is the reduction of their vulnerability to damage that occurs when foreign objects enter the flow part. One of the most effective ways to increase the strength characteristics of the blade profile is the technology of surface plastic deformation (SPD). This method is a complex of mechanical effects on the surface of the part, which result in a decrease in roughness parameters, the formation of a layer with useful residual compressive stresses, leveling the metal structure and creating the necessary microrelief. The cumulative effect of these changes is a significant increase in the fatigue strength of the material and an increase in the service life of the part.

During the operation of aircraft gas turbine engines, one of the most vulnerable elements remains thin-walled parts, especially areas with small radii of curvature, which include thin edges of blades. Under the influence of aerodynamic loads, vibrations and ingress of foreign particles into the flow, microcracks, foci of plastic

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deformation and local overheating zones are formed on the surface and in the subsurface layers of the metal. These factors, acting together, initiate subsurface fractures, which cause a noticeable decrease in the endurance limit of the part.

To prevent such defects in the practice of repair and modernization, surface plastic deformation (SPD) is widely used. However, for thin-walled elements with high sensitivity to overloads, it is necessary to use gentle processing modes with precise adjustment of parameters in each functional zone of the part. In some cases, it is advisable to combine different hardening technologies, which allows achieving the specified characteristics of roughness, residual stresses and material structure [1]. Special attention is paid to strengthening blades made of titanium alloys. The geometry of the blade back, which includes complex spatial curvature and the presence of thin edges, requires not only precise positioning of the cutting tool, but also an understanding of the distribution of mechanical stresses on the surface. Any excess of the permissible pressure during the PPD can lead to local deformation or the appearance of surface defects, which reduce the resource details.

A promising direction is the treatment of compressor blades with operational damage with steel balls in a magnetic field. This method is based on the phenomenon of magnetic retention and controlled movement of the strengthening element, which allows evenly distributing the dynamic impact of the complex surface of the blade. When steel balls come into contact with metal, local plastic crushing of micro-roughness occurs, the micro-relief is leveled, the surface layers are compacted and compressive residual stresses are formed. These stresses prevent the opening of microcracks under cyclic loads, which ultimately increases the fatigue life and improves the operational reliability of the blades. Thus, the use of the SPD method using steel balls in a magnetic field not only ensures the restoration of the operational characteristics of damaged elements, but also allows creating a surface structure that is more resistant to the effects of high-frequency vibrations, thermal fluctuations and shock loads. This makes the technology especially relevant for extending the service life of aircraft gas turbine engine blades.

Analysis of research and publications

When operating military helicopters and transport aircraft in conditions of soil and sandy runways, the intense air flow formed during takeoff and landing captures a significant amount of solid mineral particles. These particles, having high hardness and mass, when colliding with compressor blades and other elements of the flow part of the engine, cause local microplastic deformations, microcracks and tearing of material from the surface layer. The gradual accumulation of such damage changes the aerodynamic profile of the blades, reduces the efficiency of the compressor and can lead to a violation of the strength of the integrity of the structure, which as a result negatively affects the reliability of the engine [2]. The work [3] presents the results of an experimental study of erosive wear of compressor blades in a gas-solid environment that simulates operation in an aero-turbine engine. To perform the experiments, a stand was developed and manufactured that allowed testing of the titanium alloy Ti-6Al-4V at various speeds of abrasive particles. The particle speeds were determined by the image velocimetry method, which provided high accuracy of measurements when varying the supplied air pressure. Analysis of worn samples showed that erosion damage is distributed extremely unevenly. The main destruction zones were on the pressure surface of the rotor blade and on the suction and pressure sides of the stator blades. The maximum wear intensity was observed in two characteristic areas: near the leading edge at 80 of the span and near the leading and trailing edges at 95 of the span. Such localization is explained by the features of the flow around the blade profile: at 80 of the span, the flow has the highest particle velocity relative to the blade surface, which increases the impact energy, and in the region of 95 % of the span, turbulent zones and changed angles of attack of particles appear, which cause their direct impact. A schematic distribution of the zones of maximum wear can be conditionally presented as two belts of increased erosion activity: the first is located along the leading edge in the middle part of the span; the second covers the leading and trailing edges closer to the periphery. Such a distribution must be taken into account when designing and choosing methods for protecting blades from erosion [3].

