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ANALYSIS OF APPLICABILITY OF THERMOGRAPHY TO ASSESS HEALTH OF GAS TURBINE BLADES

Artur Kułaszka

Air Force Institute of Technology
Księcia Bolesława Street 6, 01-494 Warsaw Poland
tel.: +48 22 6851-388, fax. +48 22 6851-338
e-mail: artur.kulaszka@itwl.pl

Józef Błachnio[1,2]

[1]Air Force Institute of Technology
Księcia Bolesława Street 6, 01-494 Warsaw Poland
tel.: +48 22 6851-393 fax. +48 22 6851-434
[2]Białystok Technical University
Wiejska Street 45C, 15-351 Białystok, Poland
e-mail: jozef.blachnio@itwl.pl

Abstract

A gas turbine is one of the most heavily loaded, both mechanically and thermally, structural components of an aircraft turbine engine. Hence, the most common reasons for failure are overheating and thermal fatigue of the blade material. It is of great significance for the safety of aeronautical systems that service is monitored; this is carried out to verify the health of these items using all available diagnostic methods. The primary aim is to detect and identify, as early as possible, any probable hazards to the engine. The preliminary assessment of the gas turbine blades condition is carried out via a visual inspection e.g. using a video borescope. During any repair, the preliminary assessment is conducted with a visual method, which is followed with some other non-destructive inspection techniques, e.g. flaw detection, intended to provide full colour images. The essential assessment of the blade condition consists in metallographic examination which precludes further operational use of the item. Probable errors in this assessment usually result in considerable cost of unnecessary repairs of the entire engine. Presented in the paper is the pulse thermography technique being a new NDT method, which is capable of diagnosing changes in the blade condition and to detect early stages of damages to turbine blades. Results of inspections of the blades subjected to high temperature and corresponding changes in signals of thermal response of the blade material stimulated with a heat pulse have also been given. Effects of the testing work have been used to detect changes, against temperature, in thermophysical properties of super alloy used in gas turbine blades. The results have been successfully verified using metallographic examination. To conclude: the thermographic method provides good reliability of the assessment of changes in the microstructure of the blade.

Keywords: *engines, aircraft engineering, mechanical engineering*

1. Introduction

The need to accomplish the most stringent efficiency and performance parameters in new designs is driven by requirements of: improved operational results, optimized weight and dimensions etc. This enforces continuous progress both in the areas of new design features of aircraft engines as well as the materials the engines are composed of. In terms of lifetime and equipment operation, the trends aim at maximization of the availability parameter, i.e. the ratio of the equipment operation time to the time of its maintenance, which is supported by new and upgraded operation technologies as well as implementation of the operation management. At the same time new and updated maintenance methods are put into practice, in particular in the field of diagnostics that are beneficial to improvement of the operational reliability and flight safety.

However, in spite of all achievements, operation of aircraft engines is always associated with various and random-distributed failures.

The units that are the mostly exposed to failure are those that are subject to mechanical and thermal loads. The most complex and diverse impacts affect gas turbines, whilst the technical condition of turbine blades is the crucial factor that determines reliability and lifetime of the entire engine where the turbine is embedded [4, 6]. The main reason for failures of gas turbine blades is overheating and thermal fatigue of the material [5, 8, 10]. Thermal stress is caused by unfavourable conditions of the turbine operation or manufacturing flaws. The important reasons that lead to failures of turbine blades include insufficient strength of protective coatings applied to blades, use of poor quality fuel, adverse operating conditions, in particular when the maximum permissible temperature of exhaust gas is exceeded for short time periods due to faulty operation of automatic control for the rotary machine and to disturbances in internal cooling of turbine blades.

