ANALYSIS OF SOME PHYSICAL AND TECHNICAL CHARACTERISTICS OF ION-PLASMA COATING (TiZr)N ON ROTOR BLADES OF COMPRESSOR OF GAS-TURBINE ENGINE TV3-117

K.A. KORSUNOV and **E.A. ASHIKHMINA**
V. Dal East Ukrainian National University
20 Molodyozhny Bl., 91034, Lugansk, Ukraine. E-mail: uni@snu.edu.ua

Considered are the results of carried out tests on evaluation of wear resistance of rotor blades of compressor of helicopter engine TV3-117 with ion-plasma coating (TiZr)N, formerly used only in the tool manufacturing. The tests on compressor blades were carried out under the conditions close to the conditions of operation of helicopter engine during take-off conditions. The results of coating test on resistance to corrosion in air-sea atmosphere correspond in average to nine points according to the ten-point scale. The assumption was made that rate of erosion of coating depends on its microhardness and air temperature in compressor unit of the engine. To describe and analyze these dependencies the mathematic method of leveling (method of the least squares) was applied. Quadratic function describes most precisely the practical results. The calculation quadratic curve of the second order correlates well with the experimental curve reflecting the dependence of rate of erosion on microhardness. The obtained working model provides possibility of carrying out the further calculations of service life of blades in different temperature ranges, i.e. evaluation of reliability of aircraft industry objects. 14 Ref., 4 Tables, 3 Figures.

Keywords: *ion-plasma coating (TiZr)N, rate of erosion, microhardness, blade of compressor rotor, increase in life of engine TV3-117, method of analytic leveling, dispersion analysis*

Blades of the compressor rotor of helicopter engine TV3-117 are the most loaded parts subjected to the effect of static, dynamic and cyclic loads, therefore, they are manufactured of titanium alloys not inferior by their heat, corrosion and erosion resistance to other light alloys.

However during service of the helicopter Mi-24 (conditions of sand soils) especially under the conditions of helicopter hover over the ground surface, the abrasive water-air environment of high pressure (more than 4 atm) is created in the air path of unit of engine compressor. The absorbed dust particles of different size and geometric shape under the air pressure are collided against the surface of airfoil of rotor blade of compressor, creating a local microshock and, as a result, causing microcracks, spallings, scores, furrows, tears and other defects. In connection with that the strong erosion wear of blades occurs and power of engine can drop by 23–25 %. The level and character of erosion wear depend on disperse composition and amount of dust absorbed to the engine [1, 2]. For the further operation of helicopter engine the following blades defects are dangerous: fretting-corrosion on the tail part (Figure 1, *a*) and erosion wear along the airfoil (Figure 1, *b*), which result in gradual fracture of material, i.e. reduction of reliability of machinery and arising of danger of engine surge.

Also, using titanium alloys in the design of compressor of engine the risk of «titanium fires» arises. The presence of friction in the excited air flow (the temperature is above 300 °C) results in rapid inflammation of titanium, as a result of which all structural materials, including heat-resistant alloys in engine, are burnt out [1, 3].

In connection with the abovementioned, to improve the resistance to chemical and mechanical effects to the blades of compressor rotor manufactured of the alloys based on titanium, the following types of protection are applied:

• purification of fuel and air from the impurities;

• installing of dust protective equipment to the inlet device of the engine;

• development of new alloys with high technical and service characteristics;

• deposition of protective coatings.

The last item is the most challenging, as it does not result in growing cost of fuel, does not require creation of cumbersome designs and application of expensive materials. Deposition of protective coatings on the blades is possible using different methods. According to the values of corrosion resistance φ (severity point) and erosion resistance D (severity point) the vacuum ion-plasma coatings are more preferable (Table 1).

