COMPUTER AIDED VISUAL INSPECTION OF THE TECHNICAL CONDITION OF GAS TURBINE BLADES DURING THEIR OPERATION PERIOD

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Abstract

Due to specific working conditions of gas turbine blades and difficult access to them their technical condition during their operation period is generally evaluated by a visual method with the aid of advanced optical devices. This paper presents the analysis of forms and kinds of gas turbine blade damages, which affect their reliability. The paper presents features of non-destructive inspection methods used for diagnosing the technical conditions of the said blades during their operation period. Special attention was given to methods of computer aided diagnosing of the technical condition of gas turbine blades, which increase the reliability of evaluation of the said condition and therefore reduce costs and enhance the operational safety.

The process of destruction of a gas turbine blade starts with the destruction of a protective coating, in consequence of which the initial material of a blade is subject to a direct aggressive impact of the waste gas. This causes the material to directly overheat, which manifests itself in detrimental changes in its microstructure. There is need for a more common use of non-destructive methods for a current evaluation of the state of overheated aircraft engine turbine blades.

Key words: *gas turbine, blade, technical condition, diagnosing*

1. Introduction

A gas turbine is a part of a jet engine and it is a rotor engine, which transforms the enthalpy of the working medium - called also the “thermodynamic medium”- into the mechanical energy, which causes the rotor to rotate. Increased efficiency of a turbine causes its draught (power) to increase and the fuel consumption by the engine to decrease and vice versa. The efficiency of aircraft engine gas turbines (which is at a level of 30-45%) depends significantly on the waste gas temperature, which over some recent years increased by 280K, thus resulting in a better overall efficiency of a turbine and in the increase of the power factor. However, the barrier to a further increase of waste gas temperature is the problem of materials, i.e. their resistance to creeping, thermal fatigue and high temperature sulphur corrosion and erosion. Therefore it was necessary to use costly fire resistant alloys, complicated shapes of blades, thus complicating the technology of production and some other processes like cooling of blades were necessary as well. Nowadays, depending on materials a blade is made of and on the cooling intensity, blades operate at temperatures between 1120 and 1170K (without being specially cooled), at 1200-1300K (with cooling) and at 1300-1500K (with intensive cooling). Unfortunately with blades operating under complex thermo-mechanical conditions (overloads and aggressive environment) they can operate only at a material working temperature lower than that of the combustion temperature even by 350K. Therefore in order to be able to further develop and perfect the design of gas turbine blades the effort concentrates on applying fireproof coatings of a good resistance to high temperature corrosion, of a low thermal conductivity and a high structural stability. Taking into account the consequences of possible damages to rotating parts of a turbine engine - the most important task of users making the best use of available diagnostic methods is to detect early and correctly interpret signs of possible threats in order to carry out a repair at the most convenient time and thus consequently minimizing losses and preventing a failure.

2. Reasons for damages and damage forms

When operating aircraft turbine engines different kinds of turbine element damages, especially those of blades occur. The analysis of incidents so far shows that all damages, failures fall depending on an assumed classification into one or more groups of reasons, which are often interdependent. Therefore we can discern failures resulting from faults due to the manufacturing process, resulting from an improperly carried out repair or from a faulty operation.

The design and principles of operation of a turbine jet engine is dictated by the flow thru its gas tract - inlet, compressor, combustion chamber, turbine, and inlet nozzle of an enormously intensive air stream. Air taken into the inlet of an engine is not always free from foreign matter, which thereafter gets into an engine. This is due to the fact that a gas engine is mounted on an airframe, due to conditions on an apron pavement and due to faults made when operating an aircraft.

Contaminations/foreign matters getting into an engine contained in the air stream cause damages to the gas tract parts - in particularly damages to the compressor and the compressor and turbine rotor blades. Small point damages or small damages to the blade surface due to frictional wear cannot be seen during initial working hours of an engine after such a damage has occurred, so they remain undetected by a diagnosing inspector directly after they have occurred. It is possible that minor local damages or small damages to the blade surface due to abrasion may not be detected by a diagnosing technician during first hours of the engine operation after such damages have occurred or when a technician tries to detect them just after they have occurred. Damaged protective coating on the surface of a turbine blade with a simultaneous impact of high temperatures and aggressive waste gas environment causes a damaged top coating of blades to gradually degrade and a subsequently overheat this being followed by the burn-out of the blade native material (Fig. 1).