The diagnostic process intended to reveal actual technical condition of turbine components. This usually involves visual inspection that is the most popular test method [5, 9]. It enables inspection of difficult to access components of the engine using a non-destructive method. However, the reliability and trustworthiness of this method is highly unsatisfactory in giving a complete diagnosis. Such a visual examination is usually carried out by a serviceman with the use of a videoscope. The images acquired for the investigated surfaces, e.g. a blade, are then compared against reference patterns. Such results may be subsequently verified at workshops by means of destructive examination of several blades from the entire set (Fig. 1) to find out whether the full set of turbine blades is suitable for further operation or not. Such an approach is unfavourable for both economic and safety reasons.

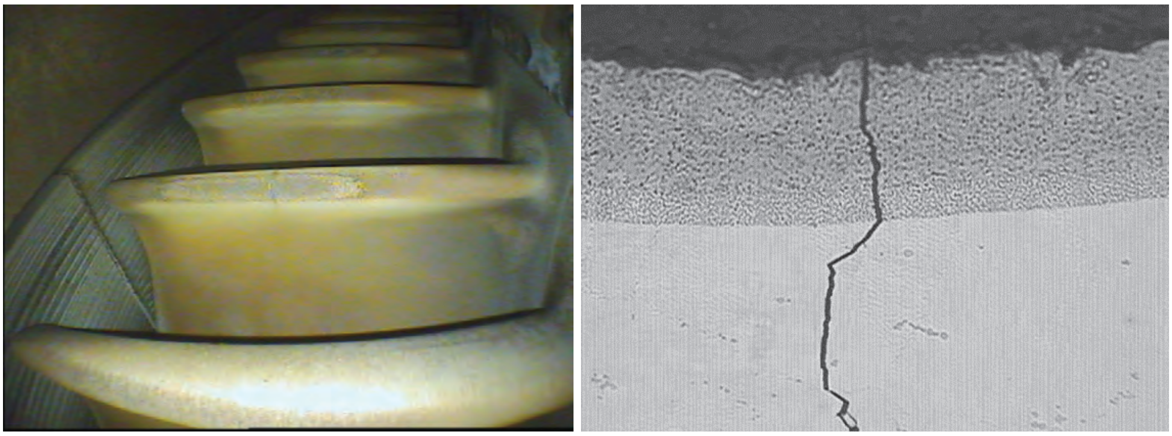

Fig. 1. Image of a crack of the protective coating with crack propagation into the parent material of the blade body [5]: videoscopic image – a) microscopic image, magn. x 450

Among numerous non-destructive methods for diagnostic examinations that experience intense growth over the recent years, the thermographic investigations deserve particular attention [2, 3, 7]. Thermal photography enables measurements of temperatures as well as examination of its distribution from the infrared radiation emitted by surfaces during testing.

The power emitted via electromagnetic radiation by surfaces of a body, over the full spectrum range, depends on the temperature of the surface. The peaks of power radiated lie within the infrared bandwidth. The infrared radiation ranges with wavelengths of 0.75 to 100 μm and falls outside the very narrow interval (0.4 to 0.7 μm) that is visible to the human eye. When a suitable detector of infrared radiation is available and the relationship between the radiation power and the temperature of the emitting surface as well as the relationship between the signal provided by the radiation detector at its output and that radiation power delivered to the detector input one can determine the surface temperature in a contactless way. The method of IR thermography based on detection of infrared radiation can be split into the passive and active variants.

2. Application of the method of thermal photography for evaluation of technical condition demonstrated by gas turbine blades

