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AN ATTEMPT OF EVALUATION OF OVERHEATING OF GAS TURBINE BLADES

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Abstract

Increase of sensitivity and reliability of non-destructive diagnosing of condition of gas turbine blades became possible thanks to discovery of relevance and relationship between change of colour of their surface and change of microstructure of material resulting from influence of high temperatures. The data in the form of digital images were obtained in lab conditions with help of a photosensitive element i.e. a CCD matrix (digital camera). Acquired images were split up to main primary colours i.e. red, green and blue. This allowed to obtain information about variations of colour intensity for individual channels of digital images and for various temperatures applied for heating of blades. Thus, from the point of view of diagnostics of technical objects, with help of a non-invasive method obtained was the important diagnostic information, i.e. change of luminance and chrominance resulting from influence of high temperature on blades. Researched was also the microstructure of surface and sub-surface layer (change of thickness of coating, change of distribution and size of excretions of reinforcing phase γ' *). Obtained information may be useful for evaluation of microstructure of material in the course of operation of gas turbine blades.*

Keywords: *gas turbine blades, evaluation of condition, heat-resistance and creep-resistance, digital image, phase* γ'

1. The matter of considered problem

The object of research considered in the present work is a gas turbine, regarded as rotor flow machine, which transforms the enthalpy of working medium (jet of exhaust gas) into the mechanical work, which causes rotation of the rotor. The work, together with mass flow rate, determines the power of the turbine indispensable for driving of receivers [1]. Gas turbines are used not only in power engineering, but also in such important area of economy as transport: water transport (ocean, sea, river), road transport (road, railway), air transport (turbojet engine, turboprop engine, turboshaft engine). Gas turbines are also applied for: military vehicles (land, water, air vehicles), in auxiliary devices: turbochargers for piston engines, main starters of aircraft engines; gas electric power stations based upon gas turbines may be fitted with sets of a few gas turbines.

Thus, the reliability of operation of a gas turbine is limited by proper operation of power receivers. The elements, which have essential influence on reliable operation of a gas turbine are the blades of nozzle unit and rotor blades. The evaluation of condition of gas turbine blades under thermal load is carried out in the course of operation with visual method on the basis of surface image and comparison of this view with standard blade surface. Such criteria of condition assessment are very subjective, because they depend on skills and vision of the person which performs diagnostics. The verification of decision of diagnostics technician is realised with destructive methods i.e. with metallographic examinations. Thus far there is no non-destructive method of examination of grade of blade material overheating based on objective criteria. With regard to important role played by gas turbines the problem of credible evaluation of condition of blades seems to be fully justified [2].

Thermal efficiency of gas turbine circulation cycle, hence the efficiency of real installation, depends significantly on exhaust gas temperature at the turbine inlet. The higher is the temperature the higher is the efficiency of conversion of fuel chemical energy within the system. The upper temperature limit depends on creep resistance of blade material. In the course of operation of turbine engines of all types (aircraft, traction and ship engines) appear various defects of turbine units. The most frequent cause of defects is overheating of material, as well as thermal fatigue of blades of nozzle unit and rotor caused by both excessive temperature and its duration as well as by chemical activity of exhaust gas [3]. Overheating of blades results from excess of admissible average temperature of exhaust gas as well as from irregular distribution of temperature on the perimeter. Fig. 1 shows exemplary momentary distribution of temperature T_4 of exhaust gas measured after the turbine and measured with help of 8 thermocouples. The operator obtains only the average temperature value for given rotational speed, but has no knowledge about appearing fluctuations and deviations from the average value (supercritical temperature).