Fig. 1. Examples of damages to the edge of attack of turbine blades due to temperature [3]

Experience gained so far during research work at the Air Force Institute of Technology shows that most of the turbine damages depend directly on the improper adjustment of an engine and on a bad quality fuel.

Improper fuel pressure, worsened physical-chemical properties of a fuel due to different kinds of contamination, a faulty mounting of an injector in the head of a flame tube, which causes generation of the carbon deposit on injectors (Fig. 2), and on other parts, result in an improper fuel atomisation. This consequently results in a distortion of the combustion process and further in consequence in a distortion of the distribution of the temperature field and distortion of the cooling of individual elements of hot parts of an engine. As final result the chamber material and the turbine blades overheat (Fig. 3).

Fig. 2. Carbon deposit on a fuel injector of a turbojet engine [3]

Fig. 3. Damage to turbine blades due to temperature[3]

Damages caused by manufacturing process faults and repair faults are the second group of damages detected within the „hot” part of an engine during prophylactic diagnostic inspection. These damages are damages which cannot be influenced by a user and which can occur during the entire operation life of an engine.

An example of an occurrence the consequences of which can be fatal is a break-off of a jet engine blade caused by applying a coating of a new kind by a diffusion process on the blade material. During blade operation this brittle coating broke with the crack propagating down into the blade native material, and consequently this blade broke off (Fig. 4).

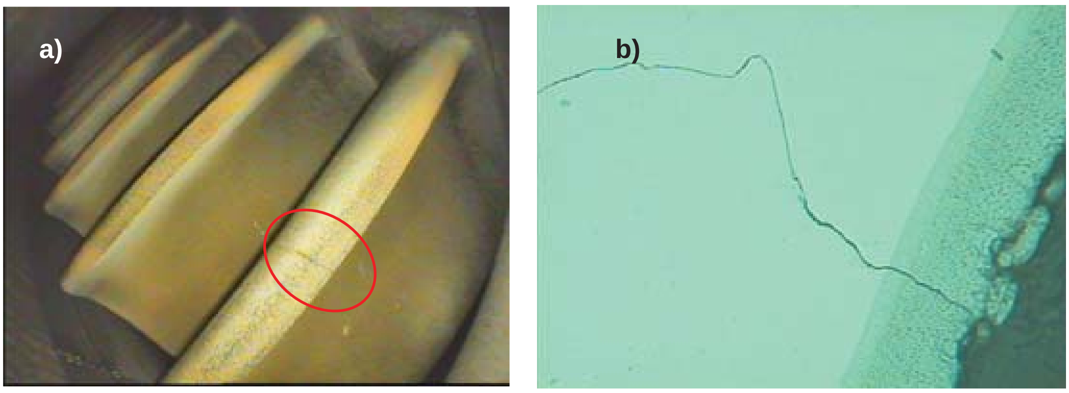


Fig. 4. Image of a break of a protective coating propagating into the blade native material [3]: a) videoscope image; b) image from a 450x magnification microscope

3. Possible diagnosing of the technical condition of turbine blades

Experience gained during implementation and execution of prophylactic programmes in order to ensure a high safety level for military aviation has shown that in spite of investing huge efforts and means when operating such a vast population of turbine engines it is impossible to completely avoid their different damages. The prospect of a costly failure of an engine and its destruction including the aircraft on which it is mounted forced designers of turbine engines to create apart from self-checking systems of their control circuits a possibility to diagnose them with the use of non-destructive testing - NDT. The above mentioned non-destructive testing is generally carried out by the following methods; visual, penetration, ultrasonic, magnetic, radiology, thermography, leak proof test and eddy current. With these methods it is possible to:

- detect material discontinuity (defectoscopy),
- evaluate material properties (structuroscopy),
- determine the object dimensions and measure the coating thickness (metrology).

The visual method is the most popular non-destructive method since the technical state/condition can be inspected without having to disassemble an object under inspection, due to an easy testing procedure and due to a relatively low cost of testing and the time to restore an object to operation is short. The visual testing should be performed as the first inspection. Thanks to it material discontinuities can be detected, first of all dangerous discontinuities emerging on the object surfaces irrespective of the object size, whether relatively small or large, and irrespective of the object shape and geometry. Most manufacturers of new turbine engines adopted this method to make endoscope testing of engines by mounting peep holes on the engine body to enable access to the inside of an engine and to inspect the engine gas tract when an engine is in use.