Table 1. Protective coatings for the parts of aircraft engines and tools [4–6]

No of coating	Coating	Method of deposition	Material of coating	Part/material	Service characteristics: T, °C; φ and D, point	Thickness, μm
1	Nickel-cadmium	Electrochemical (galvanic bath)	Ni, Cd	Blade/15Kh12N2MVFAB-Sh, 13Kh11N2V2MF	350; 2; 1	12–20
2	Vacuum ion-plasma	Ion-plasma condensation («Bulat», «Pusk», MAP-1)	TiN, ZrN, TiN–TiAlN	Blade/VT-20, VT3-1, 14Kh17N2, VK8, VT-6S	250–400; 1–2; 2–3	0.05–12
			TiC–TiCN–TiN, TiN–TiAlN, TiAlN–TiAlSiN, TiFeN–TiFeSiN, TiC, TiN–TiMoN, TiCN–TiZrN–TiN, TiN–TiZrN–TiN, TiN–TiZrN, ZrC	Cutting tool/U8, R6M5, R9K9, T15K6, U10, U13	250–400; 2; 4	
			TiC, ZrC	Aircraft unit/SAP-2, VT3-1	250–400; 2; 3	
3	Cermet	Detonation	VP-AFTs, N-VP-AFTs1 with nickel sublayer, WC–C(VK-15)	Blade/alloyed steel	400–450; 3; 1	80–100

Note. Disadvantages of coatings: No.1 — hydrogenation of material, low operation characteristics and manufacturability; No.2 — expensive equipment, low efficiency; No.3 — large sizes of parts, non-uniformity of coatings, low erosion resistance.

The aim of this work is investigation and analysis of physical and technical characteristics of ion-plasma multifunctional coating of the type (TiZr)N formerly applied only for the tool and offered for protection of titanium alloy VT-8 compressor blades of helicopter engine TV3-117.

The spraying was made on the whole surface of the blade, i.e. on the airfoil and lock part in two layers (thickness 5.0–5.5 μm) using the machine «Bulat-6». The parameters of modes of deposition of coatings are presented in Table 2. The first layer of the coating was formed by successive bombardment of blade surface by ions of titanium and zirconium in the rarefied medium of nitrogen. In the process of deposition of the first layer the cleaning of the surface and its strengthening with the compounds ZrN and TiN, partially diffused to the surface of the base, take place. The second layer of the coating has a more complicated composition including strengthening phases based on the refractory compounds ZrN, TiN, (TiZr)N, which delay the process of fracture of blade base material caused by chemical and mechanical effect of environment during engine operation. The composition of the cathode coating is, vol.%: 20 Zr; 80 Ti.

Table 2. Modes of deposition of ion-plasma coating of the (TiZr)N type

Stage of spraying	Current of accelerated ion flow I_f, V	Voltage of accelerated ion flow U_f, V	Current of arc of evaporator I_c, A	Voltage of discharge U_c, kV
Ion etching (pressure of nitrogen 10^{-1} Pa)	3	250	90	1.8
Spraying of coating (pressure of nitrogen $2\cdot10^{-1}$ Pa)	4	190	110	1.5

The data of investigations on the corrosion resistance, changes of rate of erosion and microhardness, are given in Table 3. The corrosion resistance of coting was determined by the effect of fine-sprayed sea water (sea fog) on the blade airfoil at its heating to 300, 400, 500 and 600 °C. During test of the coating (TiZr)N the growth of salt precipitates in the form of white spots occupying up to 2 % of total area of the blade was observed. No oxide-like corrosion damages were detected from the side of shank or blade airfoil. The absence of temper colors on the blade with coating evidences that the coating (TiZr)N at the effect of chemically active environment is sufficiently resistant to thermocyclic loads. The evaluation of salt-like corrosion damages according to the 10-point scale corresponds to 6–7 points, whereas oxide-like ones — to 10 points at the test temperatures mentioned above. According to the calculations the application of ion-plasma coating (TiZr)N allows increasing the corrosion resistance of blade shank by 4–5 times.

