

**THE ASSESSMENT OF HEALTH OF GAS TURBINE
BLADES WITH NON-DESTRUCTIVE METHODS**

**OCENA STANU ŁOPATEK TURBINY GAZOWEJ
METODAMI NIENISZCZĄCYMI**

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***Abstract:** The paper has been intended to present non-destructive methods for the assessment of health of gas turbine blades in turbine and turbojet engines. Results of the assessment of changes in health/maintenance status of blades exposed to high temperatures have been discussed. All the findings gained with such methods have been successfully verified in the course of testing work carried out with some metallographic methods.*

***Key words:** turbine, diagnosing of blade's health, non-destructive testing methods*

***Streszczenie:** W artykule przedstawiono nieniszczące metody do oceny stanu łopatek turbiny gazowej silników turbinowych i turboodrzutowych. Omówiono wyniki badań zmian stanu łopatek poddanych wysokiej temperaturze z zastosowaniem tych metod. Uzyskane wyniki z powodzeniem zweryfikowano badaniami metodą metalograficzną.*

***Słowa kluczowe:** turbina gazowa, diagnozowanie, metody badań nieniszczących*

1. Introduction

Reliability and durability of aircraft turbine and turbojet engines highly depend, apart from many and various structural components ‘responsible’ for the efficiency of the whole structure, upon the gas turbine, the blades of which suffer high thermal loads in aggressive environments, i.e. affected by combustion products. Structural materials used nowadays in turbine blades, in particular their creep resistance, resistance to thermal cycling (i.e. thermal endurance), high-temperature sulphur corrosion, and erosion, build up a barrier to the increase in temperature of gases in front of the turbine. High operating temperatures and high rotational speeds of the gas-turbine rotor force application of expensive heat-resisting and high-temperature creep resisting alloys, as well as designs of gas-turbine blades of complex and complicated geometric shapes. The ultimate objective is that functional qualities of these blades are significantly improved.

The main cause of damages/failures to gas turbine blades is thermal fatigue. Also, blade material overheating, while initiating microcracks, considerably contributes to changes in microstructure and deterioration in functional properties of the material, since the propagating microcracks may pretty often result in total failure of the component. Numerous instances of material overheating as well as burn-outs and, in consequence, break-offs of turbine rotor blades in jet engines. The reasons for such failures are highly disadvantageous operating conditions (Fig. 1) and manufacturing defects, e.g. application of protective coatings of insufficient strength, or coatings incorrectly spread on the blade material (Fig. 2).

Therefore, early detection and correct interpretation of any symptoms of probable hazards, carried out with any available, non-destructive diagnostic methods, is for any user of an aircraft engine extremely important. All such actions are intended to prevent any severe damages/failures, and to make any repairs in the way most advantageous from the point of view of the minimisation of losses.



Fig. 1 Temperature-attributable damages to edges of attack of turbine rotor blades, exemplary videoscope records [1]

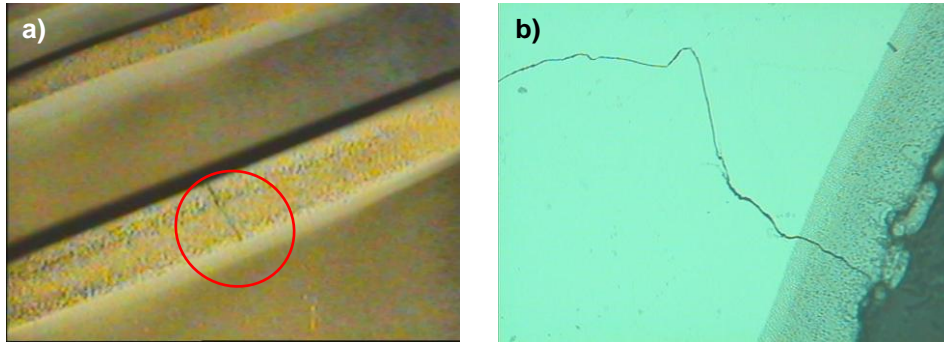


Fig. 2 A protective coating with a crack that propagates into the parent material of the blade [2]. Images from a) a videoscope, and b) a microscope, magn. x 450

2. Reasons for changes in the microstructure of a gas - turbine blade

Experience gained up to the present in the course of research work carried out at Air Force Institute of Technology [1 – 3] proves most of damages/failures to gas turbine blades directly result from improper adjustments (temperature) and the composition of an aircraft fuel blend.