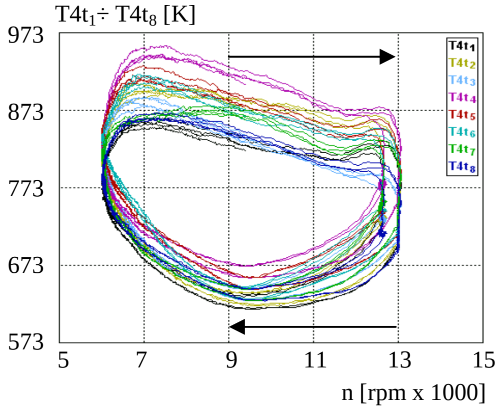

Fig. 1. Exemplary momentary distribution of temperature measured with thermocouples installed after the turbine [4]

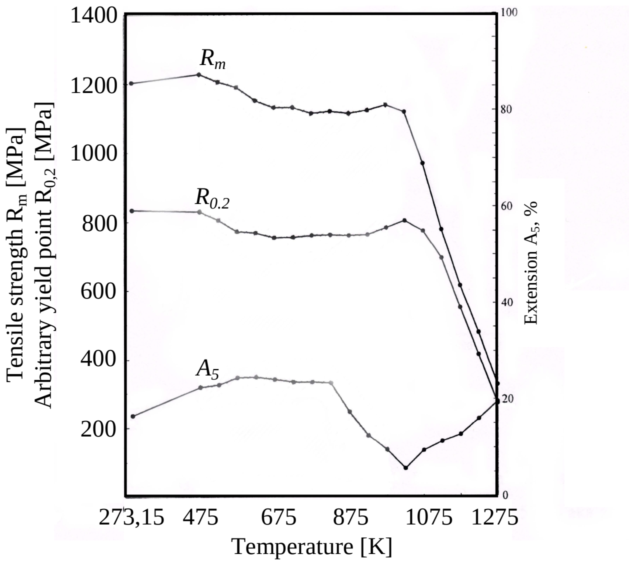

Fig. 2. Mechanical properties of alloy EI-867 as a function of temperature [5]

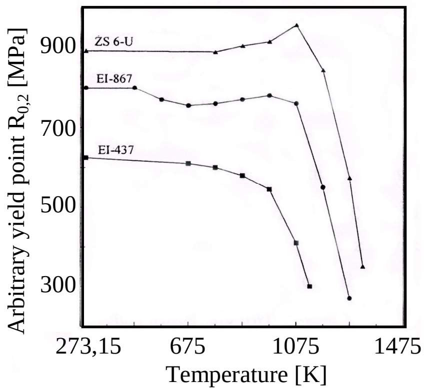

Fig. 3. Influence of temperature on yield point $R_{0.2}$ of selected superalloys [5]

Influence of temperature on mechanical properties (R_m, $R_{0.2}$, A_5) of a gas turbine blade made of alloy EI-867 is shown on the Fig. 2. The change of strength properties $R_{0.2}$ and R_m for various temperatures is of similar character. Observed is slight change of these two parameters below 473 K. Below 673 K observed are minor decrease of value; small fluctuations variations appear below 1023 K. Above 1023 K visible is distinctive drop of tensile strength and arbitrary yield point with simultaneous increase of extension. Similar phenomenon occurs for various alloys (Fig. 3), where the arbitrary yield point $R_{0.2}$ for the superalloy ŻS 6-U drops violently at 1223 K. Discussed functions for individual superalloys depend on content and properties of the phase γ'. The alloy ŻS 6-U has the greatest relative volume of reinforcing phase (ca. 56% of phase γ'), the alloy EI-867 ca. 32% of phase γ' and the alloy EI-437 ca. 13% of phase γ'. Thus, together with increase of relative volume of the phase γ' the maximum $R_{0.2}$ is the greater, the more phase contains the alloy (Fig. 3).

Increase of reliability and operational durability of turbine blades depends on many factors, but the essential criterion are the material properties (size and distribution of reinforcing phase γ' determines heat and creep resistance).

Development of non-destructive, based on objective criteria diagnostic method (computer-aided) of this machine element will contribute to improvement of reliability of gas turbines. To make the evaluation of blades condition more objective proposed is the method of acquisition of information about grade of overheating of blade microstructure through analysis of surface images recorded with help of an optoelectronic system together with photosensitive detector – a CCD matrix. Acquired data in the form of digital images describe the condition of given surface (the grade of overheating). The information about surface condition is stored in the form of digital images and perceived as change of luminance (brightness) and chrominance (hue) of gas turbine blades. The histogram parameter (distribution of brightness of coloured images) is correlated with results of metallographic examinations (modification of the phase γ') in connection with heating temperature [6, 7].

