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DAMAGE DIAGNOSTICS OF TURBINE BLADES

The paper presents the most frequently encountered types and mechanism of damage of turbines' flow elements. The methods used nowadays for diagnosis of the damage are presented. A new possibility of localisation of damaged areas of turbine blades based upon the analysis of isotherm layout is proposed.

1. Introduction

In mid eighties of the XXth century, a serious breakdown of a power-generating block in the Sankt Petersburg power plant took place. The after-effects were severe i.e. fire and damage of some parts of electrical cabling installation of the energy generator and in consequences huge financial losses. The breakdown occurred after 32000 hours of work and after 4000 hours since the latest technical inspection. This breakdown, whose effects were so important, was caused by the damage and breakage of the blades of the first stage row of blades of a low-pressure turbine. Further consequences of this event were as follows: intensive overload and plastic deformation of the turbine shaft and then a destruction of the whole block.

In the end of the year 2000, a failure of one fan engine of a jumbo jet Boeing 737 caused that the flight could not be continued. Fortunately, the plane landed safely and the damaged engine was carefully investigated. The research proved that the edges of blades of the high-pressure turbine were damaged. This failure caused an overload and in consequence – damage of blades in all four stages of low-pressure turbine.

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The number of similar breakdowns and failures in the means of mass public transport is probably essentially greater and, even if not in every case the recognition of the direct causes of the damage have been possible to detect, it can be claimed – with high probability – that they were caused by nucleation and accumulation of damage in turbines' flow systems.

Technical inspection has an essential influence on the service period of machines and appliances. The frequency and the range of inspections are established in every case upon the knowledge of service conditions and the design of a particular machine or system. Based upon this knowledge, during the inspection, the level of wear of the investigated parts is assessed by means of different diagnostic techniques. The prognosis of further safe life of the analysed part or subsystem depends on the effectiveness of these investigations and quality of the obtained outcomes. Early detection and localisation of material failures of machine parts is the key factor for their further usage, and in many case it makes it possible to avoid serious failures and catastrophes as well as probable costs and people tragedies. The most crucial factor is reliable work of turbines that are the basic part of energy generation subsystems and jet engines.

The causes of occurrence of damage of some parts of machines can be different, but in every case these causes depend on the service conditions. Duty conditions of compressors as well as gas and steam turbines can be recognised as extremely hard. Therefore, in flow elements of these systems, more frequently than somewhere else, nucleation and accumulation of material defects can take place. Modern investigations of the damage of elements of gas turbines proved that the damage of elements of turbine flow subsystems are the reason of more than half of all turbines breakdowns. Furthermore, the percentage of blade damage is equal to approximately 30%. These phenomena cause that the frequent and detailed periodical inspection of the elements mentioned above should be performed in a possibly most simple and most rapid manner and, at the same time, as effectively as possible.

2. Work conditions of turbine blades

Due to the purpose that should be accomplished by the blades in the turbine, the blades can be named as impeller blades and stator blades.

Impeller blades, called the working blades, constitute the basic subsystem of the turbine. Owing to them, kinetic energy of the medium is transferred into mechanical energy. The working blades are divided into two types i.e.: active and reactive. On the blades of active stages of the turbine, the pressure of the medium is not changed, therefore the velocity of the medium at the outlet in comparison to the inlet, what explains establishing the constant cross-section between the blades. In the passages of reactive blades, expansion and an increase of velocity of the medium take place, what is achieved due to diminishing of the area of the passage cross-section.

The main load of impeller blades is the centrifugal force of rotating masses which causes tension and torsion of the blades, bending and torsion moments generated by the medium flowing across the inter-blades passages, bending moments generated by the centrifugal force in the case when the line crossing the gravity centres of lateral blade cross-sections is not collinear with the radius line. The stator blades are bent due to the flow of the medium. Furthermore, the loads of blades are subjected to periodical changes, what causes the vibrations of the blades, and therefore additional torsion and bending take place [6].

Heat load has also an essential influence on the work of impeller and stator blades. The existence of these mechanical factors and high temperatures causes that the materials of high mechanical and thermal strength should be used to produce the blades.