Operation of aircraft gas turbine engines in conditions of high dust content and the presence of abrasive particles in the atmosphere poses a serious threat to the durability of the compressor blades. Studies show that the intensity of erosive wear directly depends on the concentration of solid inclusions in the air flow: the more sand or dust, the faster microplastic deformations, the formation of notches and local destruction of the material occur. In this case, the blade profile gradually changes, its aerodynamic characteristics deteriorate and the efficiency of the compressor decreases. As a result, the real life between overhauls of the engine operating in high dust conditions is significantly less than the standard one established by the designer, and is largely determined by the degree of erosive damage. Analysis of statistical data on the operation of gas turbine units confirms the critical importance of this phenomenon. About a third of cases of premature engine retirement (30–35 %) are associated with erosive destruction of compressor blades. For comparison, damage caused by external objects from the runway is recorded in 25–30 % of cases. Thus, erosive wear is one of the leading causes of reduced engine reliability and service life. The mechanisms of erosive damage include particle impact, surface shear, and local crushing of the surface layer of metal. These processes cause the formation of microcracks and the loss of part of the material, which is especially critical for thin-walled blades with high requirements for the accuracy of the aerodynamic profile. Understanding the physical processes underlying erosion

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allows not only to predict a reduction in service life, but also to develop protective measures: use more resistant alloys, optimize blade design, introduce coatings, and adjust engine operating modes in conditions of increased dustiness.

The working blades of the compressor of aircraft engines are subject to erosive and mechanical effects of solid particles entering with the air flow, especially in conditions of increased dustiness of the atmosphere [4]. The size, shape and concentration of abrasive inclusions determine the intensity of destructive processes on the blade surface. The main dangers for further operation are associated with fretting corrosion in the tail part of the blade and erosive wear of the blade. These defects cause local microplastic deformations, the formation of micronotches and gradual thinning of the material, which reduces the reliability of the engine and increases the risk of surge. The physical mechanisms of erosive destruction include impact and shear effects of particles on the surface layer of the metal, which leads to local stress concentration and the formation of microcracks. At the same time, fretting corrosion initiates chemical destruction of the material in places of friction, enhancing the erosive effect. Together, these processes change the aerodynamic profile of the blade, impair its load-bearing capacity, and affect the distribution of mechanical loads along the length of the blade. Studies show that wear is distributed along the height of the blade nonlinearly: the highest intensity of damage is recorded at the base of the blade and on the leading and trailing edges, while the peripheral ends remain less susceptible to erosion. Potholes in critical zones have a much stronger effect on engine operation than similar defects in external areas, as they disrupt the balance and aerodynamics of the rotor, increasing local stresses. To maintain operational safety, an industry standard [5] is used, which regulates the permissible dimensions, shape and location of mechanical damage. The standard defines the zones in which defects are unacceptable, as well as the types of damage that require repair or replacement of parts. This allows you to systematize maintenance, prevent emergencies and extend the engine life.

A particular problem is caused by damage from external objects, which lead to accelerated wear of the blades, the need to overhaul and balance the rotor, as well as replace a large number of elements. A comprehensive approach to the study of erosion and mechanical processes, which includes the analysis of load distribution, microstructural changes and chemical action, allows developing methods for protecting the blades, optimizing alloys and structures, and adjusting operating modes to increase the service life and improve the reliability of aircraft gas turbine engines.

The rotor blades of the compressor of the TV3-117 helicopter engine are key loaded elements, on as well as simultaneously acting static, dynamic and cyclic loads. To ensure the necessary strength, heat resistance and resistance to thermomechanical influences, they are made of high-strength titanium alloys capable of withstanding intensive working loads and temperatures, not inferior to other light structural materials. During operation, helicopter engines often encounter increased dustiness, characteristic of ground airfields, desert areas and unequipped sites. In such conditions, the working blades of the compressor are subjected to the abrasive effect of solid particles of soil and sand. When in contact with the surface of the blades, the particles create microdamage: scratches, risks and potholes. The nature and intensity of these damages depend on the size and mineralogical composition of the particles, their angle of attack and collision speed. Microscopic impacts of particles cause local plastic deformations and accumulation of microcracks, which gradually reduces the strength and aerodynamic efficiency of the blades [6].