2. Characteristics of materials applied for gas turbine blades

The temperature increase at the turbine inlet is limited by material problems i.e. creep resistance, thermal fatigue, sulphur high-temperature corrosion (so-called hot corrosion) and erosion. Each gas turbine used in e.g. aircraft turbojet engine consists of three units differing with character of thermal and mechanical loads:

1. Compressor, where aspirated air is compressed and heated;
2. Combustion chamber, where the air-fuel mixture is combusted;
3. Turbine, where high-temperature exhaust gas meets vanes and rotor blades and drives the compressor.

Basic materials for gas turbine blades are metal alloys (hest- and creep-resistant), mainly nickel and cobalt alloys. Requirements for these materials are as below [8, 9]:

1. High long-term creep resistance;
2. High yield point and tensile strength;
3. Good plasticity, ductility and brittle fracture resistance;
4. High thermal and thermal/mechanical fatigue resistance in the course of operation;
5. Stable structure and properties, low susceptibility for reinforcement decrease and reinforcement increase and brittleness in the course of operation;
6. Favourable physical properties – possibly high thermal conductivity and low thermal expansion;
7. Good heat resistance in exhaust gas environment.

Crucial influence on properties of an alloy has the intermetallic phase γ' described with the formula Ni_3 (Al, Ti). Chemical composition, morphology, and distribution of the phase within the structure have crucial influence on creep resistance of the alloy. Additionally, the volume fraction of the phase influences mechanical properties (fig. 3). It has been assumed that the optimum quantity of dispersion particles of intermetallic phases within the volume of grain of alloy should amount to 40-60% [5]. As a result of alloy processing the phase γ' is very comminuted. The phase results from the process of constant extraction from a disordered solid solution and is a intermetallic compound-like superstructure of A1 lattice. The fact that the phase γ' retains the lattice of matrix γ guarantees coherence of both these phases. The chemical composition of the phase γ' influences significantly the value of lattice parameter and resulting grade of mismatch to the matrix lattice. This affects the morphology of γ' phase excretions and its durability. In multicomponent alloys alloying additions are selected in such way that lattice parameters of both phases are similar. It appears that the grade of mismatch of phase lattice parameters is the function of temperature. The increase of lattice mismatch from 0,16 to 0,80 % in alloys containing niobium and tantalum causes growth of tensile strength at 1033 K by more than 200MPa [10].

3. Analysis of surface image of gas turbine blade

Fragments of gas turbine blades made of EI-867 alloy were heated in a vacuum stove (three samples at once) at five temperature values from 1023 K every 100 K (heating time one hour, cooling in the stove to the environment temperature). As a result of stove heating of blades observed was change of their surface colour (Fig. 4).