Microhardness of coating (TiZr)N on the rotor blade of compressor and base material of blades was measured using the device PMT-3 at 50 g load during 7 s before deposition of coating, after deposition of coating and every three-hour annealing of blades at 300, 400, 500 and 600 °C both with coating as well as without it. The selection of time of annealing, equal to 3 h, was predetermined by the fact that control time of flight of the helicopter Mi-24, on which the engines TV3-117 are installed, takes in full ammunition (including take-off and landing) not less than 2 h. The temperature of air in the compressor unit of engine TV3-117 is 300–400 °C. The increase of operating temperature to 450 °C in the area of the 12th stage of the compressor is possible. The blades of compressor rotor mounted to the engine in the process of capital repairs undergo the procedure of strengthening (vibro-polishing in fragmentized particles of ball-grinding discs (the size of particle is 5–10 mm)), therefore microhardness (VT-8 alloy) of such blades is much higher than those of alloy without strengthening and approximates to the values of microhardness of the same alloy but strengthened using method of screw extrusion (4.10–4.28 GPa for the temperature of 700 °C) [7]. The measurement of microhardness after thermal tests of blades both with coating as well as without it showed a tendency towards decrease of microhardness at increase of annealing temperature (see Table 3).

For comparison, let us give the following results of investigations given works [8–10] for similar coating TiN: microhardness of 21.2–27.4 GPa, rate of erosion of 19–28 mg/min.

The erosion resistance of coating (TiZr)N was determined according to the following procedure. Before and after the test a blade mass was determined by weighing at the accuracy of up to 0.001 g. The stand tests were carried out using fused alumina sand of 100–300 μm dispersion (14A F60), used for bombardment of blades surface under the pressure of 0.30–0.35 MPa. Under the conditions of the helicopter flight in the regions of sand soils, the dispersion of particles of absorbed sand was about 200 μm and more, the pressure of air in the area of the 12th stage of the compressor of helicopter engine TV3-117 reaches 0.4 MPa (maximum pressure). The testing of blades was carried out without coating and with coating (TiZr)N, before and after the annealing at the specified temperatures (see Table 3). The rate of erosion was calculated according to the formula [11]

$$v_{er} = \frac{m_0 - m_1}{t} \text{ (mg/min)},$$

where m_0, m_1 is the mass of blade before and after the test, respectively; t is the time of test.

It is seen from Table 3 that the rate of erosion of blade both without coating as well as with

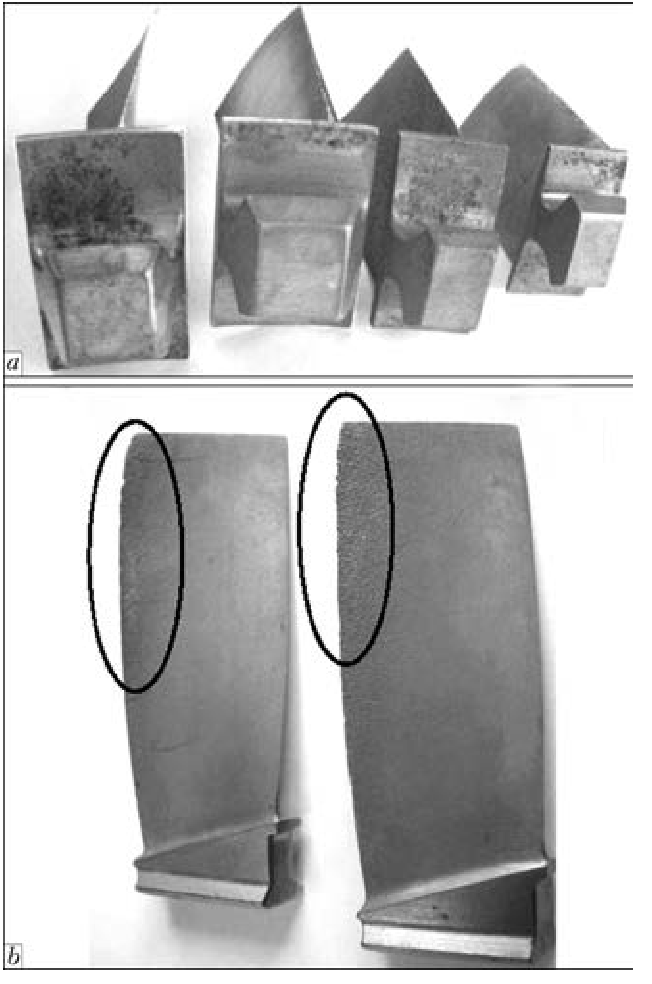

Figure 1. Service defects of rotor blades of compressor of engine TV3-117: *a* — fretting-corrosion on the locks of blades; *b* — erosion wear on the outer edge

coating depends on microhardness of material of the blade or coating, and the latter in its turn depends on temperature in the compressor unit during its operation.