The method of thermal photography has already been applied to various research studies, including determination of its applicability to evaluation of clogging in internal cooling channels of turbine blades. Improvement of general turbine efficiency and its power factor is directly related to the temperature of exhaust gas. Since further increasing of temperature proved unfeasible due to unavailability of suitable materials, it required the use of sophisticated geometrical shapes of turbine blades. This in turn, has made the manufacturing process more complicated and resulted in application of various improving measures, e.g. cooling of blades. Experience from operation of the turbine as well as investigation of turbine blades at service workshops has revealed that not only material defects are reasons for failures of blades, but also disturbances of internal cooling systems caused by clogging and obstacles in cooling channels. The turbine blades were examined with use of the conventional optical method, the RWA and the TSR (Thermographic Signal Reconstruction), where the latter is used by tomographic devices. The application of the pulse thermographic method with appropriated, purposefully developed software, enabled the researchers to easily inspect the internal system of channels designed to cool down the blades and check for any obstructions. The thermal photography method excels over X-ray examination due to the fact that it does not use hazardous to health X-ray radiation that is harmful to examining staff. and requires installation of the test equipment in dedicated rooms with protecting measure and access control. Also unit costs of each examination is lower since the method requires no expensive consumables and the examination results are available within a short time after the examination is completed. Another method that assumes measurements of liquid volumes passing through the blade cooling channels is less and needs more involvement and time when compared to the method of thermal photography.

The results from investigation of turbine blades by means of the pulse thermography (PT) applied to examination of the material discontinuity within its subsurface layers inspired the researchers to embark on studies aimed to find out whether the PT method can be also applied to evaluate microstructure alterations in gas turbine blades with use of the available equipment and instruments.

3. The underlying phenomena for evaluation of the blade microstructure by means of the thermographic method

When an amount of energy is applied to the material surface, e.g. in the form of a heat pulse (Fig. 2) the surface temperature rises rapidly. After the pulse, the surface temperature decays because the thermal front propagates by diffusion under the surface. Later, the presence of a subsurface defect (i.e. the areas that differ in thermal and physical properties) alters the diffusion rate. Consequently, monitoring of the surface temperature, such as subsurface defect appears on the surface that is cooling down at the moment as an area of different temperature. Therefore, the method offers the possibility not only to analyse discontinuities that occur inside the material body but also to reveal undesired microstructure alterations in the material under test. [2, 7].

Thermal diffusivity a is the basic physical parameter that is necessary to define temperature fields and gradients that vary in time. It also relates to the thermal conductivity λ that is rated among the most important parameter of each material. However one has to note that the thermal conductivity describes the material as a heat conductor under the conditions of steady heat exchange, whilst the thermal diffusivity is considered as a criterion for a specific material when heat exchange varies dynamically.

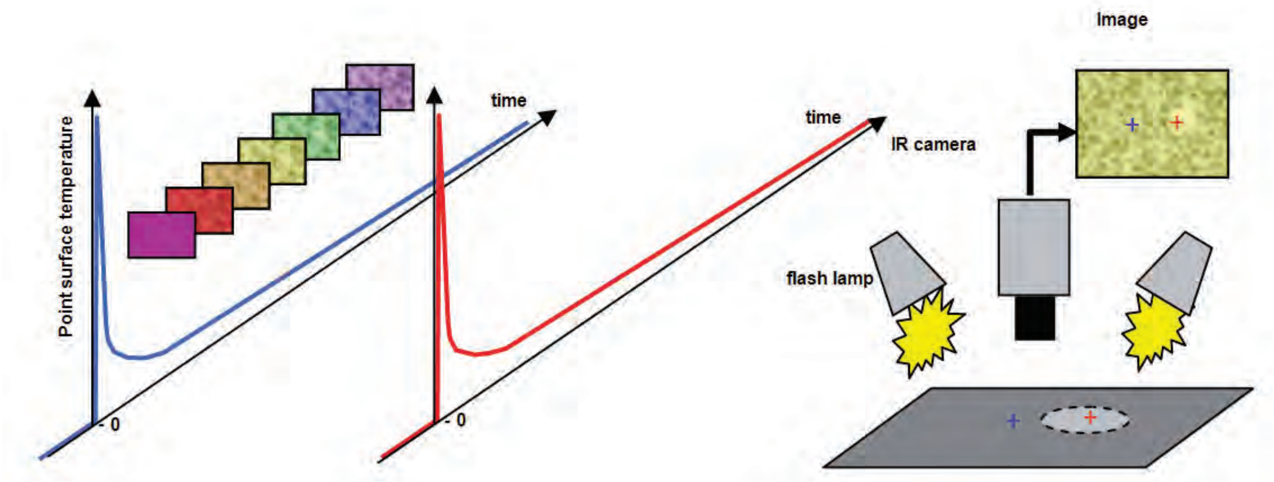

Fig. 2. The diagram for application of the Pulse Thermography [3]