Fig. 4. Images of surface of samples heated at various temperatures

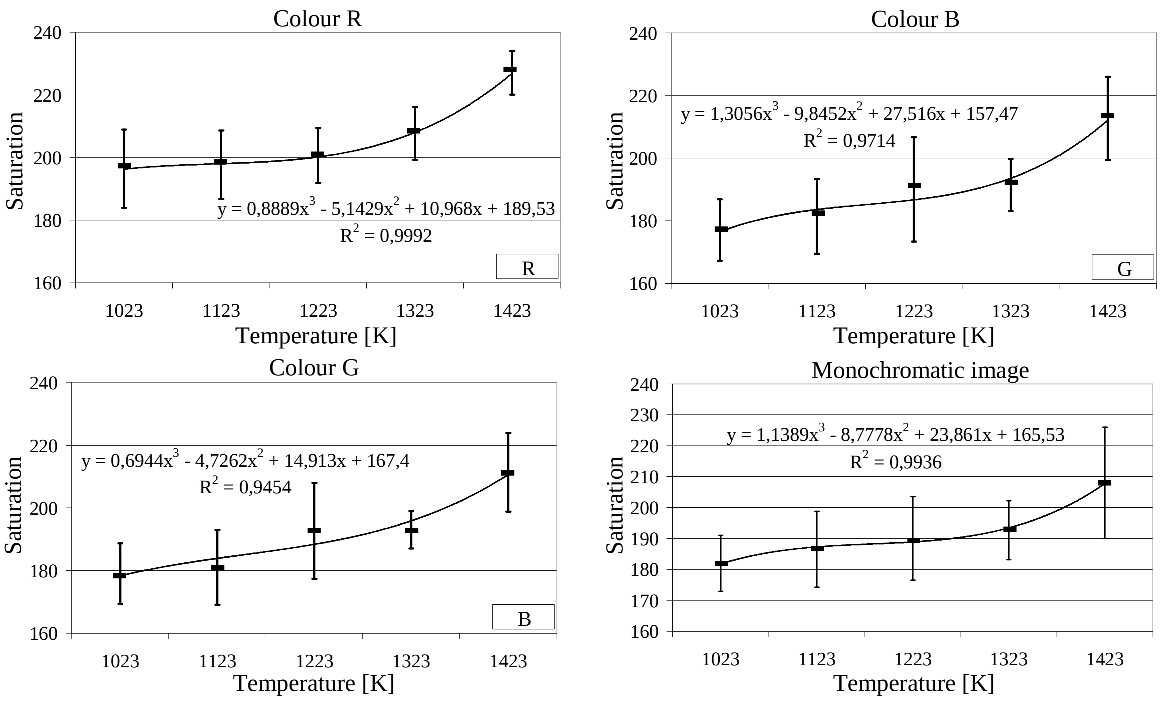

Fig. 5. Change of value of position of maximum amplitude of image saturation with RGB components and grey tones for various heating temperatures of samples

On heated surfaces separated were regions of interest of 24-bit colour depth and dimensions 200x200 pixels. Images were recorded at special stand [6], which ensured repeatability and accuracy of detection.

To determine parameters which enable description of microstructure changes (overheating) of examined surfaces used was image analysis through splitting of image to primary colours, i.e. **R**ed,

Green and **B**lue – RGB and analysis of grey tones of individual surfaces (fig. 5). Due to character of researched phenomenon considered were only changes of position of maximum saturation amplitude (histogram of brightness distribution of digital image).

4. Metallographic examination of gas turbine blades

Application of scanning microscope allowed analysis of microstructure changes resulting from high temperature. Fig. 6 shows that at 1023 K and 1123 K detected was preliminary stadium of coagulation of excretions of reinforcing phase γ', which was characterised with relative regularity and very high density.