Improper fuel pressure, physical and chemical properties deteriorated due to impurities of any kind, fuel injector in the flame tube head out of position – all these significantly contribute to carbon deposit formation on the injector (Fig. 3) and other subassemblies. A direct consequence of the presence of carbon deposits is improper fuel spray pattern. This results in disturbances in both the combustion process, and hence, the thermal-field distribution in the engine's hot section (Fig. 4).

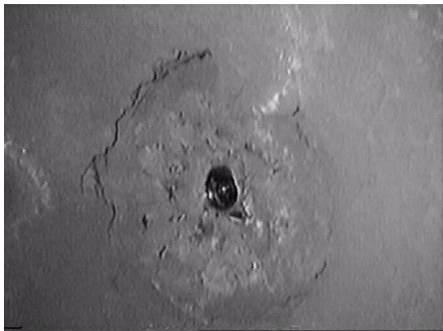


Fig. 3 Carbon deposit on the fuel injector in the gas turbine engine [3]

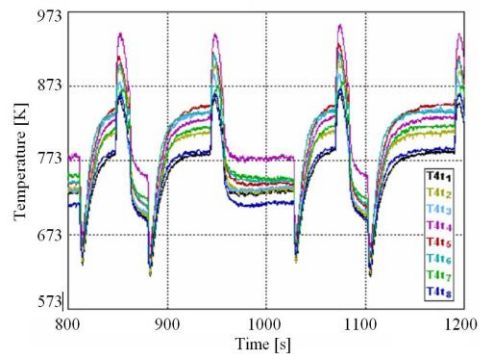


Fig. 4 Exemplary distribution of unevenness of the T4 temperature on the perimeter of the turbine in the function of time and rotation speed of an aircraft aerial engine, measured with help of thermoelements ($T4t_1 - T4t_2$) behind the turbine [4]

In effect, disadvantageous changes in the microstructure of gas-turbine blades take place. Examination of the microstructures of blades made from the EI-867WD alloy, visually qualified either as ‘fit for use/serviceable’ (new) or ‘unfit for use’ (worked out), has delivered images of the microstructure of this alloy that show growth of the strengthening gamma prime γ' phase (Fig. 5). What the morphology of the gamma prime phase points to is a change in the material of a blade recognized as ‘unfit for use’, i.e. transition from the common cuboidal shape (Fig. 5a) to the lamellar one (Fig. 5b). It proves some disadvantageous change to the microstructure has occurred due to high temperature of exhaust gas.

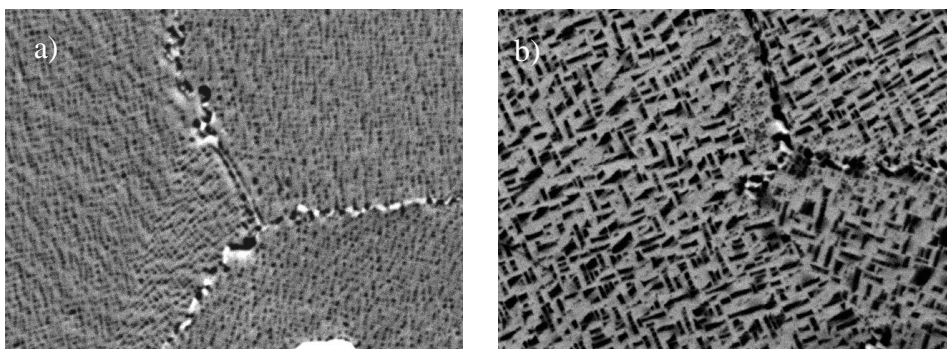


Fig. 5. The EI-867WD alloy microstructure (magn. x 4500)[3]: a) correct, b) overheated

After the critical temperature has been exceeded, the alloy suffers overheating, which results in the deterioration in mechanical properties (Fig. 6). Such being the case, the turbine blade cannot be acknowledged as ‘fit for use’, since condition thereof is hazardous to safe operation.