3. Causes of damage of turbine blades

Within the service period of turbine usage, taking into consideration the turbine's fatigue life, one can single out two characteristic states i.e. – stable state – when the turbine works under constant load and – unstable state – associated with start-up, changes of the power and stopping. In both cases, a step-by-step degradation of the material of the turbine elements exists especially in all rotating elements. The causes of occurrence of damage of turbine blades can be different and can result from complex service conditions as well as design and technological mistakes, service mistakes or an impact of unexpected external factors.

Vibrations are the main and direct causes of damage of the turbine blades. Vibrations of the blades are the source of the destroying damage process giving characteristic low-grain-type fracture. Sharp endings of the blade edges are the places where the greatest stresses occur in the case of bending. Most frequently, the fatigue fractures begin in these areas. Other sources of fatigue fracture can be e.g. material imperfections, scratch or indentation of material of the blade. Other causes, which can destroy the blade, are excessive centrifugal forces appearing due to overloads – they can cause deformation and tearing of the blades with characteristic – high-grain-type fracture. Fig.1depicts the damaged blades of the first stage of the low-pressure turbine of turbo propeller motor caused by rapid overload due to damage of blades of high-pressure section of the turbine [1].

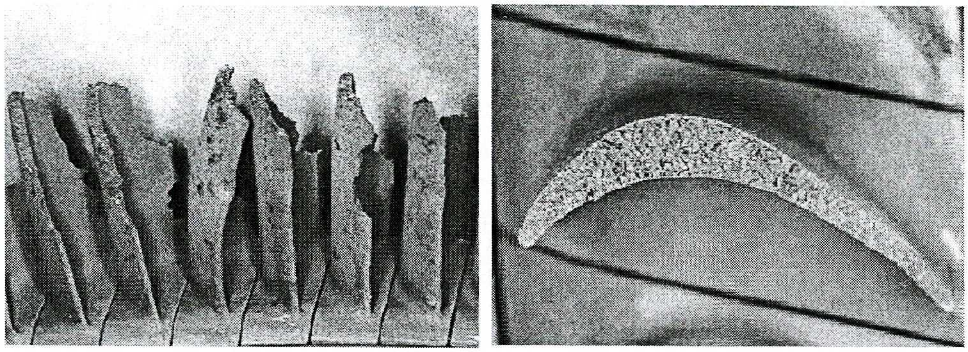

Fig. 1. Damage of the turbine blades of low-pressure section (by [1])

An essential factor causing blade damage is also the influence of very high temperatures, what is described as the phenomenon of thermal fatigue of the material.

4. Types of damage

The processes, which are most frequently mentioned when the wear process of turbine blades is considered, are as follows: fatigue, low-cycle fatigue, creeping and vibro-creeping, changes of the structure of material, brittle cracking, corrosion and erosion [6]. These processes cause deformation, decrement of material, different micro- and macro-cracks in the turbine and compressors parts. The resulting damage processes are responsible for the breakdowns of the whole systems.

4.1. Fatigue

The cause of fatigue failures is usually the phenomenon of resonance between proper vibrations and forced vibrations. Despite the fact that the contemporary calculation methods of determination of proper-vibrations are associated with adequate laboratory experiments, the obtained outcomes can still be disturbed, and the occurrence of resonance is possible. In the case when the resonance vibrations take place, the stresses in a blade increase rapidly, what can cause breakage of the blade, and the fatigue fracture is characteristic in this case. The fatigue fracture front passes to the consecutive weak places of the material, the so-called rest lines that are presented in Fig. 2.

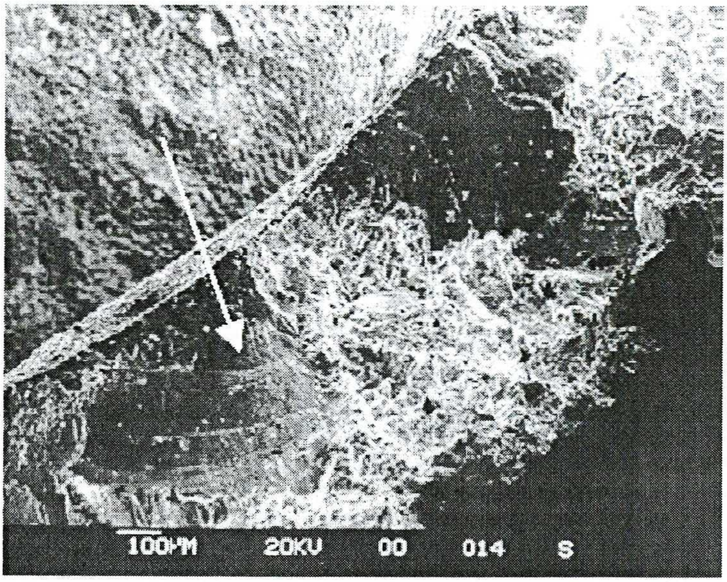

Fig. 2. Microscope photo of the fatigue fracture in the high-pressure turbine blade (by [1])