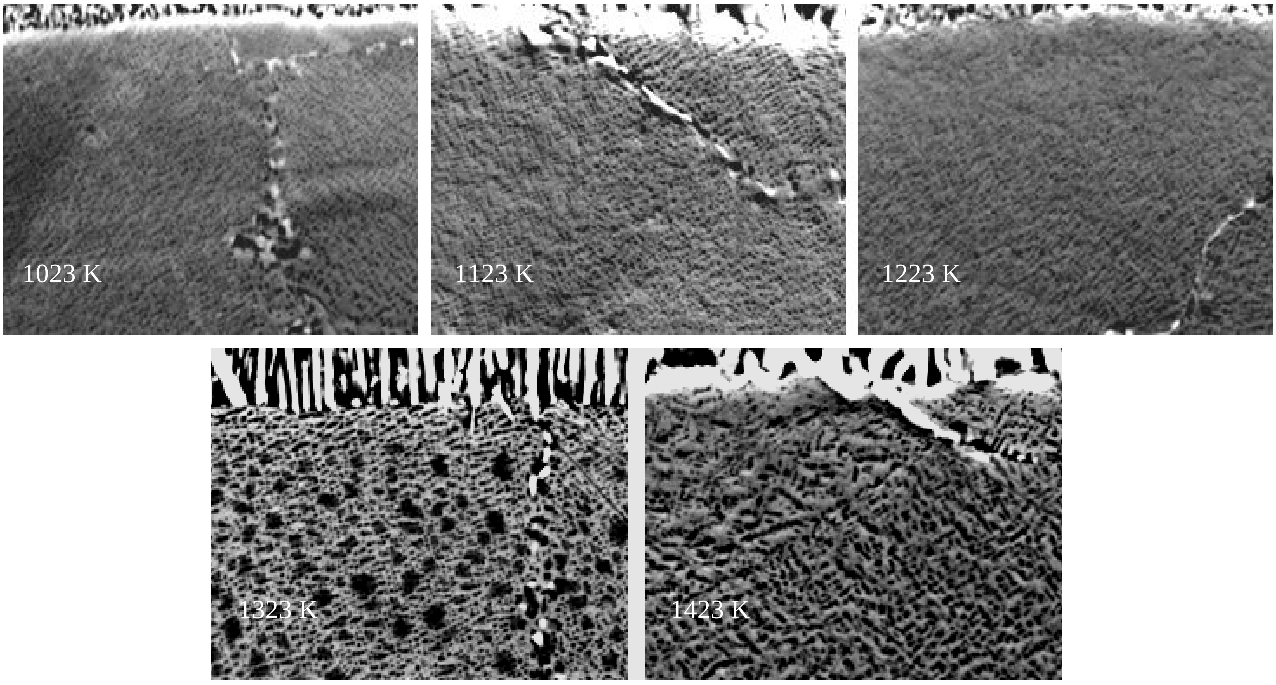

Fig. 6. Subsurface structures for individual temperatures of heating, scanning microscope (x 4500)

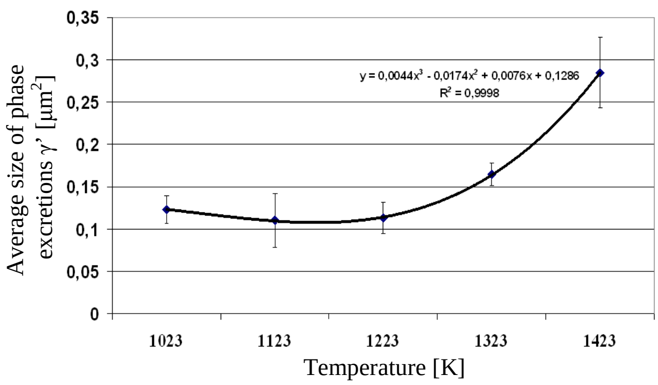

Fig. 7. Modification of reinforcing phase γ' as a function of temperature

Together with increase of temperature of examined blades the structure of the phase γ' became less regular with simultaneous change of grain size (rys 7).

The examination of microstructure proved proper structure below 1223 K. At 1323 K detected was growth and coagulation of excretions of reinforcing phase γ', and then its coagulation within solid solution. Together with temperature increase the effects of coagulation and dissolution of these excretions in solid solution become stronger. The morphology of phase γ' proves that above 1223 K the alloy EI – 867 becomes overheated, and the examined blade is no more useful. According to A. Dudziński [11] and A. Poznańska [5] growth and coagulation of of excretions of reinforcing phase γ' proves susceptibility for brittle fracture. Additionally, A. Dudziński in his work [3] states that a blade made of similar alloy EI - 929 examined for creeping above 1188 K can be assumed as overheated. Acquired images of microstructure of the alloy EI - 867 heated in higher and higher temperatures can make base for evaluation of grade of overheating of gas turbine blades.

4. Nomogram for evaluation of condition of gas turbine blade

To combine change of colour of blade surface with temperature influence on its microstructure elaborated was the nomogram (Fig. 8) for evaluation of condition. The evaluation of blade condition is based on colour analysis of surface image and is connected with material criterion (modification of excretions of reinforcing phase γ'), worsening properties of thermal resistance – creep resistance and heat resistance.