The peripheral zones of the blade back are particularly vulnerable, especially at the leading and trailing edges, where the concentration of shock loads is maximal. Analysis of operational data has shown that the blades of the first stage of the compressor suffer the greatest amount of damage. The depth of potholes in the range of 0,3-0,5 mm occurs on the first stage approximately four times more often than on the following stages, which is associated with the high relative velocity of particles in the zone of first contact of the flow with the blade, as well as with the geometric features of the first stage profile , which enhance local stresses on the material [7]. Thus, the first stage of the compressor is critically vulnerable to abrasive wear, which requires special attention when developing protective coatings, selecting materials and planning preventive repairs. Understanding the physics of the interaction of particles with the blade surface allows us to predict the nature of damage and increase the durability of the power plant in operating conditions on dusty and sandy airfields.

Ensuring the durability and reliability of compressor blades is impossible without effective methods of restoration after operational damage. One of the promising technological solutions is surface plastic deformation with steel balls in a magnetic field, which modifies the structural state of the blade and improves its mechanical properties.

Purpose of work

This study is aimed at analyzing the possibilities of using magnetic field ball processing for the repair and restoration of compressor blades after operational damage.

The work investigates the geometry and natural frequencies of engine blades operated under different conditions, with different service life and different degrees of blade damage. Fatigue tests were conducted on blades with damage in the state of receipt from operation and blades treated with balls in a magnetic field. A comparative analysis of the stress state and fatigue strength of blades after repair and treated with balls in a magnetic field was conducted. Regression models were also constructed that describe the dependence of the natural oscillation frequencies and the operating life of

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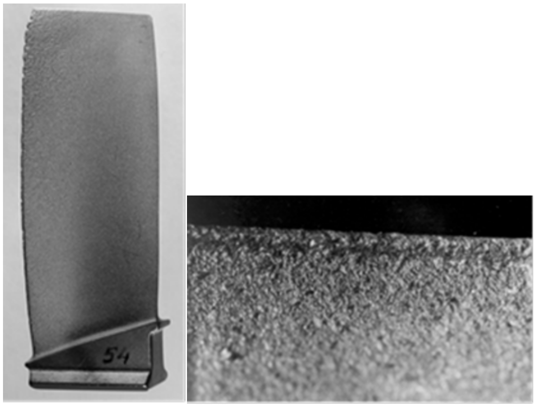
blades from engines that were in operation in different countries and, accordingly, the physical characteristics of the operational processes differ, which serves as the basis for the further development of methods for repairing and restoring compressor blades.

Research material and methodology

The object of research was the first-stage compressor blades of the TV3-117 engine, made of titanium alloys VT8 and VT8M, which have operational damage to the blade. Residual stresses were determined by mechanical method on PION-2 device - by measuring the deflection of a cantilevered specimen cut from the blade by the electroerosion method with sequential removal of metal layers by electrolytic polishing. The study of the blade profile geometry was carried out using the POMKL device. Measurements of the natural frequencies of the blades were carried out on the MIKAT-KM device. Measurements of the blade geometry were carried out with a caliper with a digital display with an accuracy of 0,01 mm. Determination of the blade endurance limits was carried out by an accelerated method on the basis of $N=2 \cdot 10^7$ cycles with subsequent recalculation using the coefficient $\alpha=0{,}8$ on the basis of $N=10^8$ cycles [8]. Stepwise regression methods were used to build regression models.

Research results

Operational damage to the blade not only forms stress concentrators, but also changes the original geometry of the blades [9–12]. The study was conducted on engine blades that were operated in different conditions, have different operating hours and, accordingly, different degrees of damage to the blade tip: engine D2 – 990 hours – (VT8, Yemen), and three engines that have damage to the tip during operation (potholes with a depth of 0,5 mm and more), which exceed the permissible standards, as a result of which the blades cannot be restored using repair technology: engine D18 – 975 hours (VT8M, Spain), engine D14 – 2048 hours - (VT8M, Algeria), engine D3 – 1652 hours (VT8M, India). The nature of damage to the blade tip is shown in Fig. 1.



a *b*

Figure 1. First-stage blade of the TV3-117 turbine with erosion damage to the blade (*a*) and leading edge (*b*)

The study of the geometry of the blades of the engines D3, D14, D18 consisted in measuring the chord in sections A2-A2 and A8-A8, i.e. in sections that clearly characterize the degree of blade wear. The measurement results are presented in Table 1. The results of measuring the natural oscillation frequencies of the blades of the engines D3, D14 and D18 correspond to the technical requirements of the drawing.