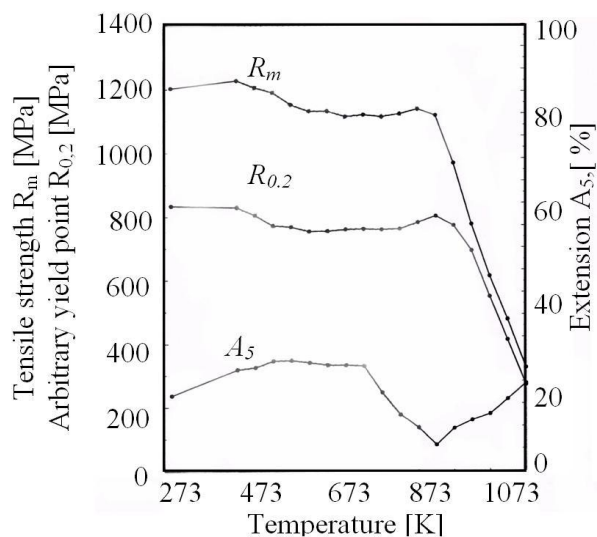


Fig. 6 Mechanical properties of alloy EI-867 versus temperature [5]

3. A method to assess changes in the microstructure of a gas turbine blade

Many and various methods are used to diagnose condition of gas turbine blades. These are as follows: visual inspection, penetrant testing, ultrasonic testing, radiographic testing, thermographic inspection, leak testing/detection, and eddy-current testing techniques. All these non-destructive methods and techniques enable:

- detection of discontinuities in materials (flaw detection);
- assessment of materials properties;
- determination of dimensions of objects and measurements of protective coating thickness (metrology);

Quite recently several new non-destructive testing methods have been developed and implemented, see [6 – 9]:

- analysis of the object surface image gained in white light – the RGB method,
- detection of infrared radiation emitted by the object under examination – a thermographic method.
- X-ray computed tomography (CT).

4. The RGB method

A visual RGB method based on three additive primary colours (red – R, green – G, blue – B) makes use of relationships between light's properties of wave and physical-and-chemical properties of surfaces under examination. These relationships prove essential to properties of the incident and reflected light, and to absorption of particular wavelengths of the electromagnetic radiation spectrum [6]. The assessment of the blade condition consists in the colour analysis of images of the surface in question, and is closely related with the material criterion, i.e. a change in the γ' precipitates morphology .

Using a nomogram that presents the relationship between changes in the blade-surface colour and the blade-heating temperature, one can assess changes in the microstructure of an alloy in question. Images recorded by means of the CCD matrix are analysed with dedicated computer software that makes use of image-processing algorithms and earlier developed master (standard) images, which allows of qualitative assessment of the surface under examination. This method has been applied to assess gas turbine blades made from the $\dot{Z}S6$ -K alloy (Fig. 7).

With use of m-files developed in the MatLab software environment one can extract and amplify properties of the images recorded for the examined surfaces. These properties are demonstrated as histograms that represent distribution of intensities for individual components of colours as well as parameters that are determined for the matrix of events.

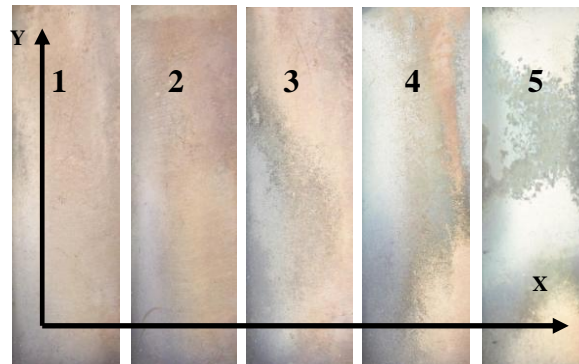


Fig. 7 Images for surfaces of gas turbine blades made of the ŻS-6K alloy, ordered according to the criterion of the increasing degree of the material overheating (1,2,...., particular states of blades) [6]

Specific parameters, such as location of the maximum amplitude (the intensity value for RGB colours), averaged valued for the entire images (intensity values that are added together in each row and then divided by the number of rows) as well as the value for the maximum amplitude are calculated for the examined blade section. The histogram brings quantitative information on intensity of the recorded image and each histogram is represented as a single vector where the vector length corresponds to the number of the intensity steps. To achieve homogeneity of values represented by various histograms the term of normalized histogram is introduced, where the individual values are divided by the total number of pixels. Fig. 6 presents examples for variations of the position value for the maximum amplitude of the image intensities for various technical conditions of blades from Fig. 8.

