The Effect of a Dusty Environment Upon Performance and Operating Parameters of Aircraft Gas Turbine Engines

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ABSTRACT

In Poland, the risk of volcanic hazards is relatively low. The Polish Air Force uses the international system of Volcanic Ash Advisory via the national weather service. In the last decade, ash clouds reached Central Europe, which significantly reduced military aviation operations. Direct contact of combat aircraft with volcanic ash have yet not been documented in Poland.

However, our military aircraft have significant experience with operating in dusty environments e.g. from landing strips. Aircraft, pilots and technical staff have been trained to operate under such conditions for a long time, which was confirmed in the missions in Iraq and Afghanistan.

This paper analyzes the effect of the environment on the low-level operations of aircraft, in particular, in dusty conditions. Special attention has been paid to the characteristics of atmospheric dust, and to mineralogical composition and size analysis. The effect of the dust in terms of the erosive wear of components inside the aircraft gas-turbine engine and the resulting changes in the essential performance characteristics of the engine has been shown. The images included in the paper perfectly exemplify the nature and extent of the erosion-attributable degradation of engine components.

Operating gas turbine engines in dusty conditions e.g. from unpaved runways, adversely affects their operation, decreasing engine performance and, in some cases, jeopardizing flight safety. Some concepts have been indicated of how to improve the rules that govern the aircraft operation to decrease the risks coming from particulate FOD.

Keywords: erosive wear, turboshaft, gas-turbine engine, particulate FOD

1. INTRODUCTION

Helicopters, especially those in military use, most often perform flights at lower altitudes, and the specificity of tasks performed by them requires their performance from the hastily made, and thus not always adequately prepared for this purpose, landing areas. However, it can also relate to those for civil use, performing agricultural aviation services or being used by the fire brigade, border guard or air rescue, because they are sometimes forced to operate flights at the altitudes from a few to several metres and use unpaved runways.

Helicopter take-off and landing raises a large quantity of dust from the ground that is ingested to the engine intake, flows through the gas path, and causes accelerated erosive wear of the internal components, especially the compressor rotors. Thus, it significantly reduces their performance and results in premature removal from the airframe.

2. CHARACTERISTICS OF ATMOSPHERIC DUST

The atmospheric dust and air pollution have different sources. Nevertheless, it is possible to separate them out into two main areas: the natural source such as that produced by disturbing dust or volcanic ash from the ground; and the artificial one caused by operation of the following industrial centres in a given area: smelters, coke plants, coal-fired plants, cement factories, open cast mines of mineral resources, or chemical plants, as well as large urban agglomerations, because they just emit large quantities of pollutants to the atmosphere.

The primary component of the soil surface layer, regardless of its type, constitutes quartz – a compound characterised by high hardness, and thus possesses the ability to erosive wear of the gas path components of gas-turbine engines. In turn, that dust, which is ingested by helicopter engines, operating at low altitudes, may contain 45% to 95% of quartz in its total weight. As a result, the process of erosive wear of components and entire sub-assemblies of the aircraft gas-turbine engines may have a fundamental impact on their durability and reliability level. This is especially important when one realizes that silicon carbide grains are characterized by hardness equal to 7 in the 10-degree Mohs scale, and corundum being equal to 9. Therefore, the hardness of the grains exceeds the analogous indicators of the materials used to produce aircraft gas turbine engines [1].

However, the granulometric composition, which is a heterogeneity indicator of dust grains, largely depends on the ground type and structure [1].

Around the operating helicopter, dust containing grains of varying diameters ranging from 1 ÷ 5 μm up to 300 ÷ 500 μm floats, and in the area of engine inlets, grains of the dimensions reaching even to 60 μm can be found. But during its flight or hover over the sandy ground, the grains with the dimensions from 70 to 160 μm (in case of loess soils less or equal to 60 μm) can be found in the ingested stream. However, it does not happen that the grains ingested by the helicopter gas-turbine engines exceed the dimension of 500 μm.

But then, a feature of the polluted (dusty) atmosphere includes the concentration of dust (content of the particular dust mass in the air volume unit), the measure of which will constitute the dust mass, expressed in grams, contained in m3 of atmospheric air. Therefore, it is a variable size and mostly depends on: climatic conditions (seasons, geographical region, intensity of rainfall, wind direction and speed or an undergrowth type in a given area, etc.), soil structure, layout, type and condition of the surface of roads within the landing area, movement intensity of wheeled vehicles, etc. and the type of industrial plant, their number or position in relation to the landing area.

It also depends on daytime, due to the movement intensity of wheeled vehicles on roads, as well as take-offs and landings only of aircraft. It decreases quite intensively with the increase in altitude. Therefore, purposefulness of locating air inlets at the highest level of the airframe to its engines occurred. It is also important to remember that the dust concentration within 0.6 ÷ 0.7 g/m3 significantly reduces the visibility, and at the same time, the concentration of 1.5 g/m3 reduces visibility to zero [1].

Therefore, it follows that the determination of dust concentration graininess limits of air ingested by the helicopter's gas-turbine engines is crucial when choosing methods of its dust collection, and the dust suction plants' parameters. Furthermore, the intensity (concentration) of dust also significantly increases during the take-off and landing of transport aircraft with a propeller drive. Why? Because the impact of a stream of air behind the propeller also raises of large quantities of dust, sand and other foreign particles, with different dimensions and weight, which as a result of air turbulence, may get to the inside of the intake system, and then to the gas path of the engine, from the ground.

