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# EXAMINATION OF CHANGES IN MICROSTRUCTURE OF TURBINE VANES WITH THE USE OF NON-DESTRUCTIVE METHODS

**Józef BŁACHNIO**

*Białystok University of Technology*
*ul. Wiejska 45 C, 15-351 Białystok, Poland*
*tel.:+48 22 6851982, fax: +48 22 6851041*
*e-mail: jozef.blachnio@itwl.pl*

***Abstract***

*The processes associated with operation of traction, marine and avionic turbine engines entail occurrence of various defects affecting turbine components, in particular turbine vanes. The main reasons for defects and deterioration of gas turbine vanes include thermal fatigue and overheating of the vane material. This is why continuous monitoring of technical condition demonstrated by crucial engine components, such as turbine vanes, is a matter of great importance. The monitoring operations involve all the up-to-date diagnostic methods intended to detect and interpret possible hazards. The initial assessment is carried out with the use of visual inspection methods, but the major phase of investigations consists in metallographic examinations, which disables further operation of the vanes. Possible mistakes during the initial assessment of the engine condition result in huge costs due to unnecessary overhaul of the entire engine.*

*Therefore, there is a need to apply non-destructive test methods to the maximum possible extent with the aim to evaluate the overheating status of the gas turbine vanes on a current basis. This paper outlines the non-destructive test methods that are currently in use and that are based on analysis of surface images obtained from the examined parts within the visible bandwidth of electromagnetic waves as well as on surface analysis of examined items with the use of a ring-wedge detector. Particular attention is paid to opportunities that enable unbiased diagnostics of changes in the microscopic structure of vanes by means of the non-destructive thermographic method as well the X-ray computer tomography.*

***Keywords:*** *gas turbine, vane, diagnostics, non-destructive test methods*

## 1. Introduction

In applications for power engineering, traction, sea transport and aeronautics, gas turbines perform as a powering component for the entire structure. Its power determines performance of the driving unit and any increase of its efficiency reflects on growth of its power and drop of its unit fuel consumption and vice versa. At the same time the turbine, as it is subjected to huge thermal and mechanical loads (in particular, its vanes of the rotor rims), determines the overall reliability and durability of the entire structure where the turbine is built-in.

Turbine efficiency substantially depends on the temperature of the engine combustion gas upstream its inlet. The barrier to increase the temperature consists in troubles with materials, i.e. their resistance to creeping, thermal fatigue, sulphur corrosion at high temperatures as well as erosion. Currently, depending on applied materials and cooling intensity, the working temperature of turbine vanes, e.g. in avionic engines, is kept within the ranges [1]: 1120 - 1170 K (with no dedicated cooling system), 1200 – 1300 K (dedicated cooling for vanes) or 1300 – 1500 K (application of intense cooling).

Further progress and perfecting of manufacturing technologies used for production of turbine vanes with the aim to increase the temperature of the combustion gas upstream the turbine was targeted to coating with heat resistant materials with good corrosion resistance at high temperatures, low thermal conductivity and high structural stability of alloys that are commonly referred to as super alloys [2].

Operation of gas turbines always entails various damages to their components. The analysis of own research works [3, 4, 5] as well as literature references [6, 7, 8, 9, 10] shows that most of defects is associated with incorrect operation (adjustment) of parts and subassemblies that collaborate with turbines, in particular the combustion chamber and the outlet jet in case of turbojet engines (Fig. 1). Only a very small number of defects that happen to turbine subassemblies arise as a result of material deficiencies, improper design or technological faults.

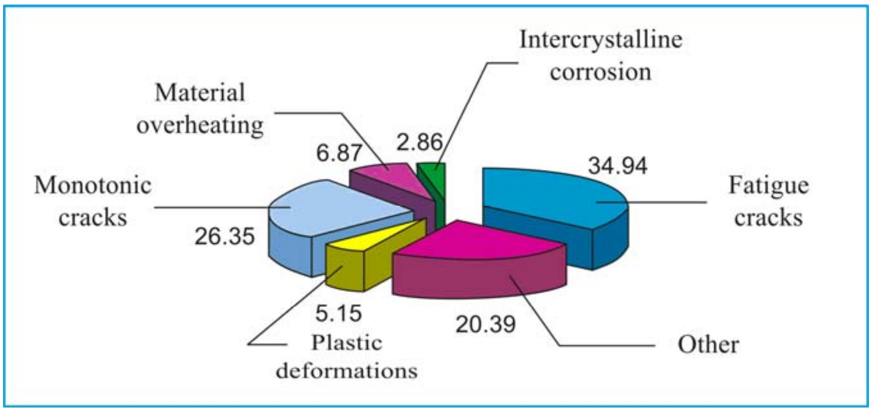



*Fig. 1. Percentages of causes of damages to aircraft-engine turbines in service [3]*