In Fig. 2, propagation of fatigue crack through the material of the blade can be clearly seen [1]. During vibrations, the opening and closing of the crack take place; these phenomena are simultaneous with crushing of the fracture planes. The increase of the number of vibrations leads to wear phenomenon which, in turn, causes that low-grain structure is obtained moreover, the smoother the surface, the longer the degradation process.

Appearing of forced vibrations of working blades can be caused by the impact of the stator blades on the medium. The presence of stator blades causes changes of pressure and velocity of the medium along the circumference and in consequence non-homogenous loading of the impeller blades. The changes of loading of the impeller blades occur with the frequency equal to the product of two quantities: revolutions per second and number of impeller blades.

Periodicity of the forces acting on the impeller blades can also be the result of the existence of the technological deviations of dimensions of the impeller blades. Taking into account the variability of the flow rate of the medium in particular vents and the variability of velocity and pressure of the gas by the outlet of the vents, one can state that even small deviation of dimensions of the stator blade can cause vibration of working blades and in consequence nucleating of crack (Fig. 3).

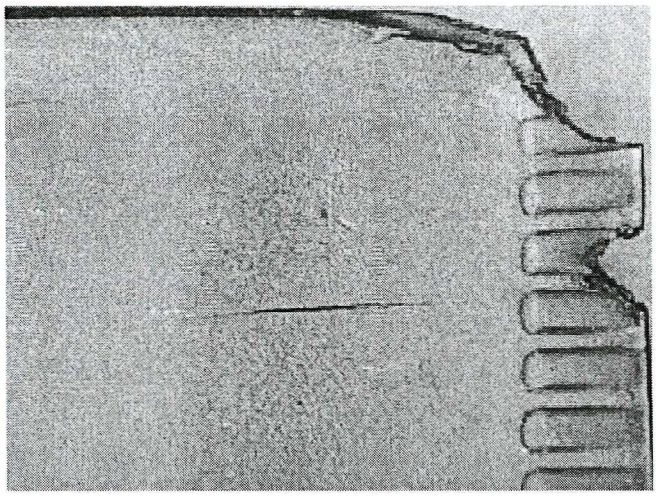

Fig. 3. Radial crack in the concave part of the high-pressure turbine blade (see [1])

Fatigue damage of blades can also arise in the result of an improper choice of the blade profile, what can cause the existence of the stress concentration zones. Other common causes of blades' failures are assembly errors, which cause diminishing of proper vibration frequencies of the blades, what facilitating as the resonance phenomenon.

Fatigue failure of working blades can originate in the places where blade-connecting wires are soldered – due to their local overheating. Overheating of solders or welds on a blade, and then its hardening due to air cooling, is usually the cause of occurrence of micro-cracks and propagation of fatigue crack.

Improper performance of maintenance works can sometimes be the cause of fatigue breakdown. In the figures underneath, the blades' failures are presented. Those were caused due to accumulation of thermal and mechanical fatigue damage originated in the zone of repair weld made on the blade, because the alloy used there was of slightly less strength than that of the material of the blade [1].

The factors, that accelerate the occurrence of fatigue failures, can be also corrosion or erosion processes, in consequence of which a loss of the material arises resulting in the occurrence of stress concentrators in notches on the edges of inlet blades.