Hence, it is a phenomenon similar in terms of effects to the one which takes place during the helicopters' take-offs and landings, because as a result of the impact on the substrate (ground) surface of a strongly disturbed air stream, are raised large quantities of pollutants of different granulometric and mineralogical composition under the main rotor, and around the airframe. Therefore, in these conditions, the suction of foreign particles to the intake system, and then to the gas path of aircraft gas-turbine engines takes place (Figure 1).

Figure 1. Mi-17 helicopter landing in the increased dust conditions [4]

3. CHARACTERISTICS OF ATMOSPHERIC DUST

In the dust conditions of the operating environment of helicopter and propeller gas-turbine engines, intense wear of sub-assemblies in their gas paths occurs. However, the most intense degradation of components takes place within their compressors and bearing systems.

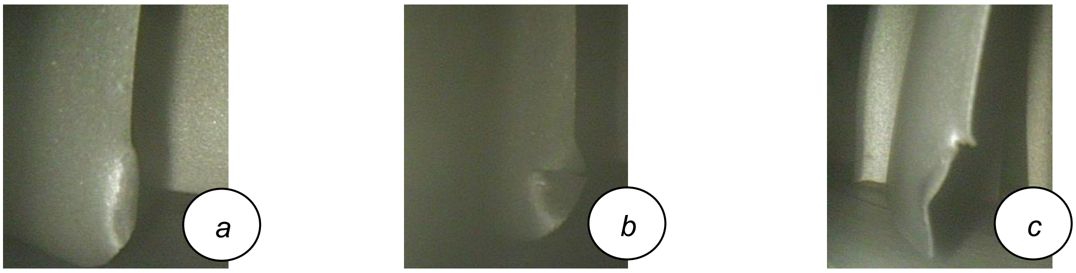


Figure 2. Successive stages of destruction, due to the impact of friction erosion, the corners (in the tip area, on the trailing edge) of a blade of the 7th compressor stage [4]

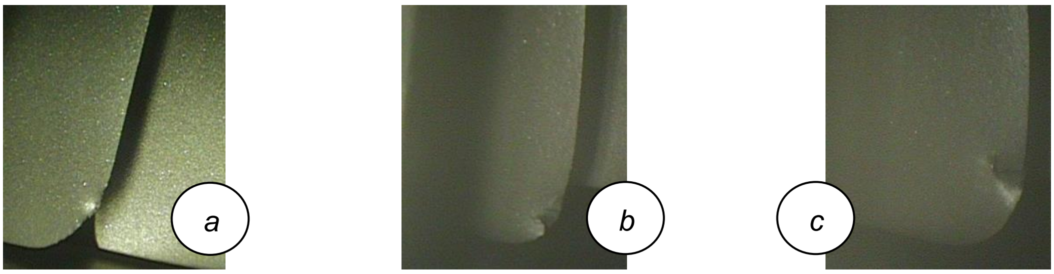
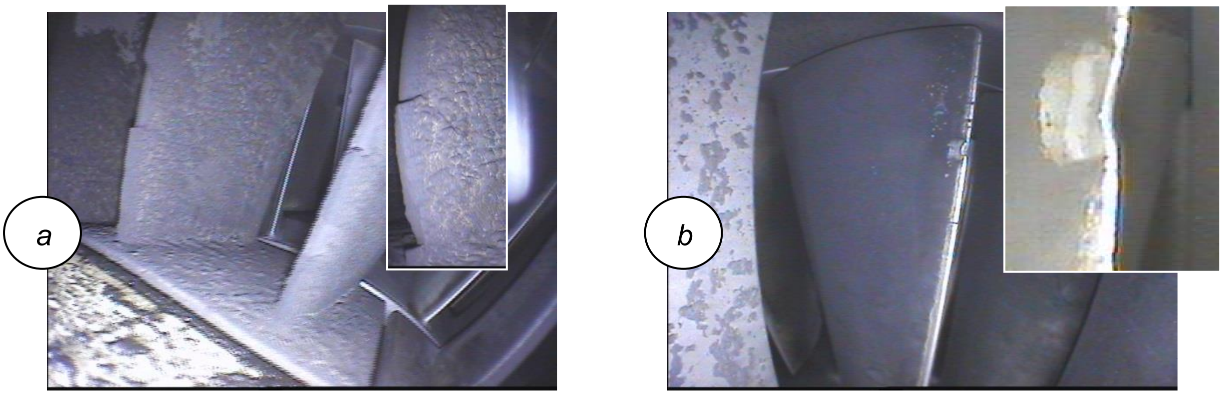


Fig. 3. Successive stages of destruction, due to the impact of friction erosion, the corners (in the tip area, on the leading edge) of a compressor blade of the 8th stage [4]

In Figure 2 and 3, the next stages of the friction and impact degradation (destruction) of the compressor blades of the aircraft gas-turbine engine are shown.

However, ingested dust particles not only change the shape of profiles of the surrounded blades, they also settle in the compressor's inlet part, disrupting its operation, making it very difficult for the aircraft gas turbine engine to operate correctly (Figure 4 and 5).