For further research, 12 blades were selected from each engine. Each batch of blades was processed according to the optimal option with steel balls in a magnetic field. The optimal scheme and processing mode were determined in previous studies [13]: the blade - $d_k = 1{,}6$ mm, $\tau = 30$ min and then additionally the zone near the inlet edge - $d_k = 0{,}35$ mm, $\tau = 30$ min.

Table 1 – Results of engine blade geometry measurements (chord, mm)

No. i /o	D18		D3		D14	
	A2-A2	A8-A8	A2-A2	A8-A8	A2-A2	A8-A8
1	26.67	28.09	26.70	28.20	26.72	27.90
2	26.72	28.12	26.55	28.22	26.85	28.02
3	27.03	27.93	26.73	28.10	26.75	27.89
4	26.56	28.03	26.75	28.09	26.7	27.92
5	27.05	28.00	26.59	28.12	26.83	28.01
6	26.82	27.92	26.56	28.22	26.87	27.91
7	27.05	28.13	26.60	28.13	26.90	27.99
8	26.55	28.10	26.53	28.00	26.73	27.94
9	26.53	26.11	26.83	28.20	26.77	27.95
10	26.98	28.03	26.30	28.28	26.79	27.87
11	27.10	27.80	26.70	28.39	26.69	27.92
12	26.53	27.85	26.72	28.40	26.58	27.95
13	26.77	28.10	26.74	28.20	26.72	28.01
14	26.80	28.00	27.05	28.12	26.67	28.00
15	26.74	27.92	27.70	28.00	26.64	27.87
16	26.81	27.80	26.36	28.01	26.69	27.80
17	26.90	28.89	26.39	28.05	26.72	28.05
18	27.59	28.23	26.50	28.07	26.77	27.79
19	26.56	27.98	26.59	28.15	26.59	27.83
20	26.92	28.15	26.42	28.22	26.70	27.93
21	26.52	28.15	26.50	28.13	26.65	27.89
22	26.83	28.10	26.73	28.21	26.80	28.03
23	26.75	28.12	26.50	28.05	26.73	27.85
24	26.66	28.19	26.65	28.17	26.69	27.89
25	26.81	28.21	26.40	28.15	26.73	27.95
26	26.52	28.03	26.72	28.03	26.65	27.83
27	26.73	28.09	26.49	28.12	26.71	27.83
28	26.90	27.90	26.60	28.10	26.77	28.00
29	26.77	27.95	26.43	28.00	26.67	27.98
30	26.53	28.05	26.70	28.03	26.80	27.89
31	26.91	28.07	26.68	28.07	26.64	28.00
32	26.68	28.09	26.81	28.17	26.69	27.97
33	26.72	28.10	26.90	28.20	26.72	27.95
34	26.83	28.08	26.73	28.17	26.67	27.92
35	26.74	28.13	26.51	28.16	26.70	28.00
36	26.55	28.10	26.45	28.11	26.72	28.01

Analysis of the data presented in Table 1 shows that the wear of the blades in the A8-A8 section is very significant compared to the theoretical profile of the blades, i.e. serial ones – the chord size $l_{A8\text{-}A8}$ is 28,5 mm.

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In the A2-A2 section, the wear is smaller (the theoretical chord size l_{A2-A2} is 26,5 mm). Thus, we can say: on the blades of engines that operated in different conditions and have different operating times, the greatest wear is observed in the peripheral part of the blade.

Fatigue tests were conducted on blades with damage in the condition of receipt from operation and blades treated with balls in a magnetic field. Endurance limit of the original blades (in operation): D3 - 448 MPa; D14 – 424 MPa; D18 – 400 MPa. The results of fatigue tests of blades treated with balls in a magnetic field under the optimal regime are presented in Table 2–4.

Table 2 – Results of fatigue tests of blades strengthened according to the optimal option (D3 engine)

No. i /o	Load level σ, MPa	Number of cycles, N ×10 ⁶	Test results	Note
1	670	20	not destr.	-
2	700	20	not destr.	-
3	730	11.87	destroyed	*l* =26 mm, en. edge
4	700	18.6	destroyed	*l* = 34 mm, en. edge
5	700	10.99	destroyed	*l* = 30 mm, en. edge
6	670	1.46	destroyed	*l* = 42 mm, en. edge
7	640	20.0	not destr.	-
8	640	20.0	not destr.	-
9	640	20.0	not destr.	-
10	640	20.0	not destr.	-
11	640	20.0	not destr.	-
12	640	20.0	not destr.	-

According to the methodology, the endurance limit based on 10^8 cycles will be 640x0,8 = 512 MPa.