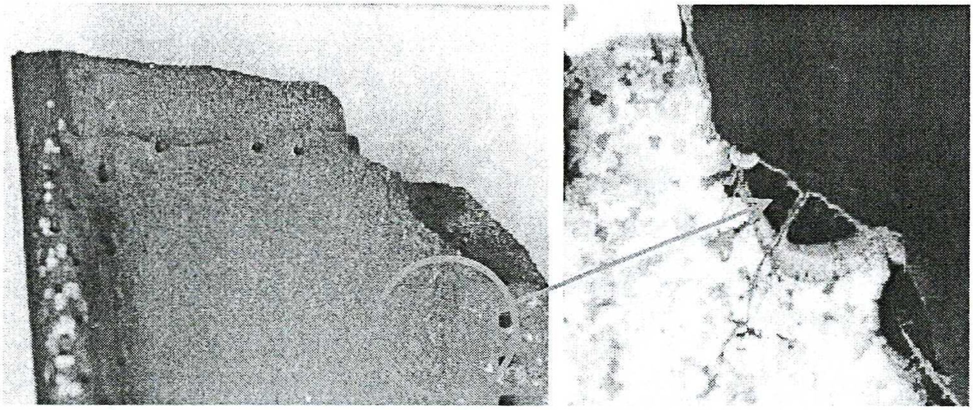

Fig. 4. The failures of the blade which have originated in the repair weld zone

4.2. Thermal fatigue

The essential phenomenon that occurs in turbine elements is the so-called thermal fatigue, which is present even in the case of low-frequency load changes i.e. in the case low-cycle changes. The problem of thermal fatigue strength is of a different kind than mechanical fatigue strength, because the nature of thermal stress effect is different, than mechanical stresses. Exceeding the yield point due to stress generated by mechanical loadings can cause relatively fast failure of material. However, the same material can hold numerous repetitions of thermal stresses – which essentially exceed the yield point. The result of the investigations performed by K. Wellinger [7] and R. Żuchowski [8], [9] was the conclusion that, if the sum of total elongations caused by mechanical loadings and relative elongations equivalent to the thermal loadings is lower than two times elongation relevant to the yield point, then the material shows quasi-elastic behaviour and withstands numerous changes of loading. Relative strains can be defined as the strains that could arise as the result of total or partial limitation of thermal elongations. If total elongations exceed the value relevant to the yield point, then the changes of loadings cause repeating plastic deformations, which means that fatigue failures of the material take place. Repeating thermal deformations, whose effect is that the mentioned elongation limit is over-crossed, bring out the following phenomena: cracks on the surface of the blades and characteristic groove-type cuts, of round edges mainly in the zones of the highest tension stresses.

The photos inserted hereunder illustrate the size and the range of the failures caused by thermal fatigue in the turbine blades of the high-pressure section. These failures were the cause of the passenger jet engine damage [1] – quoted at the beginning of this paper.

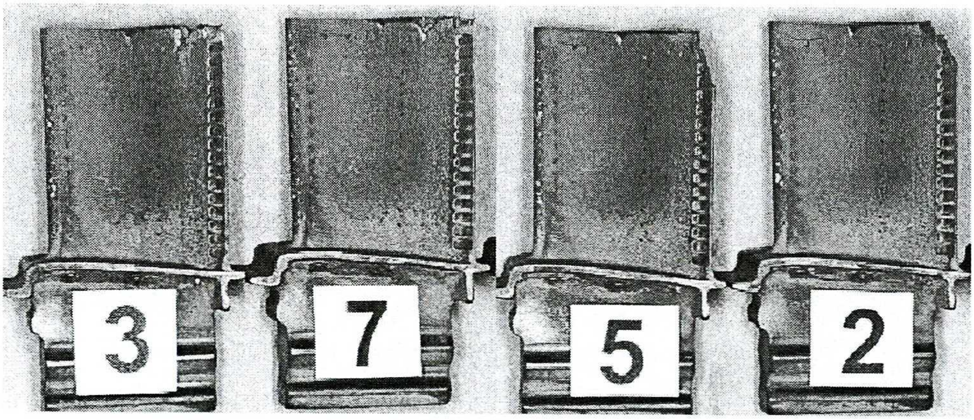

Fig. 5. Failures caused by thermal fatigue in the high-pressure turbine blades (see [1])