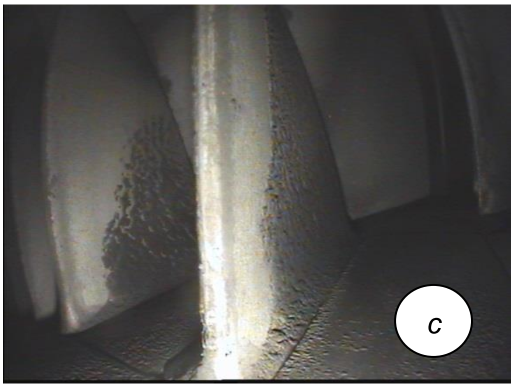


Figure 4. The effects of the aircraft gas-turbine engine operation in the increased dust environment [4]: a) Section of the row of fixed inlet guide vanes (view in the direction of leading edges). The sealed dust layer's local tear-off, b) Dent of the leading edge with the material chip of one of the blades of the first stage, c) Dust accumulated on the suction side of first-stage vanes

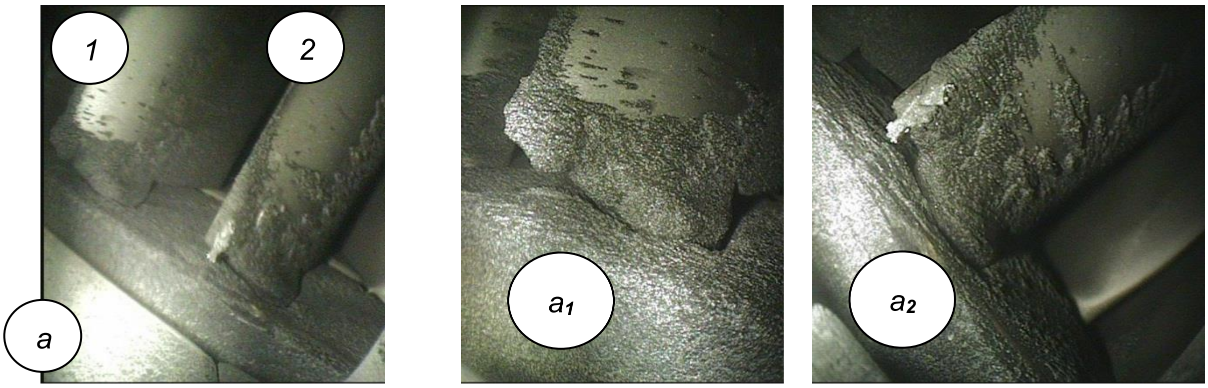


Figure 5. The effects of the aircraft gas-turbine engine operation in the increased dust environment [4]: a) Section of the first stage compressor's adjustable vanes (view in the direction of the surface of leading edges and tops). The sealed dust layer's local tear-off. a_1 and a_2) two vanes of the first stage compressor adjacent in the row

In addition, dust settling on the surfaces of the internal flame (fire) tubes of combustion chambers, forming joined deposits, changes the boundary layer nature. Gradual accumulation decreases the effectiveness of the impact of cooling air on the insulating layer. By sealing the operating space of air turbulators and distorting the flame stabilisation system, it leads to the occurrence of areas of the local excessive enrichment of a mixture, which encourages the emission of incomplete combustion products (Figure 6).

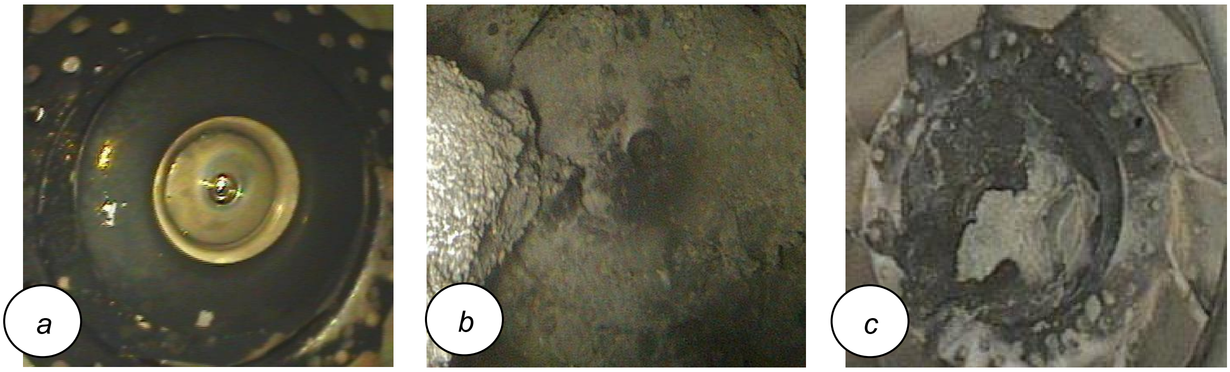


Figure 6. Fuel injectors of the same type of the engine operated in the following conditions: a) "normal", b) heavy dust (with the blocked flow through the air turbulator sealed with dust, c) heavy dust (with the blocked flow through the fuel injector nozzle sealed with dust or incomplete combustion products) [4]