*Fig. 2. Example forms of temperature defects demonstrated by vanes of the turbine rotor [6]*

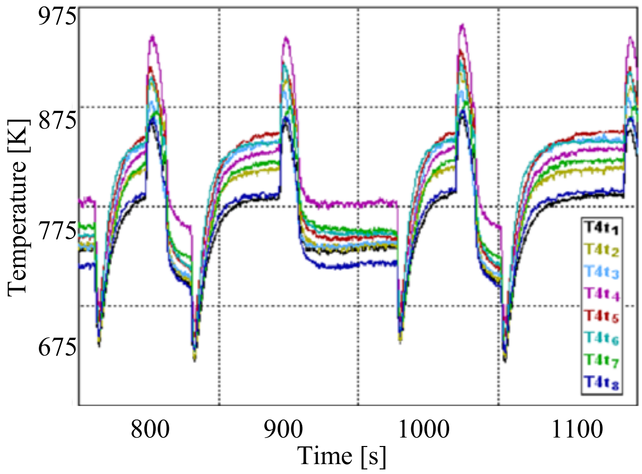



*Fig. 3. Exemplary distribution of unevenness of the T4 temperature on the perimeter of the turbine in the function of time and rotation speed of an aircraft aerial engine, measured with help of thermoelements ($T4t_1$ - $T4t_2$) behind the turbine [11]*

More frequently turbines suffer from adverse alterations to the material structure of vanes – overheating, thermal fatigue – caused by excessive temperature and exposure times as well as by aggressive composition of the combustion gas (Fig. 2). Overheating of the turbine vane material results from exceeding the permissible average temperature of combustion gas as well as due to non-uniform distribution of the thermal field along the turbine perimeter (Fig. 3). Non-uniform distribution of temperature downstream the turbine may happen due to improper atomizing of fuel due to carbon deposition on injection jets.

After exceeding the critical temperature the alloy subjects to overheating, which results in deterioration of its mechanical properties (Fig. 4). Overheating of the turbine vane material leads to malfunctioning of the gas turbine and sometimes even to accidents with disastrous consequences, which is particularly hazardous in aviation. Anyway, refining of the damaged turbine is always associated with a major overhaul and entails enormous expenses.

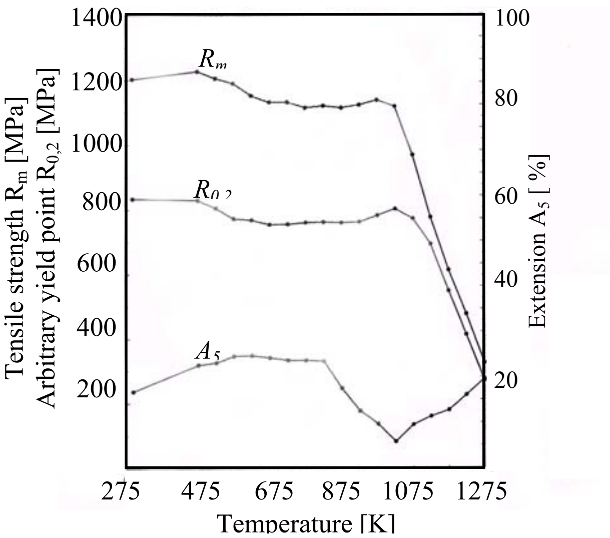



*Fig. 4. Mechanical properties of EI-867 alloy in function of temperature [9]*

The decision on the need to hand over the engine for a repair is always made by diagnostic staff after examination when, with the use of dedicated equipment, such as a videoscope, they are capable of assessing the condition of hard accessible components of the turbine. The appraisal is made by comparison of current images recorded for surface of the component under test and the pattern images that present surfaces of operable and inoperable turbine vanes of the same type. Trustworthiness of the assessment depends on many factors, including competence and professional experience of the diagnostic staff, applied methodical approach, technical condition of the measuring instruments, external circumstances of experiments, etc. To a large extend, the final conclusion represents a subjective attitude of inspectors, which is associated with a risk of erroneous decisions. Mistakes in subjective findings committed by the diagnostic staff may cause that an overheated vane shall be accepted as a good one, or an operative vane shall fail the examination. Finding of diagnostic staff can be verified only by destructive techniques, when the examined vane undergoes analysis of its microstructure across a metallographic polished section. For that reason there is a need to develop and implement a non-destructive test method (computer aided) for the assessment of technical condition demonstrated by vanes of gas turbines during the turbine lifetime.