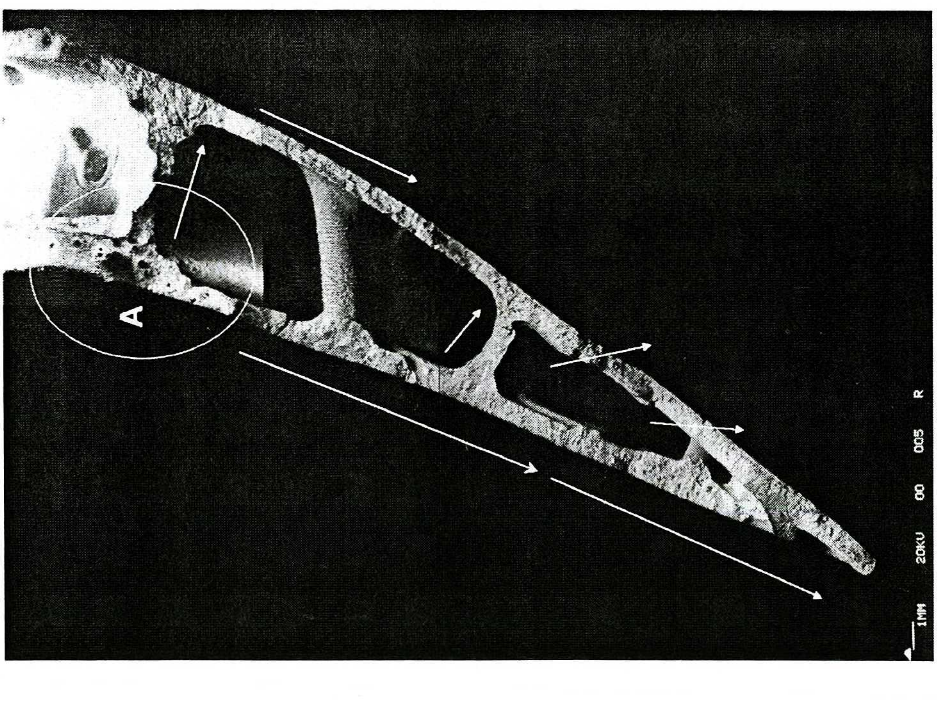

Fig. 6. Microscope image of the region of cracks caused by thermal fatigue (by [1])

Fig. 6 presents a microscope image of the cross-section of one of the damaged blades. The area denoted in the figure by capital letter A shows the region where the cracks caused by thermal fatigue arise, and the arrows show the predominant direction of crack propagation.

4.3. Creeping and vibro-creeping

Machine parts, especially turbine systems, which work at high temperatures, are subjected to the creeping process, in which stable or permanent deformations arise and increase due to constant loading conditions. In the case of steel, creep occurs particularly evidently at the temperatures exceeding 300°C; at lower temperatures deformations of creep (as comparably low) are neglected in the design calculations. Working blades and impeller turbine disks of the first sections are particularly subjected to the creep processes. The creep of material influences the technical state of the mentioned turbine parts, and determines their service life measured by the admissible time of duty. The changes of dimensions of the parts result from the creep of material, and after some time of service it leads to the failure of the material. Permanent deformations of a particular part and the time of service until the moment of failure depend on the amount of loading and temperature. In practice, there are many cases when, due to the creep of the material, deformations of turbine parts are so high that their further work is impossible. One example, worth noticing, is as follows: the constructional clearances diminish, but their existence eliminates the hazard of seizing and assures safe usage. Changes of dimensions of turbine blades due to the creep can cause the seizing and a breakdown of the whole system.

Other example of negative influence of the creep process can be diminishing of load capacity of the interference joint of the impeller disk and the shaft due to an increasing of the inner diameter of the disk as the result of the creeping.

The creeping process can be accelerated not only by an influence of high temperature but also by the periodical changes of loading. In the case of high frequency of forced vibrations, the material yield point diminishes and the consequence is rapid increase of creeping. This phenomenon was confirmed by A. Jakowluk [2]. The loaded turbine parts, dispossessed of freedom of elongation, are subjected to the relaxation phenomenon i.e. diminishing of initial stresses due to changing of some deformations from elastic to plastic ones.

4.4. Brittle fracture

During the service of turbines, one sometimes observes arising of sudden fracture of thick-wall elements (mainly impellers). Brittle fracture arises mainly in these materials, in which development of plastic deformations is not accompanied by the relaxation of stresses. However, it should be remembered that the temperature is the essential factor, which decides on the material properties. The same material, which at normal temperatures cracks in a ductile manner, at low temperatures behaves as a brittle material. The appearance of fracture surface in the case of brittle fracture confirms the micro-mechanism of fracture. During the brittle fracture, most frequently, one encounters the mechanism of intra-crystal fracture along the facility planes, but in some cases the fracture is caused by a shift of a crack front along the grains boundaries – creating inter-crystal fracture. The mechanism of inter-crystal fracture arises frequently in high temperatures. This mechanism determines the fracture process in corrosion conditions; as well.