In accordance with the obtained test results the rate of erosion of blade with the coating (TiZr)N in the range of operating temperatures to 300 °C is 3.5–5 times decreased as compared to the blade without coating, which is evidently seen from the plot (Figure 2). Here, the microhardness of coating is negligibly decreased .

In the range of working temperatures of 300–400 °C the rate of erosion of blade with coating is differed from the values of rate of erosion of blade without coating practically by the same

Table 3. Physical and technical characteristics of compressor rotor blades with coating (TiZr)N (numerator) and without coating (denominator) (base — alloy VT-8)

Characteristic	Temperature of annealing, °C				
	Without heating	300	400	500	600
Microhardness, GPa	34/6	32/5.5	25/4.5	24/3.2	5/3
Rate of erosion v_{er}, mg/min	11/38	12/61	26/63	29/168	36/347
Mean value of corrosion resistance φ, point (max 10)	9/9	9/8	9/7	8/7	8/7

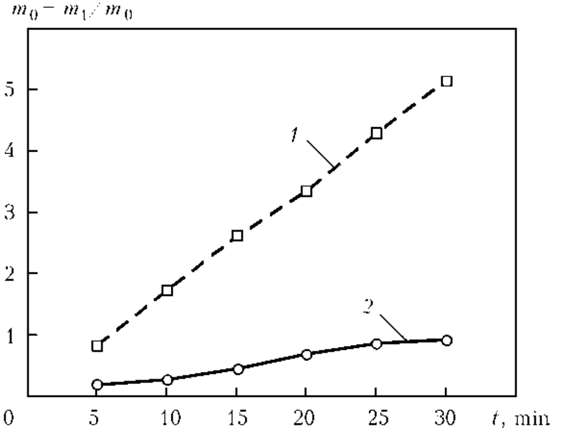

Figure 2. Loss of mass of blade at the effect of erosion environment: *1* — without coating; *2* — with coating (TiZr)N

value as at the working temperatures up to 300 °C. In its turn it proves the assumption that at such temperatures the structure of coating is sufficiently dense and also resistant to mechanical effects of dust particles getting to the running area of compressor, and the first layer performs the reinforcing functions. Microhardness of coating is decreased (see Table 3), however as is was mentioned above, it does not influence its protective properties.

At increase of operating temperatures to 500 °C the rate of erosion of the blade without coating, as compared to the blade with coating, is practically 6 times increased as far as tensile strength of titanium alloy VT-8, of which the rotor blade of compressor is manufactured, preserves high values up to 450 °C and drops abruptly at temperature increase. In this case, the coating (TiZr)N performs also heat protective functions, i.e. partially prevents heating of blade airfoil. In the range 400–500 °C microhardness of coating like that in the range of up to 300 °C is decreased negligibly, which in its turn facilitates the preserving of strength characteristics.

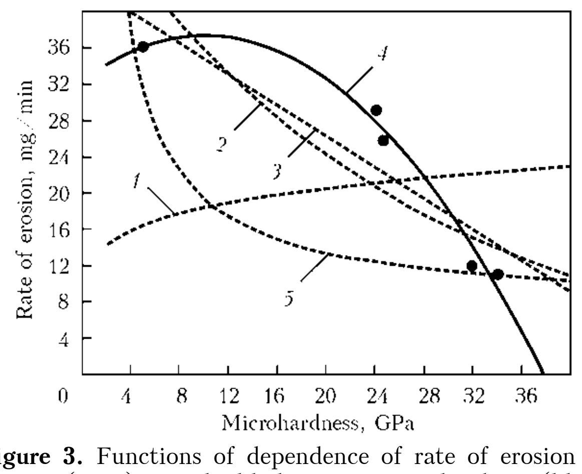

Figure 3. Functions of dependence of rate of erosion of coating (TiZr)N on the blades on its microhardness (black spots — experimental values of rate of erosion): *1* — power; *2* — exponential; *3* — linear; *4* — parabola of the second order; *5* — hyperbolic