Engines of some older design, which were not planed to be tested with endoscopes and not prepared for such inspections, are inspected now only within a limited range after they have failed, and as well thanks to newly developed diagnostic tools. In case of such engines, i.e. of an older design, especially severely tested are critical elements, „hot” engine parts – the combustion chamber, the turbine – the access to which is gained most often by removing their starters or injectors, provided the design of an engine and a servicing procedure allow that.

4. Computer aided visual inspection of the technical condition of a gas turbine blade

Diagnostic visual inspection as an element of the prophylaxis the goal of which being a high safety level of operating aircrafts was from the very beginning related to two elements - the technical resources of available testing and measuring devices and the skills (knowledge, experience) of a technician performing the testing. Introduction of the human factor and subjecting an actual diagnostic ‘reality’ to its subjective judgement was and still is a reason for many expensive errors related to decisions taken by him. Many times it happens that due to obsolete equipment but as well due to the lack of a proper knowledge on part of an inspector expensive engines were taken out of operation and directed to costly repairs, despite them being still capable of a safe operation. Therefore the development of diagnostic equipment serving for visual inspection was concentrated on making the quality of vision better by using better optical measuring paths and helping a diagnosing technician out of performing tedious measuring steps and next having to interpret the watched images.

At present for visual testing video scopes are preferably used and they replace the so far applied endoscopes (borescopes, optical fibre endoscopes)). Video analysers are commonly more and more used. These devices automatically compare 3D-images, obtained by testing, with an image saved in a computer.

With videoscopes it is possible to measure values such as the length, the surface, the depth/height, the distance from a straight line with an accuracy of 0.01 mm, determining at the same time the error of a result depending on the distance of the measuring probe from a tested object. Special software enables to carry out the above measurements both during testing and at a later time with PC class computers. There are now several manufacturers on the market offering devices of a very similar performance and parameters, however differing in that, that their method of calculation of determined values is different. These devices use a stereoscope shadow method, a laser tracer method or a scanning laser method. With all these methods mathematical relations between images from two lenses, properties of a shadow or laser tracers projected onto a examined object / flaw are employed with which one can measure the above-mentioned values with a great accuracy, or determine clearly whether we have a material caving or a material convexity. The paper [4] presents methods for measuring surface defects basing on a digital record of a videoscope image by a „Stereo" method („Stereo Probe") or a „Shadow" method („Shadow Probe") – Fig. 5.

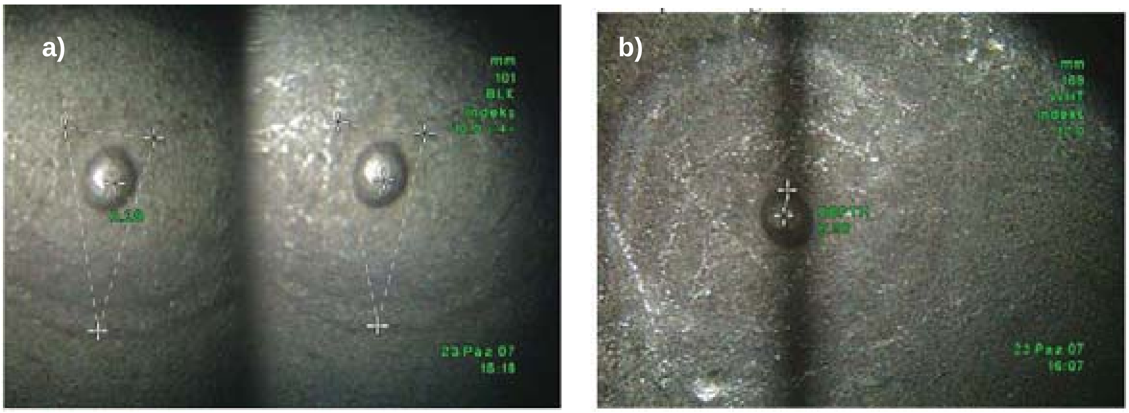


Fig. 5. Measuring the convexity radius by the [4] a) „Stereo"; b) „Shadow" method