Table 3 – Results of fatigue tests of blades strengthened according to the optimal option (D18 type)

No. i /o	Load level σ, MPa	Keelnumber of cycles, N ×10 ⁶	Test results	Note
1	700	1.26	destroyed	*l* = 25 mm, en. edge
2	670	20.0	not destr.	-
3	670	6.73	destroyed	*l* = 22 mm, en. edge
4	640	20.0	not destr.	-
5	640	4.99	destroyed	*l* = 22 mm, en. edge
6	610	20.0	not destr.	-
7	610	20.0	not destr.	-
8	610	20.0	not destr.	-
9	610	20.0	not destr.	-
10	610	20.0	not destr.	-
11	610	20.0	not destr.	-

According to the methodology, the endurance limit based on 10^8 cycles will be 610x0,8 = 488 MPa.

Table 4 – Results of fatigue tests of blades strengthened according to the optimal option (D14 type)

No. i /o	Load level σ, MPa	Keelnumber of cycles, N ×10 ⁶	Test results	Note
1	700	20.0	not destr.	-
2	730	14.98	destroyed	*l* = 30 mm, en. edge
3	700	20.0	not destr.	-
4	700	20.0	not destr.	-
5	700	15.26	destroyed	*l* = 26 mm, en. edge
6	670	0.37	destroyed	*l* = 24 mm, en. edge
7	640	20.0	not destr.	-
8	640	20.0	not destr.	-
9	640	20.0	not destr.	-
10	640	20.0	not destr.	-
11	640	20.0	not destr.	-
12	640	20.0	not destr.	-

According to the methodology, the endurance limit based on 10^8 cycles will be 640×0,8 = 512 MPa.

The results of fatigue tests showed that the blade endurance limit increased from 14 to 22 %. That is, the treatment of blades from various engines with operational damage with balls in a magnetic field significantly increases the blades' fatigue resistance.

For further research, blades from the D2 engine were selected for processing using the repair technology. The repair technology involves: cleaning and polishing of damage on the surfaces of the blade profile from the back and trough sides; polishing of the inlet and outlet edges of the blade profile; vibropolishing; checking the natural oscillation frequencies; luminescent control. Blades with damage on the inlet and outlet edges, the cleaning of which will lead to a reduction in the chord size to the size $l_{min\ A2-A2}$=25,64 mm and $l_{min\ A8-A8}$ =27,76 mm, are allowed for repair. The natural oscillation frequencies of the blades before and after repair were measured. The results of measuring the natural frequencies of the blades are in the range of 590-650 Hz, i.e., they meet the technical requirements of the drawing.

Also, residual stress measurements were carried out on 3 blades, both original and after repair. The residual stress plots, constructed using the average values, are presented in Fig. 2

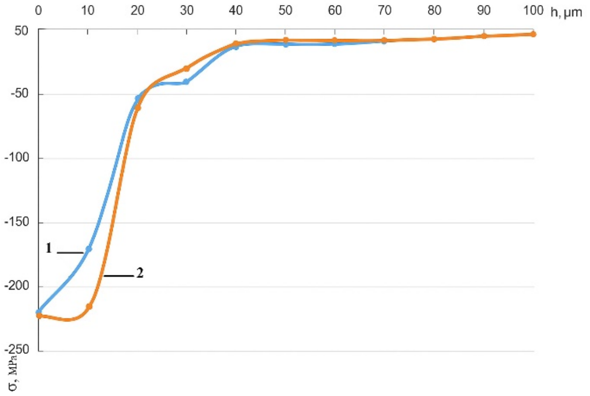

Figure 2. Residual stress distribution diagrams of the original blades (1) and after repair (2)

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The figure shows that the repair technology does not lead to a change in the stress state. For comparison, a study of the stress state of the blade feather (engine D14) after treatment with balls in a magnetic field was conducted (Fig. 3).

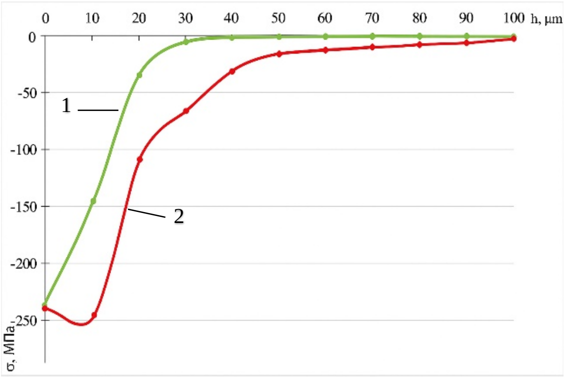

Figure 3. Residual stress distribution diagrams of the original blades (1) and those treated with balls in a magnetic field (2)

The figure shows that after ball processing we have a more favorable stress distribution diagram – on the surface, compressive stress up to 240 MPa and a greater depth of occurrence than in the original blades, which should lead to increased fatigue resistance.