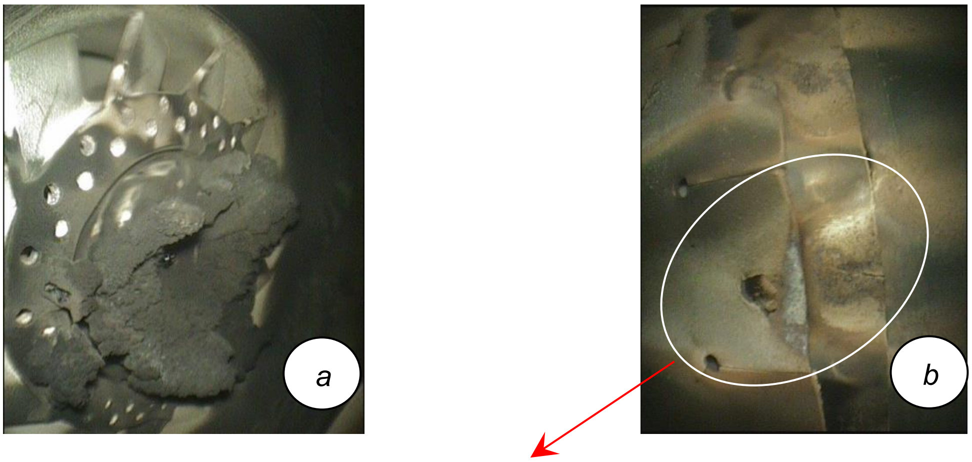
It is also accompanied by the combustion zone extension, which in turn, is the cause of carbon deposits in the back part of the combustion chamber, as well as obstruction of the holes intended for secondary air injection.

The change of the spraying angle, extension of the flame or even fuel post-combustion in the area of the turbine unit of the aircraft gas-turbine engine result in the temperature non-stationary distribution, overheating of its components, as well as burning of the insulating and protective coating, and then the base material of the combustion chamber's flame tube (Figure 7) or the sealing material.

It also determines the amplitude and frequency of the pressure pulsation in the combustion chamber itself, and those moved along the rotation axis of the rotor unit affect durability of the blades' rims of the compressor's last stages, as well as the turbine's blades or the condition of a carrier-thrust bearing of the rotor unit. The surfaces of elements sealing individual stages of the rotor are also damaged, therefore, after some period of time, dust gets into the cooling and lubrication space of the rotating unit through the sealing systems in it. In turn, it accelerates wear and damage to the bearing system. However, the contamination of a lubricant (oil) depends on the place, from which air, which is necessary to seal a given support, is taken.

It is also important not to forget about the reduced flow rate or even clogging of the cooling system, as well as of the part of the working medium flowing through the engine, which also takes part in the automatic control of its operation, because friction wear of actuators or obscuration of holes controlling the flow rate of the working medium results in exceeding values of the controlled parameters or their instability, and thus, to the deterioration of the engine performance.

The effects of this type of operation were illustrated in Figure 8 ÷ 12.



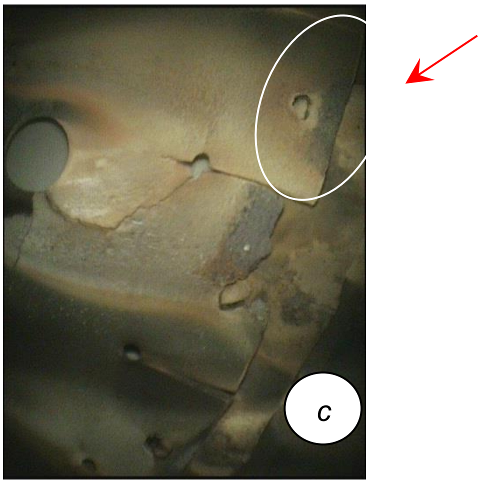
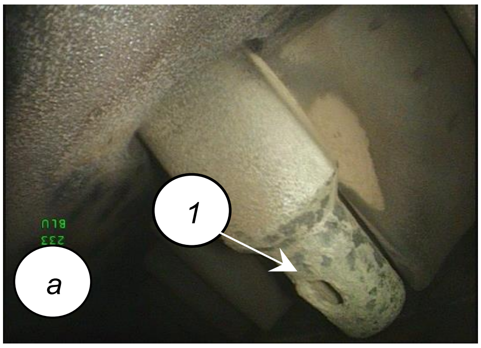


Figure 7. a) Backlogging of a mixture of dust and incomplete combustion products (slag, coke and soot) at the face surface of one of the air turbulator units – fuel injector, b) local burning of the protective coating and cracking of the material in the edge zone of one of the sections of the outer ring, c) local burning of the protective coating with the material loss and propagating from the lightening hole edge in the direction of one of the holes inserting secondary air to the inside of the flame tube, as well as other peripheral cracks of the outer ring section of the combustion chamber's flame tube [4].



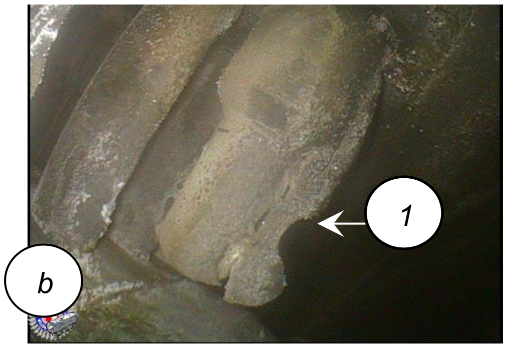


Figure 8. Temperature sensor housing in front of the turbine operating in the following conditions [4]: a) "normal", b) heavy dust (with the decreased flow rate through the hole sealed with dust 1)