The further increase of operating temperature to 600 °C results in heavy erosion wear of blade without coating, the difference of values of rate of erosion of a blade without coating from the blade with coating becomes even more significant. Blade with coating (TiZr)N, installed to the rotor of compressor of high temperatures, will have a resistance to erosion effect 6–10 times higher than the blade without coating. However microhardness of coating during operation of blade at the temperatures of more than 600 °C drops abruptly to the level of value of microhardness of material of the blade itself, i.e. titanium alloy VT-8, but meantime preserving the high erosion resistance to the effect of dust atmosphere in the compressor.

Basing on the stated data one can assume the correlation between the following physical and technical values of coating (TiZr)N: rate of erosion and microhardness, found at different temperatures.

The data of tests of compressor blades according to these values are presented in Figure 3. To confirm the assumed relation the mathematical description of experimental curve is given, which is reduced to determination of the formula of empiric equation using the method of the least squares (method of leveling).

Considering five main functions of dependencies, which are more frequently encountered in the description of experimental curves (Table 4) and, solving the systems of normal equations for them, we obtained the functional dependencies, which describe the field of experimental data with greater or lesser extent of accuracy. Comparing the values of sum of deviations S_1–S_5, one can assume that the experimental curve can be better described by quadratic function of the second order. The verification of equations of models for adequacy was performed using mean error of approximation $\bar{\varepsilon}$, the value of which (less than 12 %) shows that the model is adequate.

In particular, according to the data of Table 4, one can speak about the adequacy of the model only for the model described by the equation of parabola of the second order, where the mean error of approximation amounts to 5 %. The rest calculation models inadequately reflect the assumed dependence between the selected parameters, i.e. applying them, we obtain the values of rate of erosion with a great error.

Regarding the measurement of closeness of relation at curvilinear dependence, here not a linear coefficient of correlation is used, but correlation of η relation, the formula of which is universal at any type of dependence (see Table 4). The closeness of relation of selected signs was evaluated according to the scale of Cheddok: $0.1 < \eta < 0.3$: weak; $0.3 < \eta < 0.5$: moderate; $0.5 < \eta <$

Table 4. Functional dependencies and their analysis according to the experimental data of tests of coating (TiZr)N

Analytical values	Function (general view / calculation)				
	Power $y(x) = a_0x^{a_1}$ / $y(x) = 12.708x^{0.1587}$	Exponential $y(x) = a_0a_1^x$ / $y(x) = 53.3 \cdot 0.961^x$	Linear $y(x) = a_0 + a_1x$ / $y(x) = 43.4232 - 0.8593x$	Parabola of the second order $y(x) = a_0 + a_1x + a_2x^2$ / $y(x) = 32.3546 + 0.9871x - 0.0488x^2$	Hyperbolic $y(x) = a_0 + a_1 \frac{1}{x}$ $y(x) = 7.3 + \frac{12.6413}{x}$
S [12]	697.3	187.8	90.4	7.3	492.3
$\bar{\varepsilon}$ [13]	57	25	22	5	56
η [13, 14]	0.31	1.11	0.9	0.99	1.5
r_1 [13, 14]	Subroot expression <0	0.78	0.9	0.99	Subroot expression <0

< 0.7: noticeable; $0.7 < \eta < 0.9$: high; $0.9 < \eta < 1$: extremely high; $\eta > 1$: relation is absent.

In the power function the moderate relation between the signs is present, in the demonstrative function — the relation is absent, in linear — it is high, in the function of parabola of the second order — it is extremely high, in hyperbolic — it is absent. Consequently, the selected function of parabola of the second order reflects the strongest mutual influence of such technological values as rate of erosion and microhardness of coating.