## 2. New methods of non-destructive examinations intended to assess the condition of gas turbine vanes

Some new methods for non-destructive examinations were developed over the recent years, including

1. analysis of images for surface of examined items acquired under white illumination – the RGB method,
2. detection of infrared irradiation emitted by the item under test – the thermographic method,
3. X-ray imaging – the method of X-ray computer tomography.

### 2.1. The RGB method

The RGB imaging consists in recording of three components that make up each colour (R- red, G – green and B – blue) and takes advantage of interrelationships between wave properties of light that correlate with physical and chemical properties of examined surfaces. These interrelationships decide about angular features of the incident and reflected light as well as absorption of individual wavelengths within the spectrum of electromagnetic irradiation [12]. Evaluation of vane condition is based on colour analysis for surface images and is interrelated with the material criteria (alterations of the item shape and increase in emission of the reinforcing phase γ'), i.e. deterioration in heat-resistance and high-temperature creep resistance after exceeding the combustion gas temperature that is specific for each material. Based on the nomograms that binds alteration of surface colours (either RGB colours or greyscale) and heating temperature of vanes one can assess how the alloy microstructure has been changed. The images are recorded with the use of a CCD matrix and analyzed by means of dedicated software that takes advantage of sophisticated algorithms for image processing and already developed patterns. Thus, qualitative assessment of the examined surface can be made. The foregoing method was applied to the assessment of gas turbine vanes made of the ŻS6-K alloy (Fig. 5).


*Fig. 5. Images for surfaces of gas turbine blades made of the ŻS6-K alloy, ordered according to the criterion of the increasing degree of the material overheating*

Owing to m-files developed within the Matlab software environment it is possible to extract features of the recorded images for examined surfaces. These images are represented by histograms that combine distribution of intensities for individual components of colours and other parameters determined on the basis of the event matrix. Essential parameters of histograms, such as location of the maximum amplitude (chromaticity for RGB colours), averaged values for images (chromaticity values added up along rows of the matrix and divided by the number of rows) as well as the maximum amplitude value are calculated for the examined section of the vane image. Therefore, histograms contain quantitative information on overall brightness of images recorded for the items under test. Fig. 6 presents examples for translocation (bias) of the maximum amplitude for the image saturation associated with various degrees of deterioration demonstrated by vanes from Fig. 5.

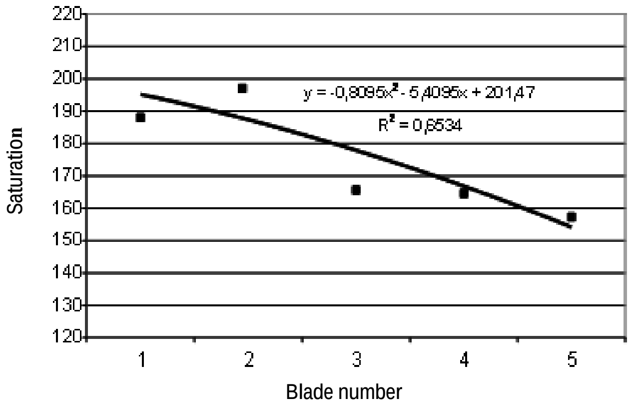



*Fig. 6. Variations of the position value for the maximum amplitude of the image intensities for various technical conditions of blades from Fig. 5 (grey scale)*

Analysis of images can be successfully carried out with the use of a use of a ring-wedge detector. The ring-wedge detector represents a ring-shaped model and is made up of two parts. The first part consists of concentrically disposed rings whilst the second part incorporates wedges with their common apex in the detector geometrical centre. Each of these areas represents a surface photo detector that converts the intensity of the incident light into an electric signal that is proportional to the intensity of that light.