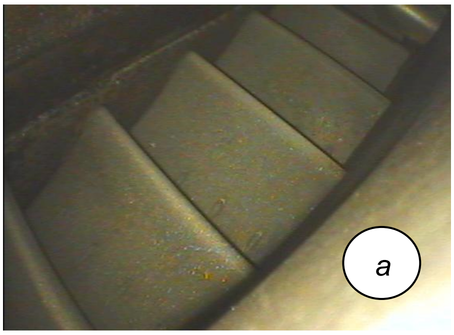


Figure 9a. Turbine vanes operated in the "normal" conditions [4]

Figure 9b. Turbine vanes operated in the heavy dust conditions [4]

Figure 10. Gas turbine operated in the heavy dust conditions [4]. The accumulating, sealing up, and after some period of time tearing-off dust on the surfaces of the leading edges and troughs of aerofoils a) row of vanes, b) blades of the first stage

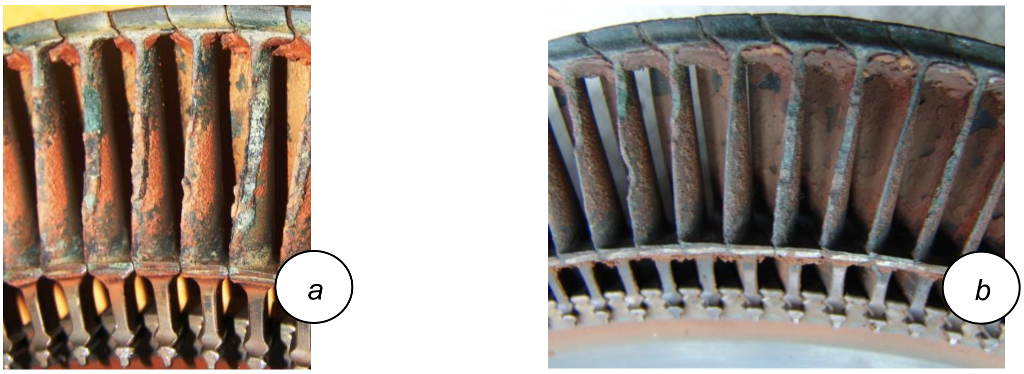


Figure 11. The removed first stage of the turbine rotor (of gas generator) [5]. View in the direction of edges: a) leading, b) trailing

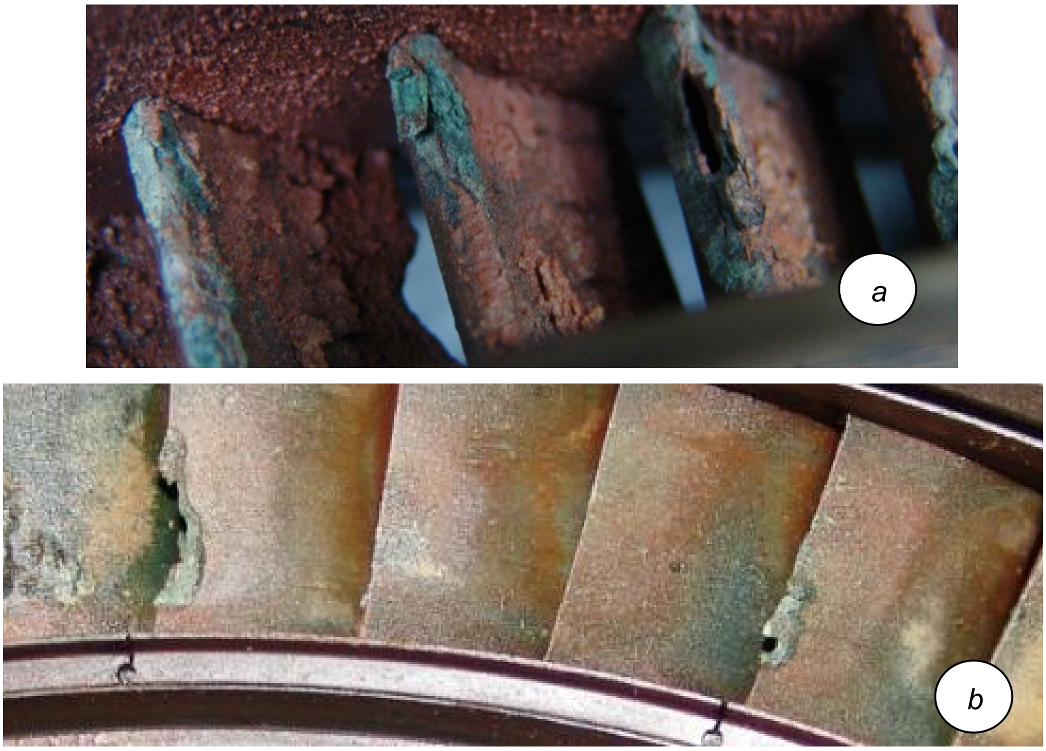


Figure 12. The removed first stage of the turbine stator (of gas generator) [5]. View in the direction of edges: a – leading, b – trailing

However, the most worn elements include the blades of the axial compressors, and it has a direct impact on the characteristics of the engine operation, and thus, its remaining life. As a result, it constitutes one of the fundamental problems in the process of construction, production and operation of helicopter or propeller aircraft gas-turbine engines.