Both of the described mechanisms can occur simultaneously, what is presented in the photo in Fig. 7. The vertical crack passes along the grains' boundaries and the horizontal one is caused by an intra-crystal crack.

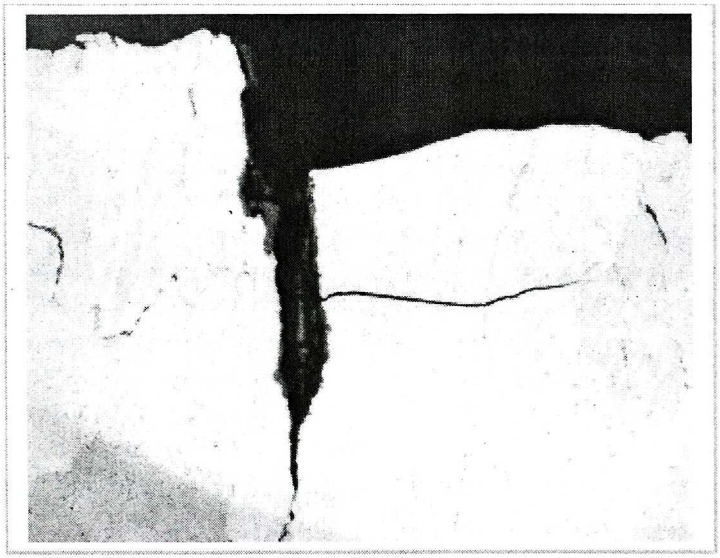

Fig. 7. Examples of inter-crystal and intra-crystal mechanism of fracture (by [1])

4.5. Erosion and corrosion

The phenomena of erosion and corrosion occur in both steam turbine blades as well as (in lower range) in the blades of gas turbines and compressors. In the case of steam turbines, most problems are associated with the work in the range of wet steam. In the liquid phase, there is strong erosive-corrosive influence on blades, sealing and a casing. Researches and experiments evidently show strong correlation between erosive damage of blades and the diameter and number of drops as well as work of the turbine under low loading. According to [5], the rate of erosion of the blades under 30% of loading is 3 times greater than in the case of nominal loading. Aiming at increasing the erosion resistance of steam turbines, one adds chromium steel and uses inductance hardening in producing the turbine elements. Detailed descriptions of breakdowns of steam turbines caused by erosive damage of blades are presented in the work [4] by Z. Orlowski.

Besides the erosion processes, the phenomenon of blade corrosion takes place, as well. Corrosive fractures of blades occur most frequently via the so-called pitting corrosion and corrosion fatigue. Small, punctual pitting holes – destroying both sides of a blade – are characteristic for pitting corrosion. On the outlet edges of blades, due to their low thickness, pitting holes can be right through the blade. These losses of material are the stress concentrators and essentially reduce fatigue strength of blades. The surfaces of fracture caused by the corrosion fatigue do not differ from the pure fatigue fracture. The differences cannot be singled out before metallographic investigations are performed. The typical symptom for this kind of fracture is the appearance of several cracks one beside another.

The losses of mass of blades, especially the blades of the last sections of steam engines, which arise due to erosion and corrosion processes, can cause destabilisation of the rotating system, and an increase of amplitudes of vibrations with frequency corresponding to the rotational speed. Erosive and corrosive defects are also the reason of changes of blades stiffness, and in consequence, changes of frequencies of proper vibrations, what can lead to acceleration of fatigue fracture of blades.

5. Diagnostic investigations of turbines' parts

It is necessary to perform frequent and detailed control inspections of turbo-systems, particularly the blades, which is due to the fact that gas turbines work in extremely difficult conditions and, moreover, the following factors act simultaneously: variable loads, high temperatures, high constant and variable stresses and sometimes caustic agents. The aim of these inspections are as follows: detection of possible damage, assessment of the level of material degradation, establishing of real level of fatigue strength of the investigated part as well as determination of prognosis for further usage.

Assessment of the level of material degradation and exhausting of its life due to the damage processes is performed by means of standard calculations as well as destructive and non-destructive tests.