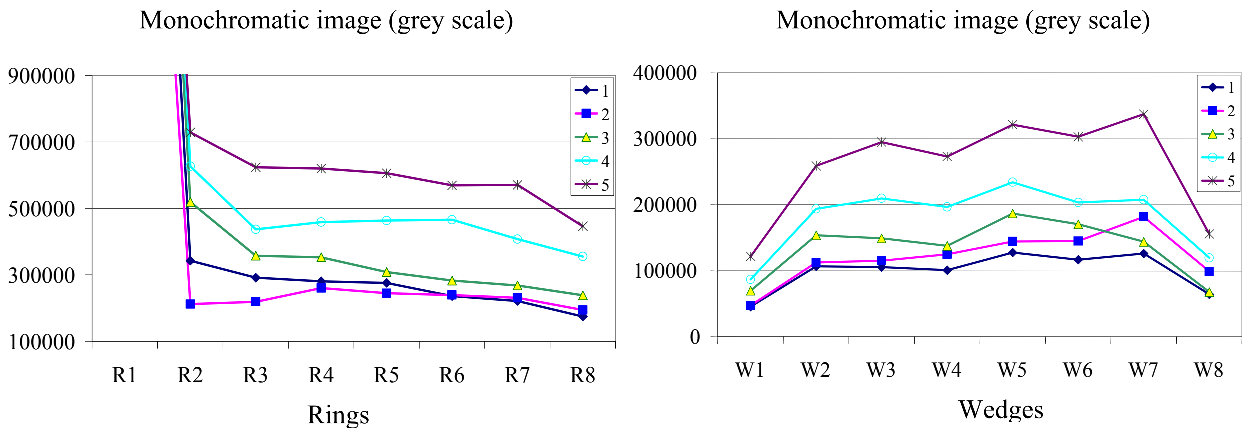



*Fig. 7. Values of rings and wedges in the grey scale for individual deterioration degrees of wedges from Fig. 5*

The computer generated hologram (CGH) has a shape that is analogical to the ring and wedge detector and is also made up of rings and wedges. Therefore CGH performs the role of an extractor that derives item features from images transformed to the frequency domain. Results from imaging and the analysis completed for surface of turbine vanes from Fig. 5 are shown in Fig. 7. Figures for wedges and rings for overheated vanes no. 4 and no. 5 clearly differ from the corresponding values for all the remaining items.

## 2.2. The thermographic method

The infrared thermographic method is based on detection of infrared irradiation and can be split into the passive and active options. The diagnosing of gas turbines with the use of the technique of passive thermography consists in recording images for distribution of temperatures at the turbine outlet (Fig. 8). When the turbine operates smoothly reference images (patterns) are recorded. Routine inspection during the lifetime period consists in the comparison of currently obtained thermographic images against patterns. Such an approach enables detection of even such defects (e.g. erosion of the entire turbine, damages to vanes, disturbed operation of the combustion chamber) that are poorly detectable with the use of other non-destructive techniques [10].

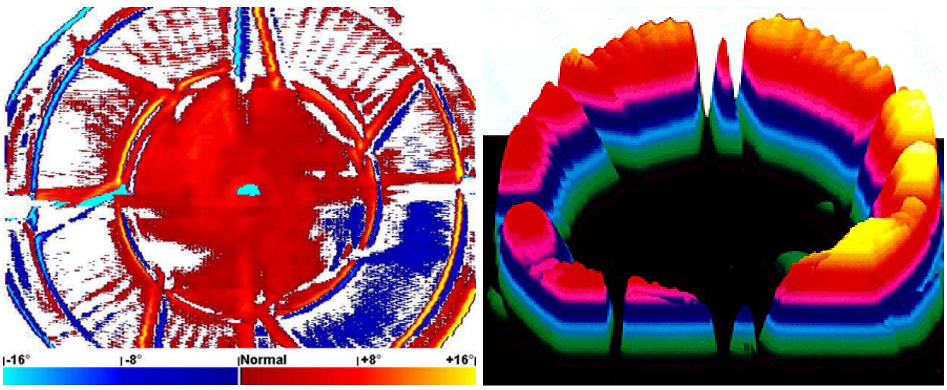



*Fig. 8. Thermographic images for the stream of combustion gas that leaves the gas turbine of a helicopter engine [13]*

Recent years have brought a development if research studies of ways to apply the method of active infrared thermagraphy to detection of material defects. Essence of such investigations consists in analysis of thermal response to stimulation by means of an external thermal pulse. Depending on the stimulation technique some options of the active infrared thermography are distinguished, such as *pulsed thermography, lock-in thermography with modulated heating* and *pulsed phase thermography* [14].