Thermal diffusivity of immobile, isotropic and opaque solids with the thermal diffusivity of a, density of ρ, specific heat under constant pressure C_p and productivity of internal heat sources of q_v is usually a function with values that depend considerably on the temperature distribution T(x,y,z,t). Such time and space distribution is described by the Fourier-Kirchhoff equation. For the Cartesian coordinate system the equation adopts the following form:

$$\frac{\partial T}{\partial t} = a\nabla^2 T + \frac{1}{\rho C_p}\frac{\partial \lambda}{\partial T}\left[\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2\right] + \frac{q_v}{\rho C_p}. \tag{1}$$

Upon the assumption that thermal conductivity for a specific body is constant (λ=*const*) and no internal sources of heat are present inside the material, the equation (1) adopts the form:

$$\frac{\partial T}{\partial t} = a\nabla^2 T\,. \tag{2}$$

Thermal diffusivity a of the medium as the measure of the medium ability to convey heat (i.e. its thermal conductivity) and its ability to accumulate heat (i.e. thermal capacitance) is expressed by means of the formula:

$$a = \frac{\lambda}{\rho C_p}. \tag{3}$$

As one can see, the process of temperature equalization in time proceeds faster when the value of the thermal diffusivity α is higher for the specific material. Tab. 1 lists example values of thermal diffusivity for selected materials at T=293K.

Tab. 1. Values of thermal diffusivity for selected materials at T=293K

Material type	Thermal conductance λ	Density ρ	Specific heat C_p	Thermal diffusion a
	[*W/(m*K)*]	[*kg/m*^{3}]	[*kJ/kg K*]	[10^{-6} m^2/s]
Aluminium (Al)	206.17	2696	0.879	87.0
Tungsten (W)	168.54	19350	0.134	65.0
Molybdenum (Mo)	137.07	10200	0.0255	52.70
Nickel (Ni)	92.33	8900	0.457	22.7

4. Results from thermographic investigations of gas turbine blades

The investigations were carried out for new blades made of the EI–867 WD alloy which were installed in a gas turbine rotor which was incorporated into a turbojet engine. The blades were not cooled inside the engine. The manufacturing process of the blades included cold forming. The alloy belongs to the very few materials that are free of titanium and contain less admixture of chromium, which makes the alloy susceptible to corrosion. For that reason a protective coating of aluminum layer is applied onto the blades. The standard (technical conditions) TU (ТУ) 14-1-232-72 specifies requirements with regard to chemical composition of the EI–867 WD alloy (Tab. 2).

Tab. 2. Composition (% w/w) of the EI–867 WD according to the HN62MWKJu (ХН62МВКЮ) standard

C	**Mo**	**Si**	**Cr**	**Ni**	**Co**	**Mo**	**W**	**Al**	**B**	**Fe**	other
max	max	max		rest					max		
0.1	0.3	0.6	9.0		14	10.3	5.0	4.5	0.02	4.0	0.3 V, 01 Ba max

The blades were heated up with a very short heat pulse and the thermal response (echo) of the material was recorded (variations of temperature on the examined surface) for selected areas with use of thermographic measuring and logging instruments. Additionally, the blades were heated in an oven in the presence of exhaust gas from combustion of aircraft kerosene at various temperatures (from 1123K to 1523K) and then subjected to the same investigation procedure on the thermographic workbench. As a result from the completed investigations the difference in thermal and physical response was revealed for the blades under test before and after heating at various temperatures (Fig. 3).