5.1. Methods of non-destructive investigations

The purpose of non-destructive tests is detection of every type of inner and surface imperfections in the material of the investigated part. They have very essential meaning because they allow for an assessment of the level of wear and the suitability for further usage of the part, without cutting out any specimens what would require a repair of the part later. Because the assessment of the material wear level by means of non-destructive tests is not adequate, they are sometimes performed along with destructive tests. Non-destructive tests are used usually for initial assessment of the material state and for determination of the places from which the specimen for further investigations should be cut out, but the results of non-destructive test could be the a sufficient reason for elimination of the constructional part from further use.

The non-destructive tests used most frequently for investigation of turbine parts are as follows: measurements of creep strains, measurements of hardness, investigations of structure of the material by means of X-ray methodology, ultrasonic investigations, tests performed by means of magnetic particles, method of dye penetration or measurement of crack depths.

Measurements of creep strains consist in periodical measurement of permanent strains of turbine parts.

The measurements of hardness of the materials of constructional elements allow for detection of changes taking place during service of these parts, but the results of the measurements are not used directly for an assessment of the margin of life, they are considered as auxiliary ones.

Direct observation of structure of the material is possible by means of portable microscopes. It allows for investigations of changes taking place in the structure of material on the previously prepared area of the part. The investigated area has to be cleaned by grinding, polishing and etching.

Ultrasonic and magnetic methods consist in applying the relationships between the changes of properties, structure of materials, acoustic parameters of ultrasonic waves and magnetic properties. The advantage of these methods in comparison to the method of surface investigations is a great volume of investigated material, comprising part or the full cross-section of the investigated element. The goal of multi-directional ultrasonic investigations is detection of sub-surface defects in the investigated material. Scanning of the investigated area is performed by means of longitudinal and transverse waves. Then, using suitable software, verification of quantity and size of cracks is performed. The ultrasonic method is used mainly for the inspection of cracks in stator blades and impeller blades.

Magnetic method is used for assessment of fractures of casings and external surfaces and orifice of the central impeller. This method consists of the following phases: spraying the suspension of magnetic particles, magnetisation of the investigated element using electric current, registration of the distribution of magnetic suspension which represents the surface of the orifice along with possible grooves and cracks.

The method of colour dye indicators belongs to penetrating methods; it is used for detection of cracks in impeller shaft pins, blade cuts, orifice of central impeller, stator blades and disks. The method consists in using colour indicator dyes, which penetrate into the grooves and micro-cracks of the investigated material.

Measurements of crack depths are used for detection of surface cracks. The method of head potential and induced eddy current are used. For both methods of crack detection and measurements, the surface has to be clean and carefully grinded. The method of eddy currents is frequently used for detecting cracks in blades and central orifices of impellers.

5.2. Methods of destructive tests

Destructive methods are performed with the use of specimens, cut out from the particular part. The objective of the method is verification of diagnostic investigations outcomes obtained by means of non-destructive tests. The specimen sets are made of the cut-out pieces of the appliances. The range of investigation encompasses determination of mechanical properties and structure of the material. The tests are performed in ambient conditions as well as at temperatures similar to actual service conditions.

The structural tests are carried out by means of a microscope, their goal is to determine the layout, size and type of carbide extrusion as well as the stage of development of decohesion symptoms and the processes associated with creating of micro-cracks or the deformation process stage. Other tests, that could also be performed, are the following ones: resistance to creeping, resistance to brittle fracture and fatigue tests, based on which the prognosis of fatigue life of the constructional part can be formulated.

6. Thermovisional diagnosis of blades

As it was proved in paper [3], the analysis of thermographs registered by means of sensitive thermo-vision cameras allows for precise identification of surface damage. In the present chapter, we will examine the possibility of localisation of damage in impeller blade. The localisation is performed based