*Pulsed thermography* consists in determination and analysis of temperature distribution on the examined surface during its cooling after preliminary uniform heating up by means of a thermal pulse (Fig. 8). For a one-dimension model and a homogenous material, the formula for variation of temperature during cooling of a surface preliminarily heated up with a short thermal pulse looks like as follows [16]:

$$T(t) - T(0) \sim Q\alpha^{-\frac{1}{2}} t^{-\frac{1}{2}}, \tag{1}$$

where:

Q - energy of the thermal pulse applied to a surface unit,
α - thermal diffusivity,
*t* - time when the surface is being cooled down,
*T(0)* - temperature at the selected location or on the area of already heated surface,
*T(t)* - temperature at any moment of the cooling down process.

When any material defects or alteration to its microstructure occur, they affect the heat diffusion velocity and make the foregoing relationship inapplicable.

Thermograhic examinations employed samples of turbine vanes made of the Ei-867WD alloy. Samples were subject to heating within the temperature ranging from 1023 to 1423 K. Obtained results made it possible to find out that relationships between parameters associated with a thermal response of the material for examined vanes to a heat pulse was altered. Then, metallographic examinations were carried out to assess alterations in the microstructure of samples – chiefly alterations to the reinforcing phase γ' - $Ni_3(Al,Ti)$. Results of those studies are demonstrated in Fig. 9 as a nomogram.

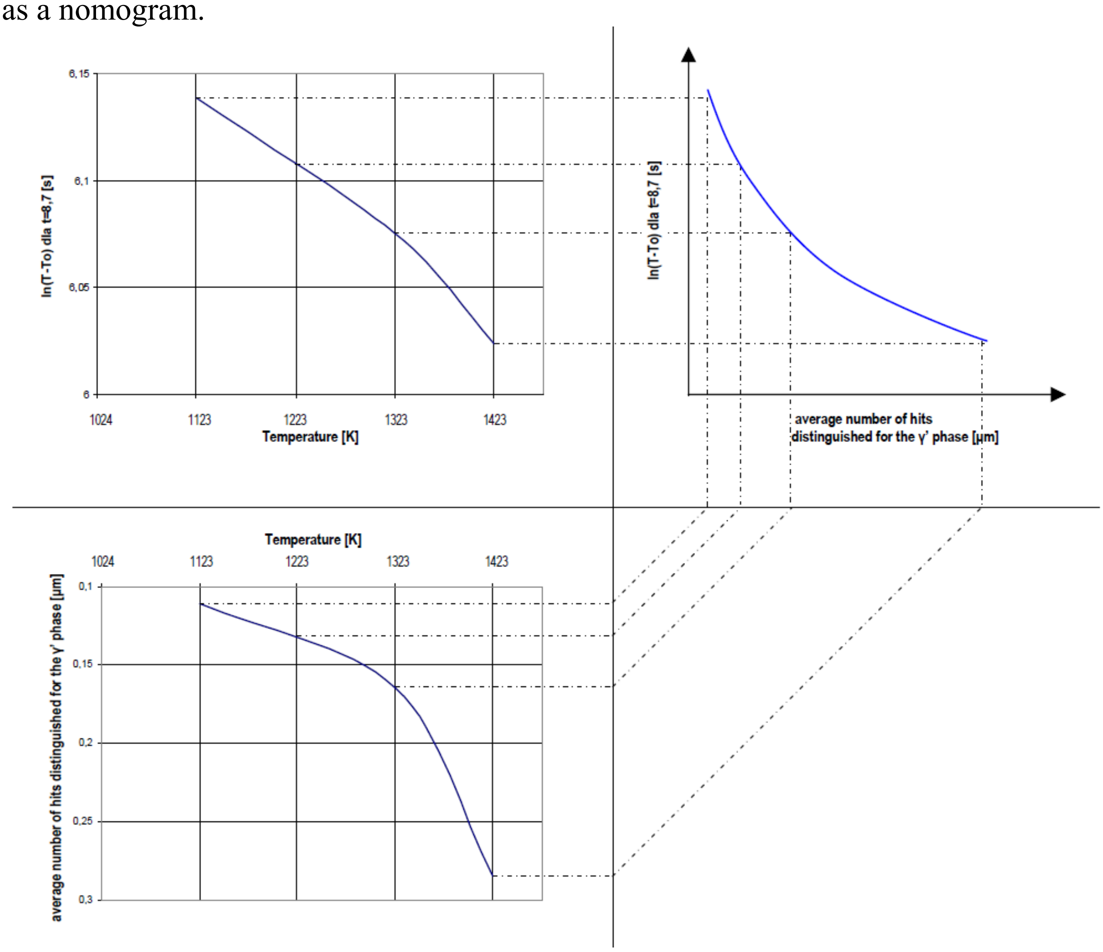



*Fig. 9. The nomogram to assess microstructures of samples taken from a gas turbine made of the EI – 867 WD alloy plotted on the basis of the relationship between variation of the parameter ln(T-To) for the signal attributable to the thermographic method and variation in the number of hits for the γ' phase at various ageing temperatures [15]*