Another method of diagnosing gas turbines is a thermo-graphical method consisting in recording images of the temperature distribution at the turbine outlet. With a regular, proper running of a turbine sample thermograms are obtained. During a routine check carried out during operating an engine generated thermograms are compared to sample thermograms. In case even a slight anomaly occurs this is a warning prompting to determine a probable reason for the difference between such an anomaly and a sample. Thanks to this approach to the problem flaws can be detected (e.g. a turbine erosion, damaged blade, improper operation of a combustion chamber), which are difficult to detect with other non-destructive methods.

To detect surface flaws (e.g. corrosion pits) one can apply a TaiCaan Xyris 4000 LT profile measurement gauge. With the aid of this gauge (after disassembly of turbine elements) the surface of a gas turbine edge of attack is scanned at several points of the blade feather.

Unfortunately under conditions at an air force base only one engine type operated at Polish Air Force can be subject to such an examination, however, the labour effort are substantial; this is the PW229-F100 engine of the F-16. The design of this engine is modular, thus individual groups/modules can be replaced when operating an aircraft.

Another method being developed and applied for diagnostics is a „RGB" visual method basing on basic colours: red – R, green – G and blue – B. Relations between the wave features of the light and the physic-chemical features of examined surfaces serve for measurements. These relations determine the angle relations between the projected and the reflected light and the absorption of individual spectral waves of the electromagnetic radiation [4]. Images recorded by a CCD matrix are next analysed with the help of a special software employing a special image processing algorithm and ready sample patterns with which one can qualitatively evaluate the condition of a surface under examination. This method was used to evaluate blades of a turbine engine made of a ŻS-6K alloy (Fig. 6). Blade feathers are coated with an aluminium alloy to protect them against the high temperature gas impact.

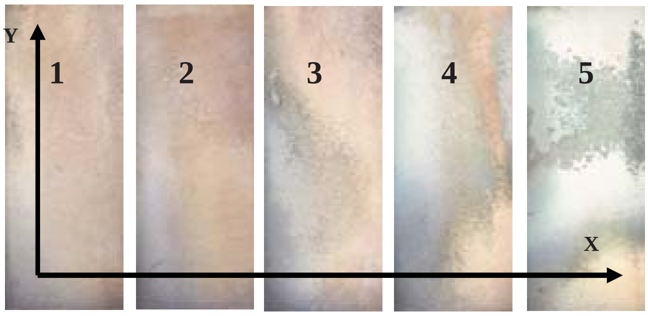


Fig. 6. Images of a gas turbine blade surface coated with the ŻS-6K alloy, arranged in an order of the increasing material overheating

With the aid of m-files saved in a Matlab programme environment features of recorded images are presented in form of histograms of the brightness distribution for individual colours and parameters determined from the matrix of events

For a section of a blade image under examination the histogram parameters are calculated; these are: the location of maximum amplitude (the RGB colour saturation value), averaged image values (summing by lines of the saturation values, divided by the number of lines) and the maximum amplitude value. The histogram contains quantitative information on the brightness of an obtained image of an object. A histogram is represented by a vector of a length corresponding to the number of brightness levels, which is given by:

$$h(l_k) = \sum_{m=1}^{M} \sum_{n=1}^{N} p(l_k, (m,n)) \,, \tag{1}$$

where :

$h(l_k)$ - sum of points of a l_k -th gray level and

$$p(l_k,(m,n)) = \begin{cases} 1; \; dla \quad L1(m,n) \neq l_k, \\ 0; \; dla \quad L1(m,n) \neq l_k. \end{cases} \tag{2}$$

To standardize values contained in a histogram a so-called „unified (standard) histogram” was implemented, the individual values of which are divided by the total sum of pixels *norm* = *m·n*:

$$h_{zn}(l_k) = \frac{\sum_{m=1}^{M} \sum_{n=1}^{N} p(l_k,(m,n))}{norm} \,, \tag{3}$$

where *m, n* - dimensions of an image.

If in the process of recording an image constant, stable and repeatable conditions occur and if obtained results are in form of symmetric courses of a Gaussian distribution then to describe colour changes in the gained pictures only the saturation value (the position of the maximum amplitude) will suffice.