The images presented in Figures 2 ÷ 4 as well as 13 ÷ 14 and 16 show that as a result of the impact of dust erosion on the engine internal components, which causes the changes in geometry of the aerofoils of individual stages of the compressor rotor rims, it must also result in the deterioration of its characteristics, the decrease in stocks to the stable operation limit, pressure ratio and power, with the simultaneous increase in specific fuel consumption by the engine, and the increase in temperature in front of its turbine.

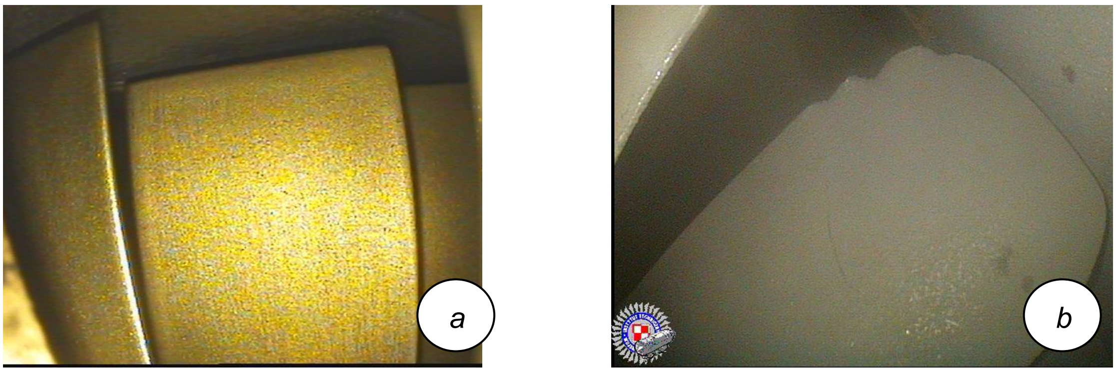


Figure 13. Suction side and trailing edge of compressor blades (7th stage) operated in the following conditions: a) ”normal”, b) heavy dust [4]

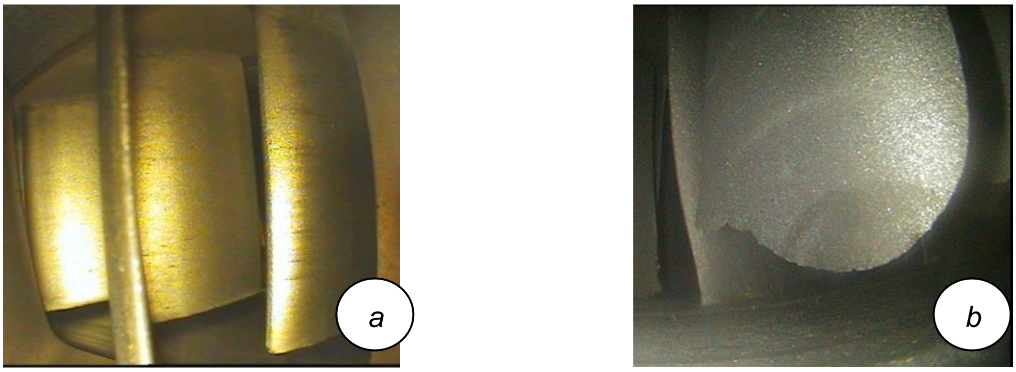


Figure 14. Suction side and trailing edge of the compressor blades of 8th stage operating in the following conditions: a) ”normal”, b) heavy dust [4]

However, it is not always felt by the aircraft crew, because only the enhanced observation of temperature in front of the turbine, in terms of the maximum engine speed, can be a symptom of the mentioned threat.

Therefore, together with the increased erosive degradation of this rotor’s unit, the movement of a limit of stable operation of its compressor and its operating range line occurs, resulting in a significant decrease in the limit of its stable operation [1].

This type of damage occurs as a result of wear, both friction and impact ones. The first of them occurs when dust particles, which move with air, pressed (as a result of aerodynamic and centrifugal forces that affect them) to the surface of rotating aerofoils, cutting into their material with sharp edges, and moving on their surface, cut it in the direction of the trailing edge (Figure 15a).

However, the second one occurs when dust particles, under the influence of inertia forces, strike their operating surface, which is characteristic for wear of the initial stages of the compressors’ rotors (Figures 15b and 16).

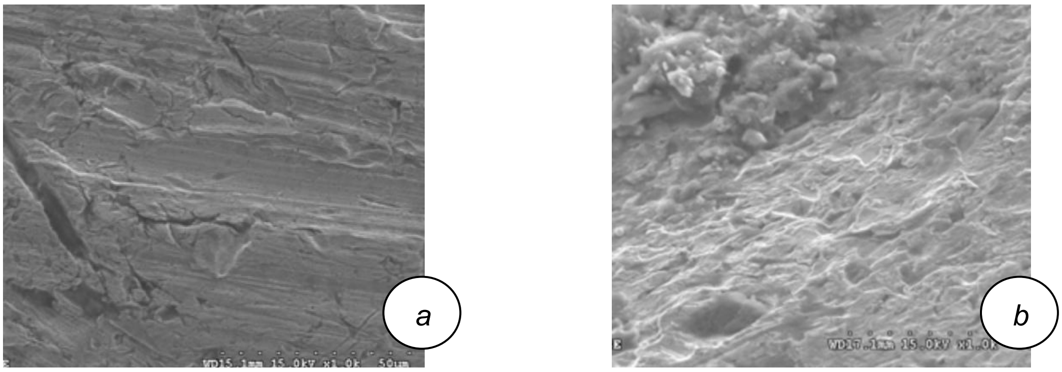


Figure 15. The effect of erosion: a) friction and b) impact on the surface of the fan rotor blade [2]

What effects further operation of the engine is the uneven way that damage occurs along the height and blade's chord. Nonetheless, its leading edges are the most exposed to them, resulting in their dents, curves, buckling and tears, and then, the trailing edges (Figure 16).