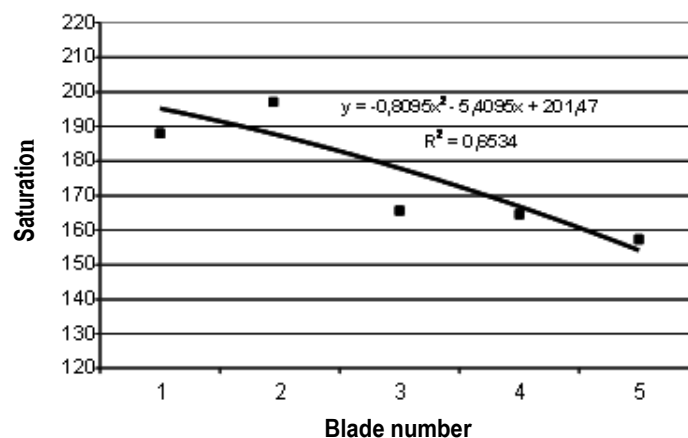


Fig. 8 Variations of the position value for the maximum amplitude of the image intensities for various technical conditions of blades from Fig. 7 (in grey scale) [6]

Satisfactory results can be achieved when the ring-wedge detector is used for the analysis. The ring-wedge detector is a circle-shaped structure that is made up of two parts, where the first part is represented by concentrically deployed rings and the second part comprises wedges with the common vertex in the geometrical centre of the detector. Each of these areas is considered as a surface light-detector that transforms intensity of the falling light into the signal that is proportional to that intensity of the falling light.

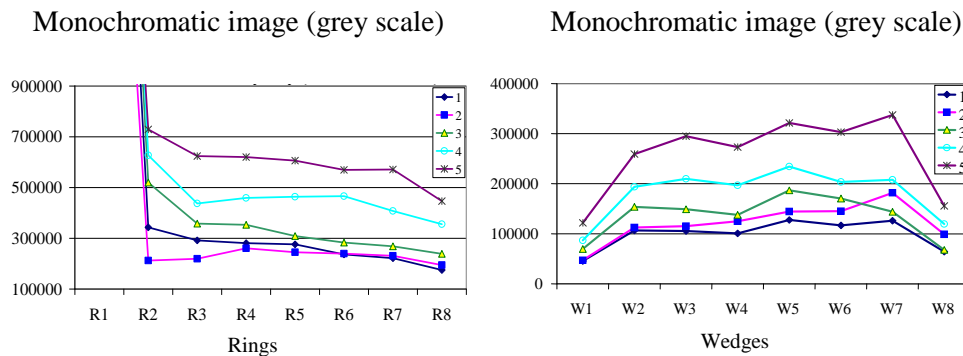


Fig. 9 Values of rings and wedges in the grey scale for individual deterioration degrees of wedges from Fig. 7 [6]

The hologram produced by the computer software (KGH) presents the shape that is identical to the ring-wedge detector and is also made up of ring and wedge areas. Therefore the computer hologram (KGH) acts as the extractor of features from images that are presented in the domain of frequencies. Results of the analysis of images for surfaces of the turbine blades from Fig. 5 are shown in Fig. 7. Values for wedges and rings overlapped to overheated blades no 4 and no 5 are clearly different from the remaining ones.

Every instrument that is equipped with a CCD matrix may produce RGB components with slightly different spectral characteristics which, in turns, is associated with some restrictions to the range of parameters, e.g. intensity of colours. Therefore not only is it necessary to develop algorithms for a specific type of equipment but also standard patterns are necessary for each individual types of surfaces, e.g. blades of individual turbines.

5. Active thermography

Examination of gas turbine blades has been carried out with the Echo Term System equipment applied, with the pulsed thermography method. It consists in finding and analysing temperature distribution on the surface under examination in the course of its being cooled down, after having it earlier heated uniformly up with a heat pulse (Fig. 10).