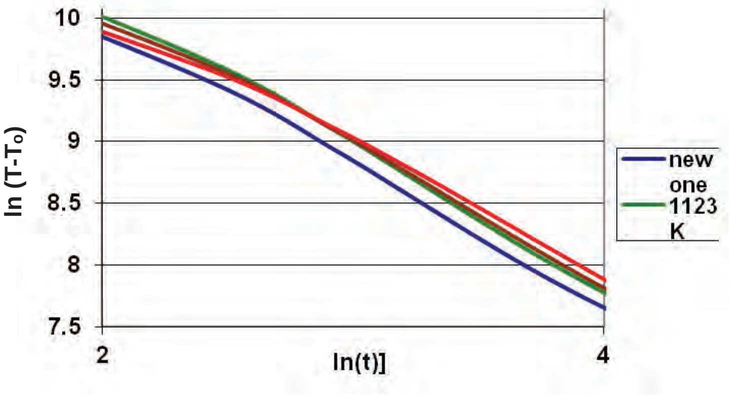

Fig. 3. Results for the response of the blade material to a thermal pulse for new and preheated blades

5. Metallographic investigations

The completed metallographic investigations of blades previously subjected to heating at various temperatures demonstrated that high temperature induces changes in microstructure of both the coating material and the parent alloy EI–867 WD. The thickness of the aluminum protective coating increases with growth of the heating temperature (Fig. 3, 4) with simultaneous deterioration of its heat resistance. The process of grain growth takes place in the alloy (Fig. 5) that adversely affects its mechanical properties [1]. The alterations are particularly visible within the reinforcing γ’ phase since modification of the structure is observed for that phase (Fig 6). The temperature of 1123 K is conducive to growth of small particles within the γ’ phase. At the temperature of 1323 K, mid-sized particles of that phase expand. Finally, at the temperature of 1523 K the particles with the largest initial size exercise further growth due to coagulation. In consequence, the number of particles with the largest sizes gradually decreased with the temperature growth and is much less than in the material of new blades and the ones subjected to heating at the temperature of 1123 K (Fig. 7). At the same time the distance between individual particles of the γ' phase became larger. The revealed growth, clustering and corrugation of particles within the γ' phase lead to substantial deterioration of heat resistance demonstrated by the alloy [1]. When the number of particles developed to the γ' phase is adopted as the criterion of the material applicability for further operation, one is able to determine a threshold limit for the blade lifetime.

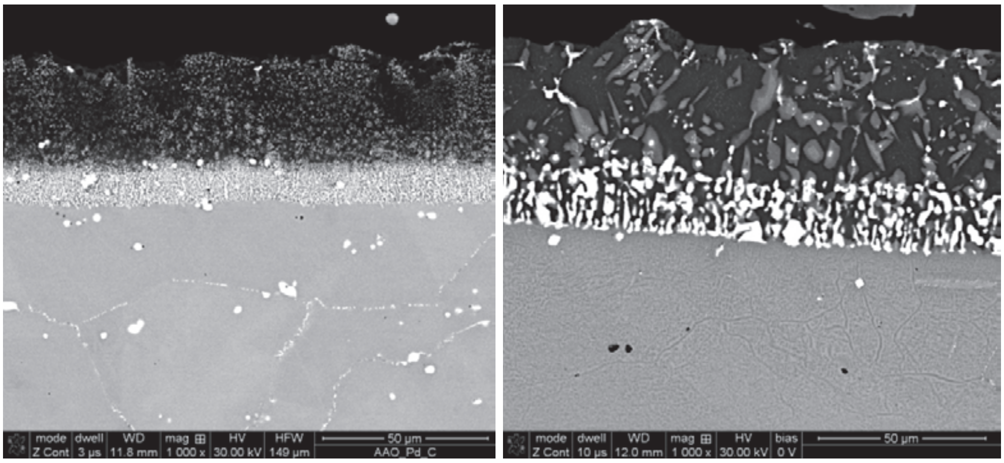

Fig. 3. Surface layer of a new blade and the one preheated to the temperature of 1423K