The geometry of the blade profile in sections A2-A2, A8-A8 and the thicknesses of the leading and trailing edges of the output blades were also measured after repair (Table 5, 6).

Table 5 – Results of measurement of the geometry of the output blades (engine D2)

No. i /o	Chord original size , mm		C1 , original size, mm		C2 , original size, mm	
	A2-A2	A8-A8	A2-A2	A8-A8	A2-A2	A8-A8
1	26.44	27.85	1.3	0.5	0.60	0.21
2	26.65	27.72	1.31	0.5	0.58	0.22
3	26.66	28.03	1.31	0.57	0.62	0.23
4	26.97	27.88	1.31	0.58	0.62	0.21
5	26.58	27.90	1.12	0.47	0.60	0.20
6	26.83	27.94	1.27	0.55	0.61	0.23
7	26.65	27.60	1.3	0.50	0.60	0.22
8	26.54	28.15	1.29	0.47	0.62	0.24
9	26.59	28.14	1.39	0.52	0.68	0.23
10	26.53	27.58	1.2	0.56	0.59	0.21
11	26.71	28.43	1.41	0.50	0.61	0.22
12	26.88	28.11	1.23	0.60	0.59	0.21
13	26.71	27.99	1.4	0.50	0.61	0.21
14	26.70	28.17	1.34	0.48	0.62	0.22
15	26.55	27.95	1.41	0.55	0.61	0.22
16	26.40	28.08	1.42	0.56	0.60	0.21
17	26.60	28.02	1.45	0.49	0.59	0.20
19	26.39	27.65	1.52	0.58	0.60	0.22
20	26.63	28.00	1.2	0.57	0.59	0.21

Table 6 – Results of blade geometry measurements after repair (engine D2)

No. i /o	Chord after renovation, mm		C1 , after renovation, mm		C2 , after renovation, mm	
	A2-A2	A8-A8	A2-A2	A8-A8	A2-A2	A8-A8
1	26.38	27.69	1.3	0.49	0.60	0.25
2	26.47	27.57	1.35	0.50	0.60	0.24
3	26.60	27.84	1.3	0.55	0.62	0.22
4	26.92	27.55	1.3	0.52	0.63	0.24
5	26.60	27.68	1.12	0.47	0.60	0.22
6	26.74	27.76	1.27	0.55	0.62	0.25
7	26.48	27.47	1.3	0.50	0.62	0.25
8	26.60	27.96	1.29	0.45	0.63	0.25
9	26.49	27.90	1.35	0.50	0.62	0.22
10	26.56	27.39	1.22	0.55	0.59	0.23
11	26.70	28.15	1.41	0.50	0.60	0.25
12	26.72	27.86	1.25	0.47	0.61	0.23
13	26.61	27.81	1.41	0.53	0.62	0.21
14	26.64	27.86	1.35	0.48	0.63	0.22
15	26.51	27.92	1.42	0.57	0.60	0.23
16	26.32	27.85	1.44	0.55	0.65	0.22
17	26.63	27.82	1.47	0.47	0.60	0.21
19	26.30	27.57	1.53	0.57	0.61	0.23
20	26.60	27.95	1.22	0.59	0.58	0.19

According to the results of measuring the geometry of the blades before and after repair, it can be said that the dimensions do not change significantly. Fatigue tests of the blades in the state of receipt from operation (initial) and after repair (D2) were also carried out. The ultimate strength of the initial blades is 360 MPa. The test results are presented in Table 7.

Table 7 – Results of blade fatigue tests after repair

No. i /o	Load level σ, MPa	Number of cycles, N ×10 ^{6}	Test results	Note
1	510	20	not destr.	-
2	540	14,13	destroyed	*l* = 20 mm, en. edge
3	510	20,0	not destr.	-
4	510	20,0	not destr.	-
5	510	16,79	destroyed	*l* = 35 mm, en. edge
6	480	20,0	not destr.	-
7	480	20,0	not destr.	-
8	480	20,0	not destr.	-
9	480	20,0	not destr.	-
10	480	20,0	not destr.	-
11	480	20,0	not destr.	-

According to the method, the endurance limit based on 10^8 cycles will be 480×0,8 = 384 MPa. We see that the endurance limit after repair increased insignificantly, by 6 %. While after treatment with balls in a magnetic field up to 22 %.