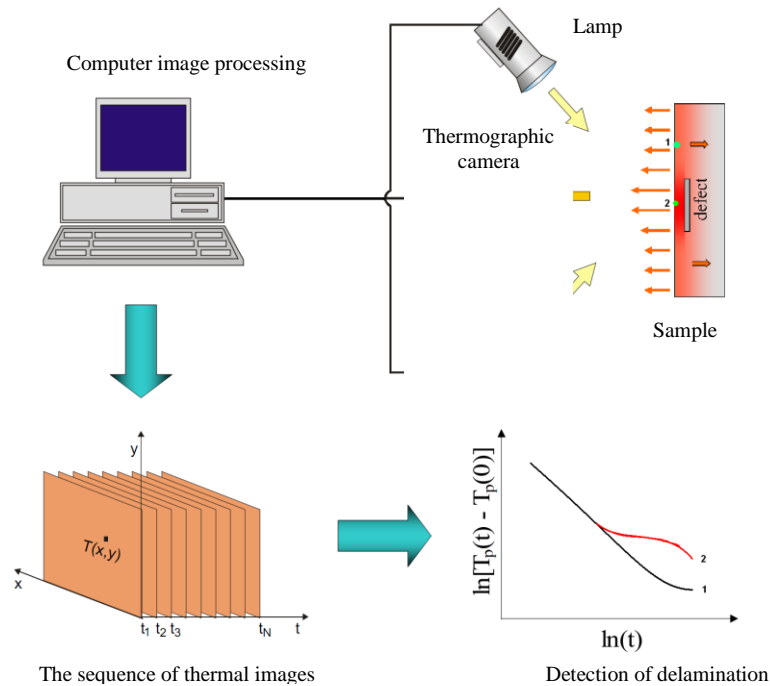


Fig. 10 A diagram of the pulsed thermography measuring system [7]

Diversified physical properties of materials enable special-line diagnostic methods to be applied to evaluate materials health, structural condition, material identification, etc. The pulsed-thermography technique was applied to get discrepancies in temperature values in the course of cooling down the material samples' surfaces earlier subjected to excitation with a thermal pulse (Fig. 11).

Subject to thermographic examination were gas turbine blades made of the EI-867WD alloy classified into the following categories: new, in service and fit for use, damaged in the course of turbine engine operation. The results gained have shown changes in the dependences between parameters of thermal responses of materials of blades under examination to a stimulating thermal pulse (Fig. 12). The dependence of the blade material's thermal response in the form of $\ln(T-T_0)$ against average size of precipitates of the γ' phase allows of the evaluation of the blade material's condition. On the basis of this dependence, if permissible changes in the microstructure are known, one can evaluate whether the blades are fit for use (serviceable), or unfit for use (unserviceable). High working temperature, of the 1200 K order and higher [3, 8], results in disadvantageous changes in the alloy microstructure and that of the protective coating. With account taken of the material criterion, i.e. a disadvantageous change in the morphology of precipitates of the γ' phase, one can evaluate the 'fit for further use' threshold.

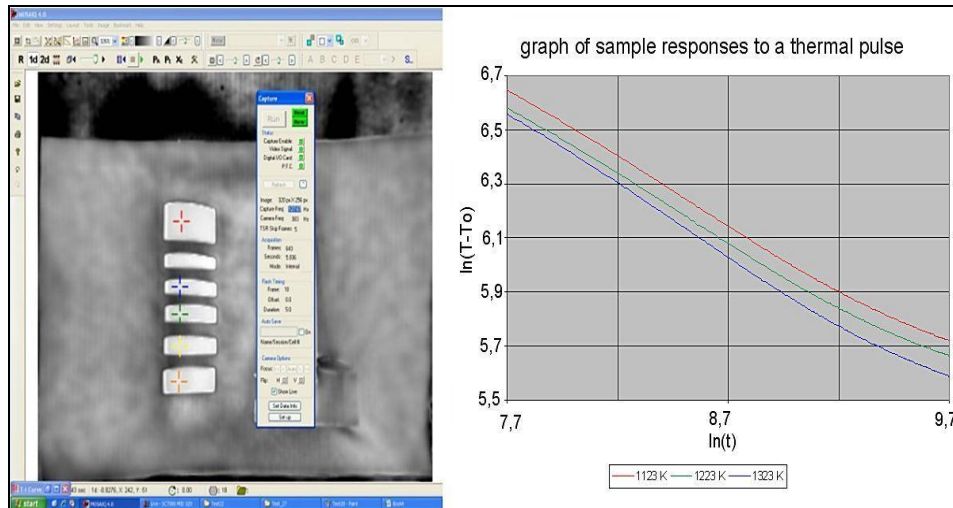


Fig. 11. Thermograms from blades examination, and temperature curves for a selected location upon the blade surface [8]