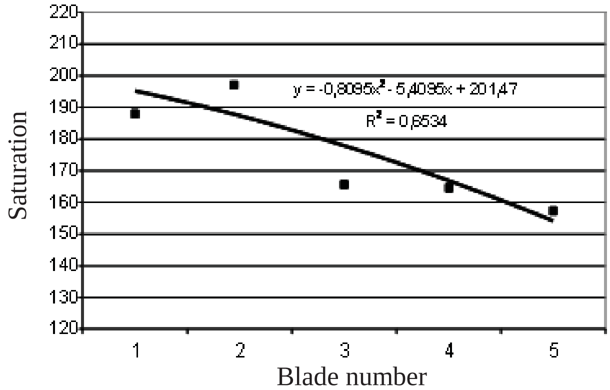
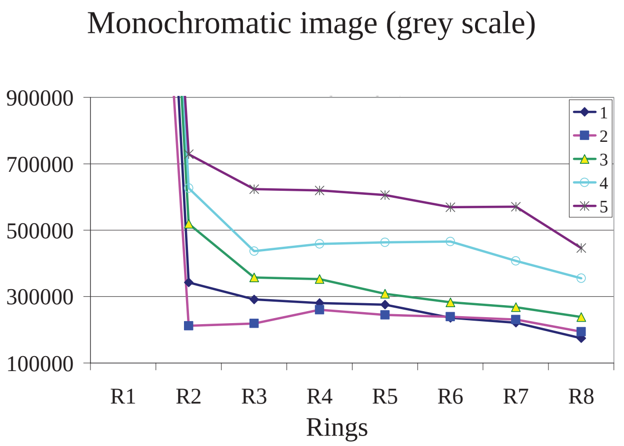


Fig. 7. Examples of a changing position of the maximum amplitude of the image saturation for different conditions of a blade [4]

Histograms of monochromatic images (gray shades) are obtained through averaging basic colour components: (R+G+B)/3. Fig. 7 shows examples of a changing position of the maximum amplitude of the image saturation for different conditions of a blade shown in Fig. 6.

For the analysis of images very useful is a ring-wedge detector. A wing-wedge detector is an element in form of a wheel. It consists of two parts the first one constitute concentrically situated rings, where the second part are wedges with a common apex in the middle of the detector.



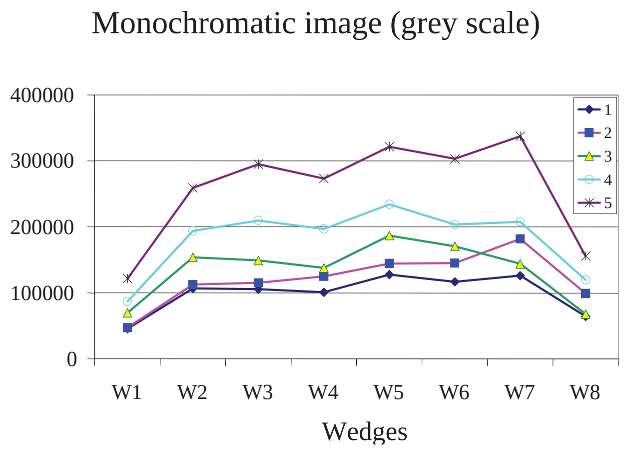


Fig. 8. Values of rings and wedges in grey shades for different blade technical conditions [5]

Every area is a surface photo detector, which transforms the intensity of the projected light to a signal proportional to the intensity of this light. A computer-generated hologram (KGH) is in its form which is similar to that of the ring and-wedge detector and consists as well of areas of rings and wedges. Therefore a KGH plays a role of an ‘extractor’ of features from images, which are presented in the frequency domain. The results of carried out analysis of images in grey shades of a blade surface of the turbine shown in Fig. 6 are presented in Fig. 8. The values of rings and wedges for overheated blades 4 and 5 definitely differ from other values.