The relationship between the thermal response of the sample material, represented as the value of *ln(T-To)* and the average number of hits for the γ’ phase enables to assess the technical condition of the sample material. This relationship, in conjunction with the permissible alterations to the microstructure, serves as a basis to judge whether the sample material is suitable or not for further service. High temperature affects both the variations of the aluminium coating and the alterations to the structure of the γ’ phase.

The investigated microstructure of the surface-adjacent layer reflects changes in the EI – 867 WD alloy and confirms overheating of the alloy structure after the vane samples had been heated at temperatures ranging from only 1223K (Fig. 10 and 11). When the material criterion is adopted, i.e. how the number of hits to the γ’ phase has changed and it is the criterion that determines the applicability of vanes for further operation, one is able to determine a threshold limit for the vane lifetime. Results from metallographic tests confirm that the vane material loses its high-temperature creep resistance at the temperatures above 1223K due to clustering of fine-grained cubical particles of the γ’ phase (Fig. 10), and formation of plates (Fig. 11).

*a)* *b)*

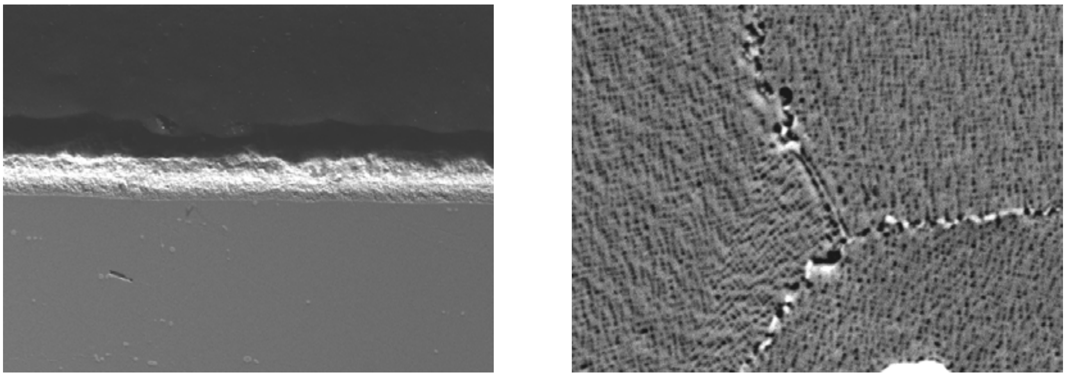


*Fig. 10. The metallographic structure of a blade that has been aged at temperature of 1023K: a) coating (x450); b) the surface-beneath layer (x4500)*

*a)* *b)*

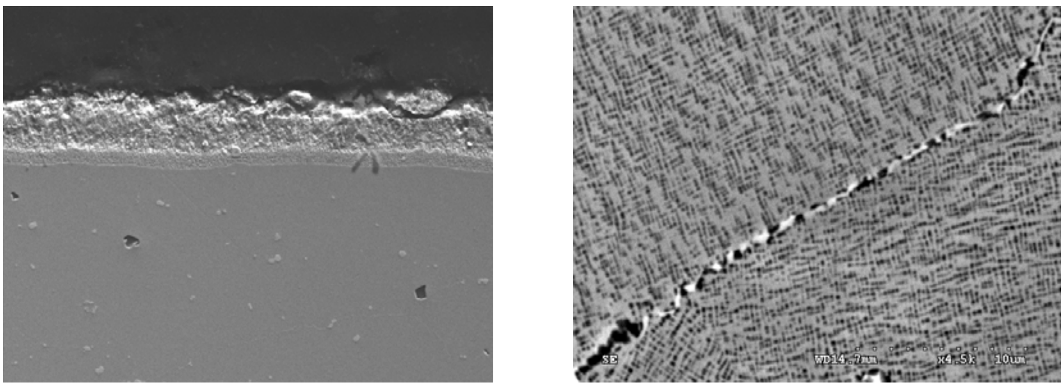


*Fig. 11. The metallographic structure of a blade that has been aged at temperature of 1223K: a) coating (x450); b) the surface-beneath layer (x4500)*