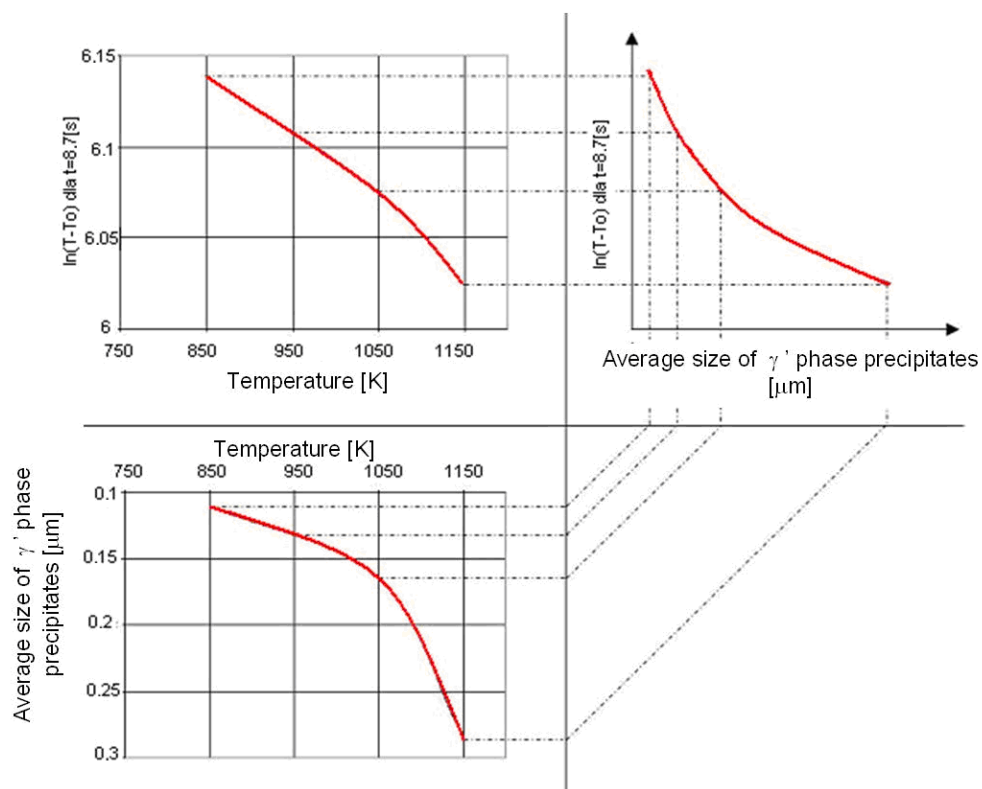


Fig. 12. Thermal response of the blades EI-867WD alloy in the form of $\ln(T-T_0)$ against average size of precipitates of the γ' phase [8]

6. The tomography method

Tomography is a collective name for a set of diagnostic techniques intended to obtain a 3D image that present cross-sections of the test piece. Many fields of technical diagnostic systems widely use the method of computer tomography (CT). 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. A tomograph (X-ray scanner) along with an implemented computer software is used to enable processing of tomographic images.

To diagnose condition of gas turbine blades it is necessary to reproduce internal structure of the test piece with very high accuracy e.g. in order to determine dimensions of walls or to detect defects (failures). It is why the best results can be obtained with the use of the method with a linear detector (Fig. 13). That method assumes that the radiation beam is confined by means of a slit diaphragm (beam stop) to a flat beam in order to use a digital linear detector (only one row of sensors). After rotation of the test piece by 360° a flat X-ray image is obtained for the slice. In order to obtain a 3D image for the entire test piece the detail must be additionally moved along a horizontal plane with a full revolution after each step. The full 3D image is obtained after processing of all the collected information.