In this work, regression models of natural oscillation frequencies and blade life were also built. The blades of the first stage of the compressor of the TV3-117 engine,

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made of titanium alloy VT8 and VT8M, which have operational damage to the blade feather, were selected as the object of research. The studies of observed engines that were in operation in different countries, respectively, the physical characteristics of the operational processes differed. The blades had different operating hours and, accordingly, different degrees of damage to the blade feather. The engines were operated in the following countries: Yemen, India, UAE, Peru, Cyprus, Algeria, Spain. Operational damage to the feather creates not only stress concentrators, but also leads to a change in the geometry of the blades. Initially, a selection of informatively significant features was carried out (for this, stepwise regression methods were used). Feature selection allows you to discard uninformative features that complicate the model, reduce its interpretability, and sometimes introduce erroneous (noisy) data that reduce the accuracy of the model. After that, using the selected feature groups, regression models were built. Linear regression models were chosen as regression models. Since feature selection was previously performed, the models were built much faster and are relatively simple.

The study of the blade geometry consisted of measuring the chord in sections A2-A2 and A8-A8. x_1 is the average temperature in the region where the operational process took place; x_2 and x_3 are the chord values in sections A2-A2 and A8-A8; x_4 is the total operating time, hours; x_5 is the operating time before the first repair, hours; x_6 is the hardness of the original blade, HRC; x_7 is the yield strength of the original material, MPa; x_8 is the tensile strength, MPa; y is the frequency of natural oscillations of the blades, Hz.

Linear regression model for the full data set ($x_1 – x_8$)

$$y = – 0.2800 x_1 – 0.0791 x_2 – 0.0812 x_3 + 0.5604 x_4 – 0.1232 x_5 – 0.2217 x_6 – 0.3890 x_8$$

Model accuracy: 0,0003.

The obtained regression model shows that the greatest influence on the frequency of natural oscillations of the blades is not only the operating conditions and blade geometry, but also the amount of service life, the hardness of the original blade, and the ultimate strength of the blades.

Second-order linear regression model with a first-order component:

$$y = 0.8079 + 0.2148 x_1 – 0.2214 x_3 + 0.0310 x_4 + 0.3649 x_8 – 0.3694 x_1 :x_3 + 0.0352 x_3 :x_4 – 0.1712 x_3 :x_5 – 0.4127 x_3 :x_8 – 0.9691 x_4 :x_8 – 0.5155 x_1^2 + 0.0123 x_3^2 + 0.2760 x_4^2 .$$

Model accuracy: 0,00065.

The regression model shows that the natural frequency is affected by a significant relationship between wear and operating conditions, wear and service life, and wear and ultimate strength.

Thus, in the operating conditions of helicopter engines, the use of erosion-resistant coatings in the upper part of the blade blade is of particular importance. This solution reduces the intensity of edge destruction under the influence of abrasive particles and, in combination with the strengthening treatment of the blade, ensures an increase in the engine's service life (Table 8).

Table 8 – Neural network model for the combination for the full data set (x_1 -x_8)

Layer number	Number of neuron in the layer	The input number of the neuron			
		0	1	2	3
1	1	3.6311	-4.6286	17.2227	-3.9438
	2	1.0208	0.4336	-11.2933	7.2829
	3	4.8576	3.1807	-50.3267	28.6725
	4	1.2853	-4.7502	-11.1495	1.7869
	5	0.9485	5.0594	10.1262	-2.3578
	6	-0.1418	0.0050	-5.1386	-5.0073
	7	-0.3975	0.7221	-6.3940	-4.0722
	8	-1.2545	0.0242	-5.7687	-4.2826
2	1	-4.6557	-3.7127	-13.5488	0.5368

Conclusions

A study was conducted of the geometry and natural frequencies of the compressor blade blades made of titanium alloy VT8M, which were operated under various conditions. and have damage to the blade that exceeds the permissible standards and does not allow the blades to be restored using repair technology.