A degree of erosive wear of the compressor blades is also affected by: movement speed of particles, their size, and type, speed, pressure, temperature and the angle of the air stream in the engine inlet, as well as its rotational speed, the curvature of profiles of blade aerofoils and the material type protecting their surfaces and the base material, which they were made of.

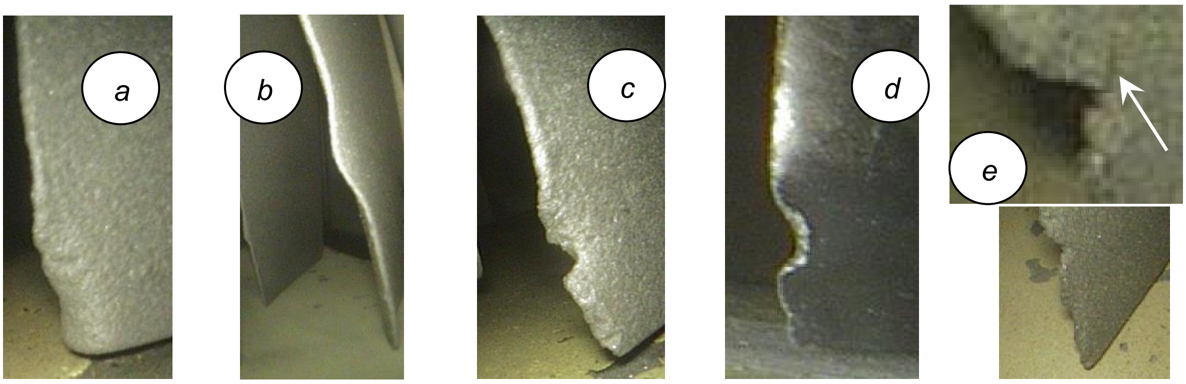


Figure 16. Leading edges of the blades of the first stage compressor [4].
a), b), c) and d) damage to the top part of the blade. e) crack propagating from the leading edge

During the tests of erosive wear of blades of the axial compressor of TW3-117 turboshaft, it was found that the most susceptible ones do not include those of I and IV ÷ VI stage of the rotor, taking into account all the measured characteristics and parameters of their profiles. Moreover, their greatest wear was found on the leading and trailing edges (Figure 17 ÷ 18) [4].

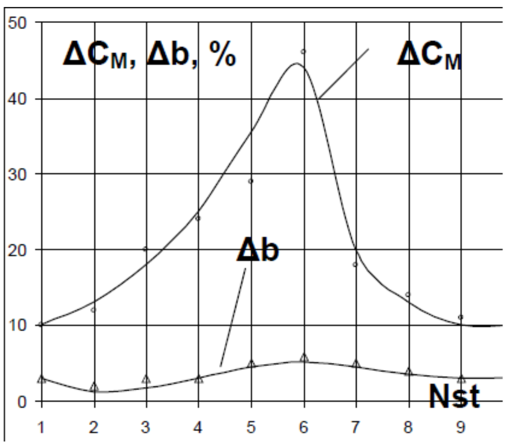


Figure 17. The change of ΔC_M maximum thickness and Δb profile chord along the compressor's gas path [3], Nst - stage number

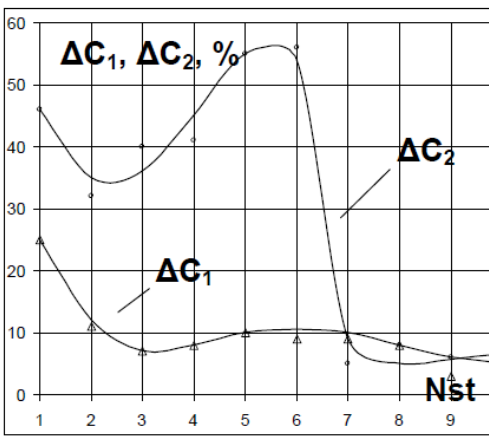


Figure 18. The change in thickness of ΔC_1 leading edge and ΔC_2 trailing edge of the profile along the compressor's gas path [3], Nst - stage number

4. IMPACT ON ENGINE PERFORMANCE

The operation of gas-turbine engines in the heavy dust conditions of air ingested by them negatively affects many parameters of their operation and characteristics, as a result of which, their performance is worsened, and in some cases, it threatens aircraft safety itself.

Relatively large quantities of dust is present on ground landings. The engines of these aircraft and helicopters, which perform their tasks in the mentioned conditions, are equipped with the devices that remove dust from the air that they ingested at their inlet. The air dusting on the ground landings causes increased wear of these engines, which are relatively low suspended to the airframe, e.g. under its wings, than those which were located high, e.g. in the rear part of the fuselage, from about 10 to 15%.