### 2.3. The method of X-ray computer tomography

Tomography is a collective name for diagnostic methods that are intended to obtain 3D images that present a cross-section of the examined item and thus a number of tomography techniques are known. For diagnostic purposes the method of Computed Tomography- CT is widely applied. It is the variation of X-ray tomography that makes it possible to obtain 3D images owing to X-raying of the object from various directions. The use of a tomograph (X-ray scanner) along with implemented computer software enables to produce tomographic images. The appliances use an X-ray tube as a source of irradiation

Detectors of X-rays that are applicable to the computer tomography chiefly include ionization chambers and scintillators. Data streams from such detectors conveys information on absorption or scattering of X-rays by individual components of the item under test. These data are stored in the computer memory and then subject to digital analysis in order to obtain greyscale images.

Nowadays the images are reproduced chiefly by means of the analytic methods. They offer the best results but they require really high computation performance. The method of 2D Fourier analysis uses the Fast Fourier Transformation (FFT) method to interpret the obtained absorption profiles. The FFT method is applied to each exposure and therefore the absorption coefficient can be determined for each voxel. The absorption coefficients are then converted to CT number, which are also referred to as Hounsfield Units (HU) [17].

$$1HU = K\frac{\mu_p - \mu_w}{\mu_w}, \quad (2)$$

where:

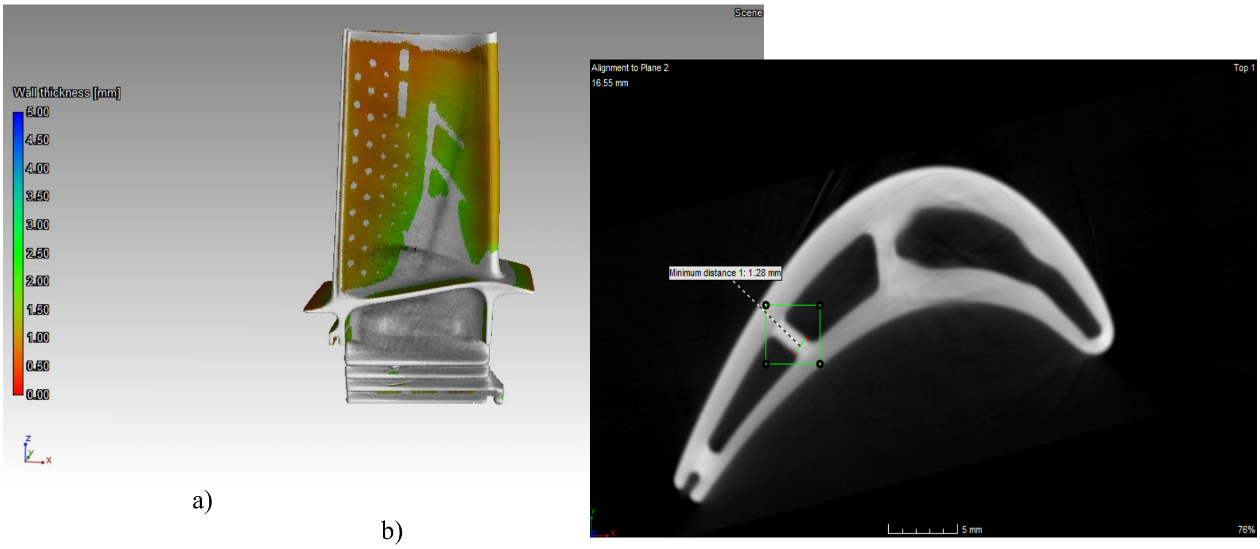
$K$ - amplification coefficient for images (a characteristic parameter for each individual tomograph),

$\mu_p$ - absorption coefficient for each pixel,

$\mu_w$ - absorption coefficient for water (the reference value).

The CT numbers range from -1000 to +4000. Best results of diagnosing the condition demonstrated by vanes of gas turbines are obtained when the technique with a linear detector is applied. Results of CT examination can be used for measurements of geometrical parameters of vanes, for instance to measure the thickness of their internal walls with cooling channels or to examine structures of materials, to detect defects or to support the diagnostic process during repairs or overhauls. Images for scanned items can be presented with the use of colours (Fig. 12) and scaled to desired dimensions to determine shapes of internal walls (size and location of defects). Geometrical parameters of internal components can be also measured with a high accuracy to establish tolerances for their actual dimensions. In addition, spectrum of the CT signal can be used to analyse alterations to microstructure of the alloy (Fig. 13).