Fatigue tests were conducted on the blades in service and after treatment with steel balls in a magnetic field in the optimal mode . The results of the fatigue tests showed that the endurance limit of the blades increased from 14 to 22 %.

The blades were restored using repair technology, the geometry of the blade profile was measured in sections A2-A2, A8-A8 and the thicknesses of the leading and trailing edges of the output blades and after repair, and the stress state and natural frequencies of the blades were studied.

Fatigue testing of the original blades was conducted and after repair, the endurance limit increased by 6 %.

Regression models of natural oscillation frequencies and blade life were constructed. The obtained regression models show that the greatest influence on the natural oscillation frequency of blades is not only the operating conditions and blade geometry, but also the amount of life, the hardness of the original blade, and the ultimate strength of the blades.

6. Based on the obtained results of experimental research, the feasibility of introducing the method of ball treatment in a magnetic field of the blade feather as a technological operation in the process of repairing compressor blades, which allows significantly increasing fatigue resistance, is substantiated.

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ДОСЛІДЖЕННЯ ВПЛИВУ ОБРОБКИ КУЛЬКАМИ В МАГНІТНОМУ ПОЛІ ПЕРА ЛОПАТОК З ЕКСПЛУАТАЦІЙНИМИ ПОШКОДЖЕННЯМИ НА ВТОМНУ МІЦНІСТЬ

Гюльнара Пухальська — канд. техн. наук, доцент кафедри технологія машинобудування Національного університету «Запорізька політехніка», м. Запоріжжя, Україна, *e-mail: puhalska66@gmail.com,* ORCID: 0000-0001-8118-4179

Сергій Субботін — д-р техн. наук, професор, завідувач кафедри програмних засобів Національного університету «Запорізька політехніка», м. Запоріжжя, Україна, *e-mail: subbotin@zp.edu.ua,* ORCID: 0000-0001- 5814-8268

Сергій Леощенко — канд. техн. наук, доцент кафедри програмних засобів Національного університету «Запорізька політехніка», м. Запоріжжя, Україна, *e-mail: sergleo.zntu@gmail.com,* ORCID: 0000-0001-5099-5518

Дмитро Безхлібний — аспірант кафедри технології машинобудування Національного університету «Запорізька політехніка», м. Запоріжжя, Україна, *e-mail: dmitriym713@gmail.com*, ORCID: 0009-0002-3403-4615

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Мета роботи. *Дослідження впливу обробки кульками в магнітному полі пера лопаток, які мають різний ступінь ушкодження пера лопаток в експлуатації, на їх границю витривалості.*

Методи дослідження. *Механічний метод для дослідження залишкових напруг, експериментальний метод для визначення витривалості лопаток, методи покрокової регресії для побудови регресійних моделей.*

Отримані результати. *На лопатках двигунів, які працювали в різних умовах та мають різне напрацювання, найбільший знос спостерігається у периферійній частині пера (перетини А7-А7 і А8-А8). Обробка лопаток з різних двигунів, що мають експлуатаційні ушкодження, кульками в магнітному полі суттєво підвищує опір лопаток втомі, границя витривалості лопаток збільшується від 14 до 22 %. Побудовані регресійні моделі частот власних коливань і напрацювання лопаток. Отримані регресійні моделі показали, що найбільший вплив на частоту власних коливань лопаток мають не тільки умови експлуатації та геометрія лопатки, а також величина напрацювання, твердість вихідної лопатки та границя міцності лопаток. Експлуатація гелікоптерних двигунів в умовах підвищеної запиленості та абразивного зношування вимагає нанесення на верхню ділянку пера лопатки захисних покриттів з високою ерозійною стійкістю. Додаткове застосування методів поверхневого зміцнення забезпечує підвищення надійності, втомної міцності та подовження ресурсу роботи газотурбінного двигуна.*

Наукова новизна. *Запропоновано метод, який дозволяє ефективно обробляти перо лопатки із пошкодженнями, що виникли під час роботи, що забезпечує зростання їх довговічності та надійності. В результаті підвищуються показники витривалості та подовжується термін служби деталей.*

Практична цінність*. Отримані експериментальні дані дають підстави рекомендувати метод обробки пера лопаток сталевими кульками в магнітному полі як технологічну операцію для ремонту компресорних лопаток, що зазнали експлуатаційних ушкоджень типу вибоїн на вхідних кромках.*

Ключові слова: *лопатка, ерозія, ушкодження, кульки, магнітне поле, витривалість, напрацювання, регресійна модель.*

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