Erosive wear of the blades of individual stages of the compressor's rotor, material losses, and the increase in roughness of their surface contribute to the decrease in pressure ratio, power, and the increase in specific fuel consumption, and thus, to increase the exhaust gas temperature in front of the turbine.

Comparative studies [6] show that the pressure ratio of axial and centrifugal compressors, which operate in the same pollution accumulation conditions, much faster decreases in the first one, at the same time, reducing its efficiency (Figure 19-20).

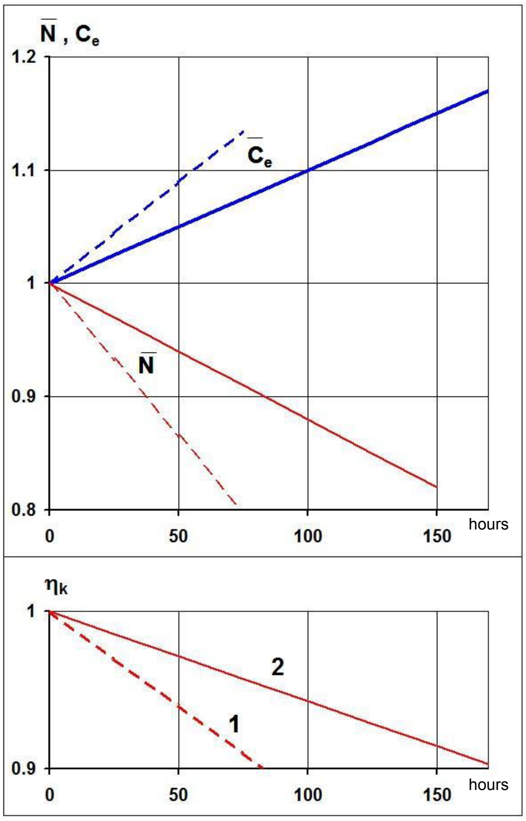


Figure 19. The change in N power, Ce fuel consumption and ηk efficiency of the engine with the axial - 1 or centrifugal - 2 compressor [6]

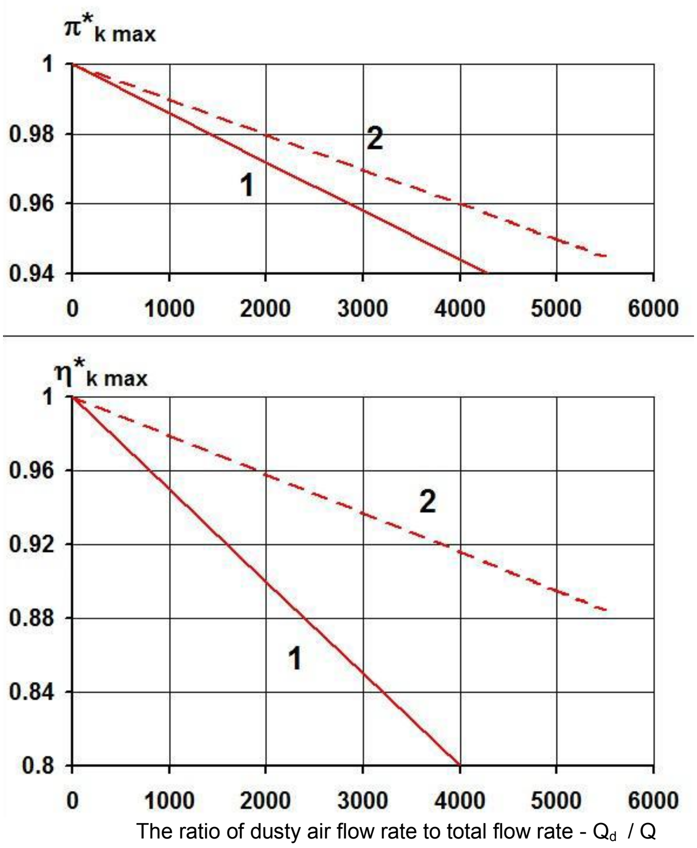


Figure 20. The change in πK pressure ratio and ηK efficiency of the engine with the axial - 1 or centrifugal - 2 compressor [6]

5. CONCLUSIONS

The problems associated with erosive wear of components, and especially blades of gas-turbine engines, are not completely solved. Although it is possible to deal with sea salt or dust accumulation on their surfaces, through special procedures, including the washing with the addition of specially selected detergents, the already used particle separators seem to be ineffective to prevent erosive degradation of gas-path components.

In addition, during the performance of technical services, the visual inspections of the surface condition of inner space components of all engine types, currently operated by the military aviation, are carried out too rarely or almost never. Endoscopy allows to assess and predict the intensity of wear and if inspections are performed regularly in the air base, the components deteriorated or damaged by erosion can be detected early.

The following elements should be more often controlled:

- The condition of filters of the lubrication and fuel system, and if necessary, they should be cleaned or replaced with new ones. It is important to systematically take oil samples from clearly defined places, and control their content, and if necessary, to clean the instance and change oil to the new.
- Surface condition and testing of operation correctness of the exhaust gas temperature measurement system in front of or behind turbine units.

There is also a need for carrying out work to better protect the blade surface, including the improvement of methods related to the application of multi-layer coatings, as well as the choice of materials that make it possible to increase the resistance of these components of aircraft gas-turbine engines, which are the most exposed to erosive wear, and most of all, the blade aerofoils. It is also necessary to continue the efforts aimed to increase effectiveness of various types of particle separators.

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