A method applied nowadays more and more often in the technical diagnostics and basing on a computer analysis is a method or recognising images. Optical methods of recognising images can be generally divided into correlative and non-correlative. Correlative methods base on an optical comparison of a recognised image to a sample image and next on an analysis of an obtained correlative signal. Non-correlative methods base on an analysis of characteristic features describing an object and are used only when a clear definition of a target sample/pattern, to which an object shall be compared, is difficult to make. So far these methods are applied only in the industry in quality assurance, for recognition of facial features and fingerprints, for land development assessment from aerial photographs. Also there is an ongoing effort to develop methods of image recognition as a common and useful diagnostic tool for operating aircrafts including diagnostics of gas turbine blades.

The use of modern computer aided diagnostic tools enhances the reliability of the assessment of a technical condition of gas turbine blades. It will enable also to gradually eliminate a detrimental effect of the so-called „human factor” on the examination results, therefore improving the flight safety and reducing the operating costs of turbine engines. Due to the fact that an actual diagnostic reality is subject to ‘human’ subjective evaluation was and is still is a reason for many costly errors related to decisions made by a man. In Fig. 9a we can see blades of a RD-33 high-pressure engine turbine rotor with an „indication” that can mean that on one of them an edge of attack crack develops. The lack of appropriate decisions due to reasons as mentioned above results in what can be seen in Fig. 9b, which is a break-off of a turbine blade.

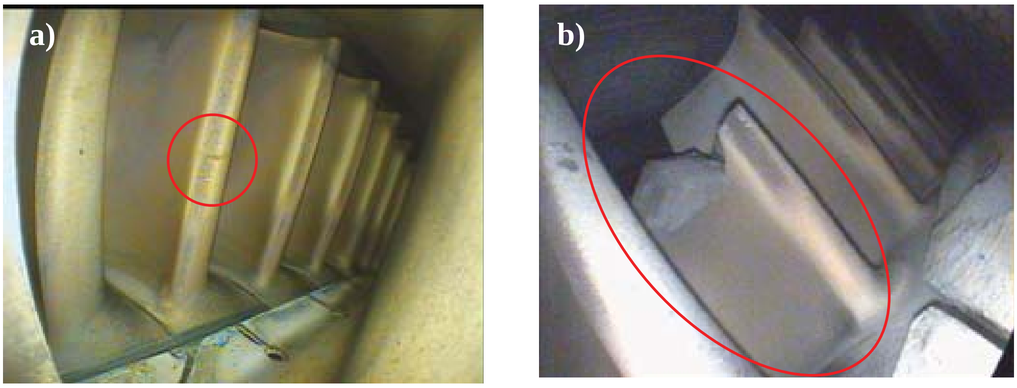


Fig. 9. Blades of a RD-33 high pressure engine turbine rotor : a) with an indication which can point to a crack in the blade; b) a broken off blade

5. Conclusions

During operating an aircraft turbine engine there occurs warming of turbine blades up to a temperature exceeding a normal working temperature. The process of destruction of a gas turbine blade starts with the destruction of a protective coating, in consequence of which the initial material of a blade is subject to a direct aggressive impact of the waste gas. This causes the material to directly overheat, which manifests itself in detrimental changes in its microstructure.

A reliable evaluation of such changes by visual methods allows in some cases to extend the service life of an engine – a so-called „supervised operation" – even after a defect has been detected, or to withdraw an engine from operation to prevent a tragic event due to a turbine damage. On the other hand a bad decision of a diagnosing technician generates high costs, which have to be borne for elimination of threats to the flight safety or from a superfluous general overhaul of an engine amounting even to millions of PLN.

Taking into account all that, we see that there is need for a more common use of non-destructive methods for a current evaluation of the state of overheated aircraft engine turbine blades.

References

[1] Błachnio, J., *The effect of high temperature on the degradation of heat-resistant and high-temperature alloys*, Solid State Phenomena, Vol. 147-149, pp. 744-752, 2009.
[2] Lewitowicz, J., *Podstawy eksploatacji statków powietrznych*, ITWL, T. 4, Warszawa 2008.
[3] Kułaszka, A., Chalimoniuk, M., *Sprawozdania z prac badawczych*, ITWL, Warszawa 2000-2008 (niepublikowane).
[4] Karczewski, Z., *Endoscopic diagnostics of marine engines*, Diagnostyka, 3(47), pp. 65-69, 2008.
[5] Błachnio, J., Bogdan, M., *Diagnozowanie stanu eksploatowanych łopatek turbiny gazowej*, Diagnostyka, Nr 1 (45), s. 91-96, 2008.