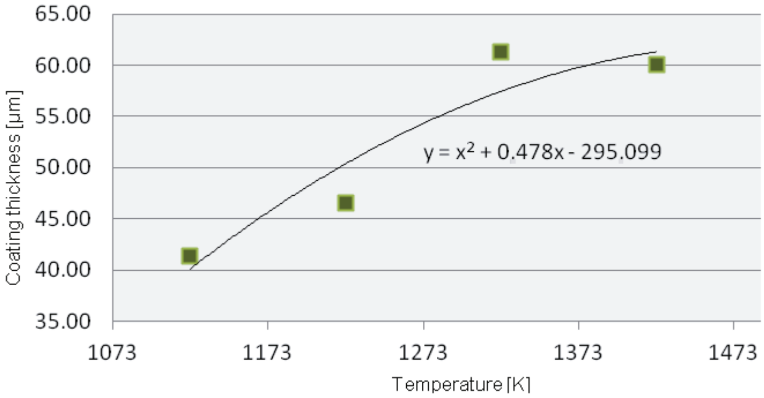

Fig. 4. Graph for variation of the aluminum coating for blades subjected to preheating

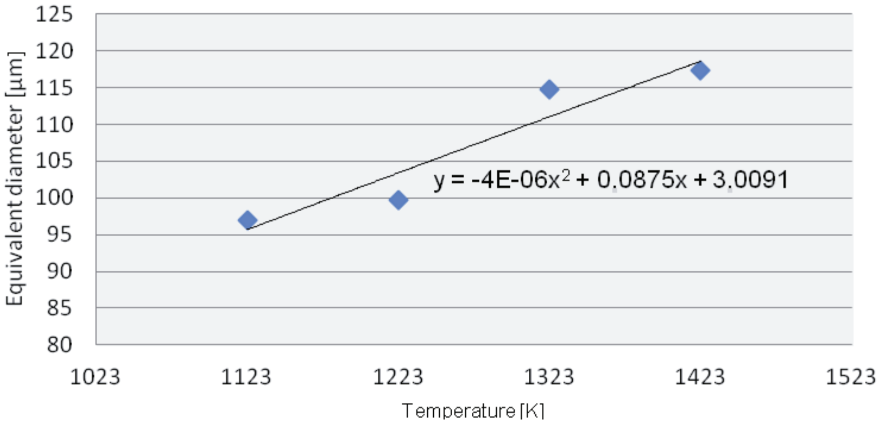

Fig. 5. Alteration of the average grain size for the EI-867WD super alloy used to manufacture the turbine blades, for a new blade and blades heated at various temperatures. The average grain size is expressed as the diameter of an equivalent circle with the same surface as of the grain

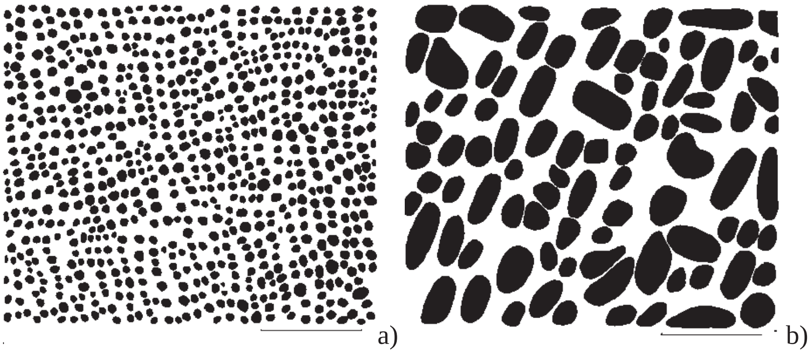
a) b)

Fig. 6. The microstructure of turbine blades after heating at temperatures: a) - 1123 K, b) - 1423 K (magn. x20000) – one can see coagulation, alteration of shapes and corrugation of the γ' phase formations.