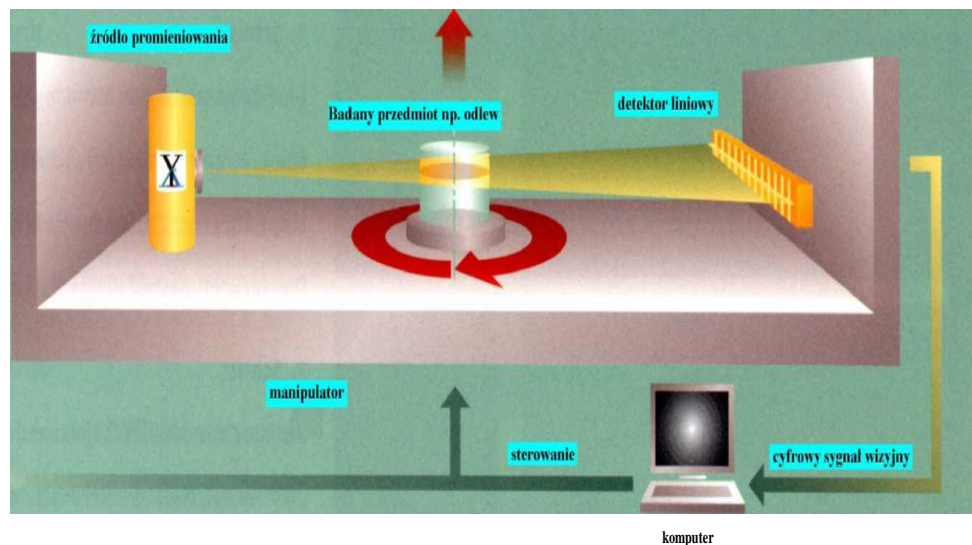


Fig. 13 Example of a tomographic examination with the use of a linear detector [9]

Tomographic examinations enable to verify correctness of the part manufacturing with very high accuracy and to diagnose possible internal defects (cracks, clogging of cooling channels, etc.) in blades that may directly result in thermal defects during operation of engines (Fig. 14).

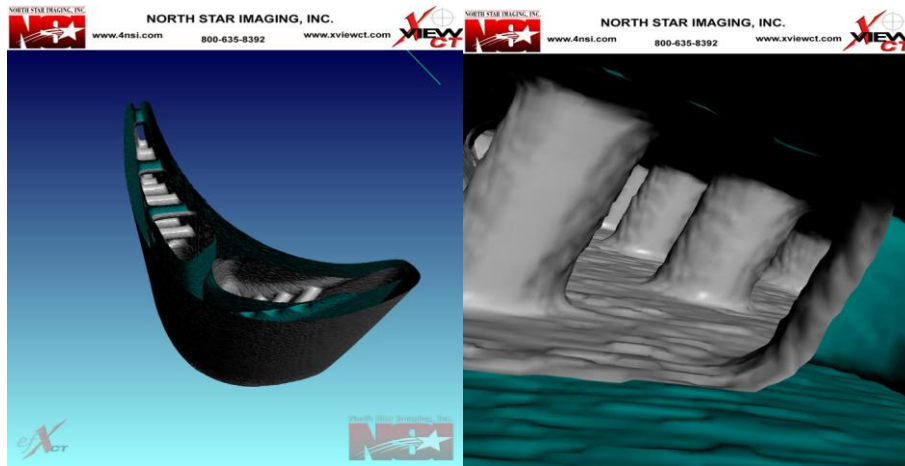


Fig. 14. The image of the gas turbine blade by means of the tomography from North Star Imaging [10]

7. Conclusions

- 1) The destructive process that affects the gas turbine blades starts with destruction of the protective coating. This results in the overheating of the blade material and manifests itself in unfavourable changes in the microstructure;
- 2) The RGB method for digital processing of images of turbine blade surfaces in visible spectrum of an electromagnetic wave enables the assessment of blades condition, in particular changes in their microstructures;
- 3) To analyse surfaces of gas turbine blades one can successfully apply a ring-wedge detector;
- 4) Thermography enables determination of dependencies and relationships between parameters of signals of material's thermal response and changes in states of blade microstructures;
- 5) The CT (computed tomography) method enables fast and very accurate diagnosing of the condition of blades, i.e. blade geometry, failures/damages, structural defects and other anomalies;
- 6) The above-presented NDT methods are expected to considerably improve the probability of detection of changes in blades condition, and in particular, to carry out in the non-destructive way the hitherto unavailable assessment of changes in blade microstructures.

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