Thus, CT examination makes it possible to achieve a high accuracy in verification whether the examined items are manufactured with sufficient accuracy or not as well as to find out alterations in the alloy microstructure or to detect internal defects, e.g. fractures, clogging of cooling channels of vanes, etc.




a) b)

*Fig. 12. Image for the gas turbine vane obtained by means of the tomograph from YXLON [17]: |a) determination of the profile thickness, b) example how to measure dimensions of internal walls.*

a) b)

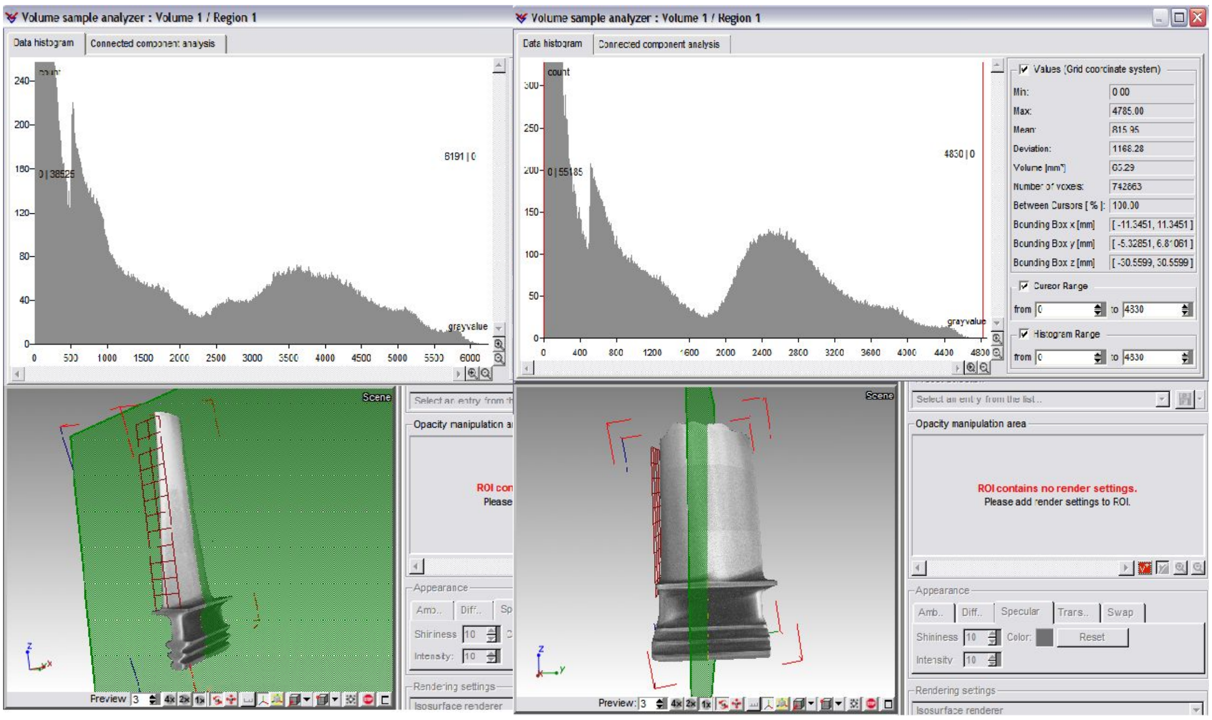



*Fig. 13. Spectra for CT signals obtained by means of the tomograph from YXLON [17] for vanes made of the EI-867WD alloy with a) correct microstructure, b) overheated microstructure.*

## 3. Conclusions

- The process associated with deterioration of gas turbine vanes starts from destruction of its protective coating. It subsequently leads to overheating of the base material that is demonstrated by detrimental alterations to their microstructure.
- The developed RGB method for digital processing of images recorded to surfaces of turbine vanes within the visible bandwidth enables to evaluate the technical condition of vanes, in particular evaluation of amendments to microstructure of vane materials.

- Analysis of images recorded for turbine vanes can be efficiently carried out with the use of a ring and wedge detector.
- The thermographic method offers investigation of interdependencies and interrelationships between signal parameters of thermal response from the vane material and alterations to the microstructure of vanes.
- The method of Computer Tomography enables quick and very accurate diagnostics of vane condition, i.e. measurement of geometrical dimensions, defects, structural faults and other irregularities.
- Application of NDT techniques presented in this paper shall substantially increase the probability that any alterations to technical condition of vanes shall easily detected as well as enable non-destructive evaluation of alterations to the material microstructure that has been unfeasible to date.

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