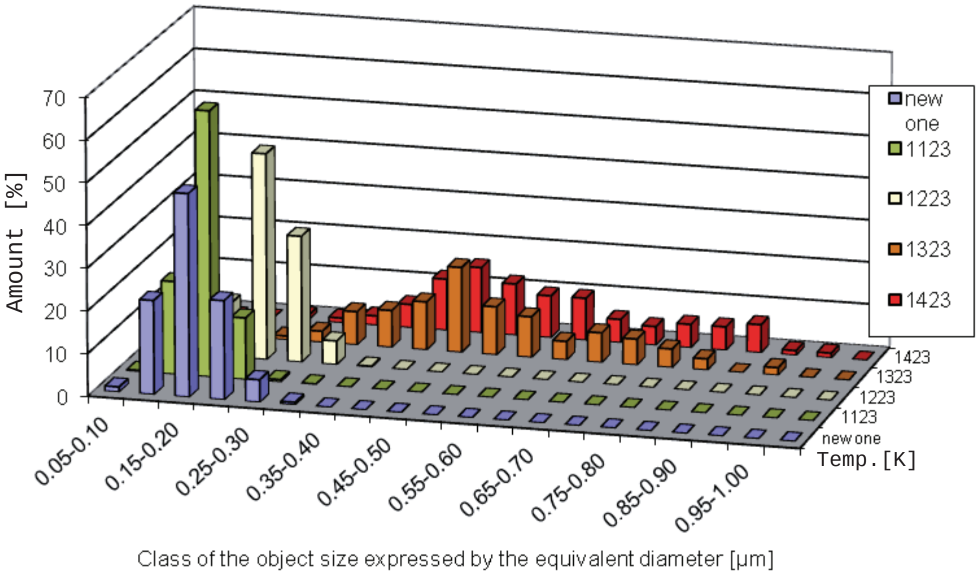

Fig. 7. Number of precipitations within individual size classes of γ' phase particles for the material of turbine blades, for a new blade and blades heated to the temperatures from 1123 K to 1523 K

6. Conclusions

The process of gas turbine operation is associated with overheating of turbine blades to temperatures that exceeds the temperature of regular operation. The reasons for such a phenomenon include manufacturing flaws, unreliability of the design and incorrect operation and maintenance of the engine. The deterioration process of gas turbine blades starts from impairment of the protective coating, thus the parent material of the blades is exposed to direct chemical and mechanical impact of exhaust gases. Such a situation directly leads to overheating of the blade material that is manifested by unfavourable alteration of the microstructure. Reliable evaluation of such alterations by means of non-destructive techniques may significantly prolong lifetime of the engine, even after detection of the defect. Faulty engines can then be dicomissioned to prevent disastrous consequences that ensue after engine failure.

The results from thermographic investigation of gas turbine blades outlined in this paper cover both new blades and the ones that have already been in use. These results provide the unambiguous proof that the thermographic method is suitable for diagnostic of the technical condition demonstrated by gas turbine blades. They also revealed clear interdependencies and relationships between thermal loads applied to the blades during the engine operation and variations in the signal of thermal response (echo) as well as alterations in microstructure of the blade material. These results serve as proof that it is possible to draw up conclusions for the non-destructive thermographic technique; whether the material of gas turbine blades suffered from overheating events.

The method of pulse thermography (PS) presents a reasonable alternative to other techniques of non-destructive examinations by virtue of very short time until the examination results are available; as well as low unit cost of the investigation. It is the method that can enable comprehensive analysis of the entire population of blades from each batch during inspection of the blades at repairing workshops. This makes it possible to eliminate destructive metallographic examination methods which infer the condition of an entire batch of blades from only a few specimens of that batch.

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