The degree of approximation of calculation data to the real values of empirical series shows a coefficient of accuracy of leveling the curve r_1 (correlation index), which should be more than 0.95. The index of correlation (see Table 4) is maximum for the parabola of the second order ($r_1 = 0.99$) and more than 0.95, which proves the proper selection for description of relation of two physical and technical values, its adequacy and high precision of description of test results of the coating.

The calculation values (Table 4) show that dependence of rate of erosion on microhardness of coating can be very precisely described using parabola of the second order.

So, according to the abovementioned, using the blade with proposed two-layer coating (TiZr)N in the unit of compressor of aircraft engine one can avoid different operation defects which are often encountered. At the erosion effect on the blade the first layer operates as the reinforcing element preventing initiation of microcracks, spallings and burrs on the coating as a whole. And the second layer of coating due to density and high microhardness protects the blade from impact loads caused by abrasive particles and has an improved resistance to fretting-corrosion. Experimental data showed that even during operation at the elevated temperatures up to 600 °C the erosion resistance of the blade at the use of coating (TiZr)N almost 10 times increases. And the resistance of blade to the corrosion damages independently of the operation temperature 4–5 times increases as compared to the blade without coating.

The function (parabola of the second order) theoretically derived basing on the practical results determines the dependence of rate of erosion of two-layer coating (TiZr)N on its microhardness, reflects close correlation of selected parameters, extremely good correlates (index of correlation is 0.99) with experimental values, which, in turn, allows using the given model during manufacture of parts and units designed for the operation conditions similar to the above-described ones.

1. Maksimov, N.A., Sekistov, V.A. (1977) *Aircraft and helicopter engines. Principles of structure and flight operation*. Moscow: Voenizdat.
2. Boguslaev, V.A., Muravchenko, F.M., Zhemanyuk, P.D. et al. (2003) *Technological control of service characteristics of gas-turbine engine parts. Blades of compressor and ventilator*. Pt 1. Zaporozhie: Motor Sich.
3. Rzhavin, Yu.A. (1995) *Axial and centrifugal compressors of aircraft engines*. Moscow: MAI.
4. Dushkin, A.M., Proshchin, A.B. (1988) Protective coatings on steel blades of compressor. *Aviats. Promyshlennost*, **7**, 13–15.
5. Boldov, V.V., Kordit, E.A., Yakubovich, E.A. (1987) Examination of properties of vacuum-plasma coatings on titanium nitride base. *Ibid.*, **9**, 61–62.
6. Bogomolov, V.A., Larina, G.B., Polyanin, B.A. et al. (1988) Zirconium nitride wear-resistant coatings for light alloys. *Ibid.*, **3**, 51–53.
7. Kachan, A.Ya., Ovchinnikov, A.V., Pavlenko, D.V. et al. (2012) Technological peculiarities of manufacturing of GTE compressor blades from titanium alloys using screw extrusion. *Vestnik Dvigatelestroeniya*, **1**, 92–97.
8. Khvorostukhin, L.A., Nozhnitsky, Yu.A., Bolmanenkov, A.E. (1988) Investigation of erosion strength of ion-plasma coating of titanium nitride. *Aviats. Promyshlennost*, **6**, 59–61.
9. Boldov, V.V., Kordit, E.A., Yakubovich, E.A. (1987) Investigation of properties of vacuum-plasma coatings on titanium nitride base. *Ibid.*, **9**, 61–62.
10. Miloserdov, I.V., Paperny, V.L., Makarov, R.V. et al. (1989) Physical-mechanical characteristics of coatings produced by ion bombardment method. *Ibid.*, **12**, 39–40.
11. (1960) *Methodical guideline on analyses and tests of aircraft materials and parts*. Issue 960. Moscow: RDI on service and repair of aircraft engineering of air forces.
12. Linnik, Yu.V. (1958) *Least-squares method and principles of mathematical-statistical theory of processing of observations*. Moscow: Fizmatgiz.
13. Lisiev, V.P. (2006) *Theory of probability and mathematical statistics*. Moscow: MSU of statistics, economy and informatics.
14. Shanchenko, N.I. (2008) *Lectures on econometrics*. Ulianovsk: UGTI.

Received 27.03.2013