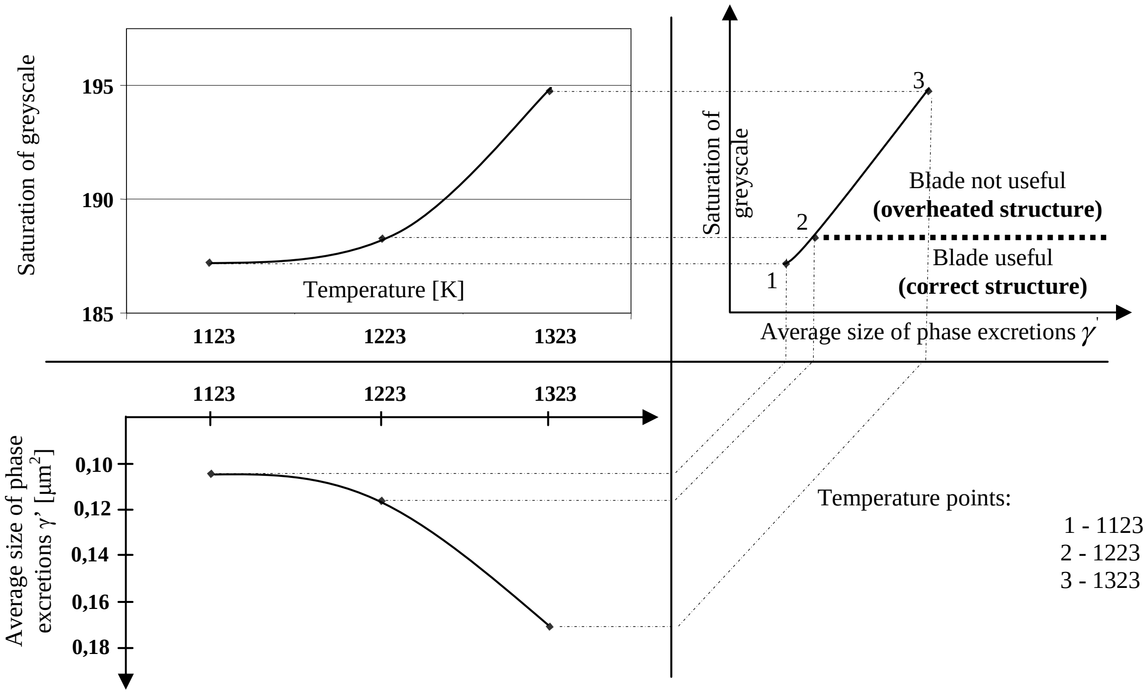

Fig. 8. Nomogram for evaluation of condition of gas turbine blades based on relation between change of grey tones of examined surface and change of size of phase excretions γ' for various heating temperatures

On the basis of the nomogram, which shows relation of hue change (greyscale) as a function of heating temperature of blades, can be evaluated the change of microstructure of the alloy EI – 867. High temperature influences both change of thickness of aluminium surface layer (variable surface which reflects the light) and modification of structure of the phase γ'. Practically, changes of aluminium coating cause change of luminance and chrominance recorded by the optoelectronic system together with photosensitive detector, a CCD matrix. Examined microstructure of subsurface layer reflects changes of the alloy EI – 867 and proves overheating of structure of this alloy (Fig. 6 and 8) after heating of fragments of the blade in temperatures above 1223 K. Taking the material criterion i.e. change of size of phase excretions γ', as the criterion allowing further use of a blade, it is possible to determine the limit of usefulness for further operation.

5. Conclusions

Depreciation of microstructure of blade material consists in growth of intermetallic phase γ'(Fig. 6). The phase has crucial influence on properties of nickel alloys. In special cases the growth of the phase γ' leads to coagulation of excretions and their further dissolution in solid solution. The chemical composition of the phase γ' affects significantly the value of its lattice parameter $a\gamma'$ and correlated grade of mismatch Δa with matrix lattice $a\gamma$, where $\Delta a = (a\gamma - a\gamma') / a\gamma$. This influences the morphology of excretions of the phase γ' and its durability. It appears that the grade of mismatch of lattice parameters is the function of temperature.

Proved was the correlation between heating temperature (change of grey tones of examined surface) and changes of microstructure of the alloy EI-867 (growth and coagulation of excretions of reinforcing phase γ'). Proposed was the methodology of evaluation of usefulness of blades heated in high temperatures on the base of developed nomogram. With help of non-invasive methods used for diagnostics of technical objects efforts were made to acquire important cognitive information, which in practice can be used for evaluation of microstructure changes i.e. state of overheating, as well as thermal fatigue of elements and components of technical objects being subject of variable thermal loads. In next research works will be analysed the problem of credibility (errors) of developed methodology.

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