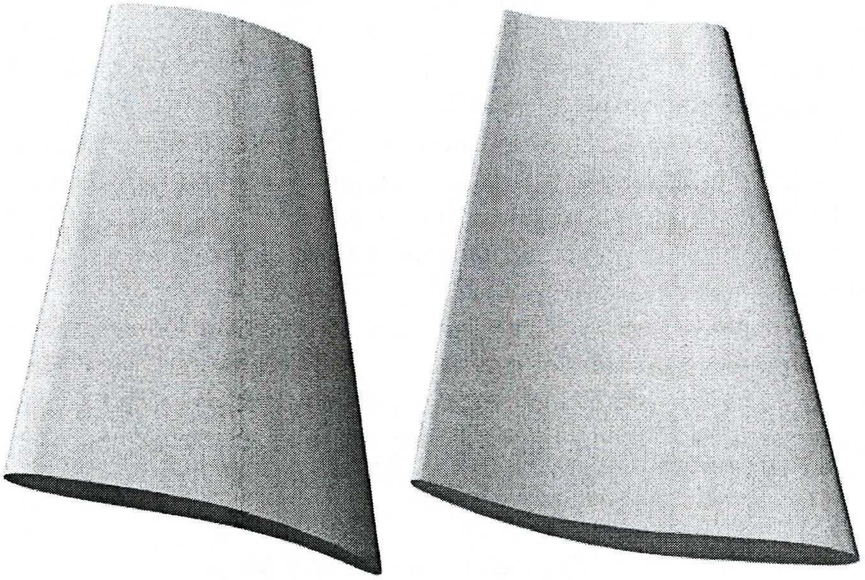

Fig. 8. The turbine blade used for numerical simulations

upon the analysis of isotherm layout obtained as the output of the software package ANSYS-5.7. Similar thermographs can be obtained using thermovision appliances. The exemplary blade had the following characteristics and parameters: it was made of duralumin, density $\rho = 2700$ kg/m^3, coefficient of thermal conductivity $k^* = 215$ W/m°K for the undamaged area and $k = 21.5$ W/m°K for the damaged zone. The blade was subjected to the thermal loading by means of a point source of heat at constant temperature 400°K. The initial temperature of the blade was equal to 293°K. The shape of the blade is presented in Fig. 8.

The damage was simulated in the upper, boundary part of the blade, on the concave and convex surfaces in the regions marked in Fig. 9.

The division of the blade into the eight-node finite elements 3D – SOLID 70 type is presented in Fig. 10 and Fig. 11.

As the result of the performed numerical investigations, we obtain the hereunder-presented images of isotherms on the convex part of the blade. They are presented the isolines (Fig. 12) and (Fig. 13).

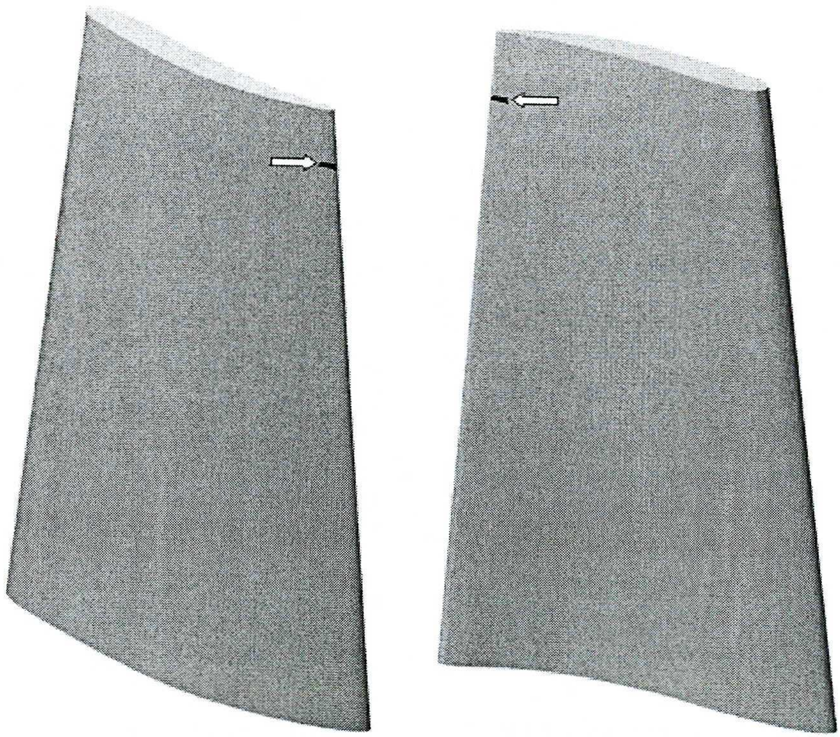

Fig. 9. The blade with the marked damaged regions in the concave and convex parts

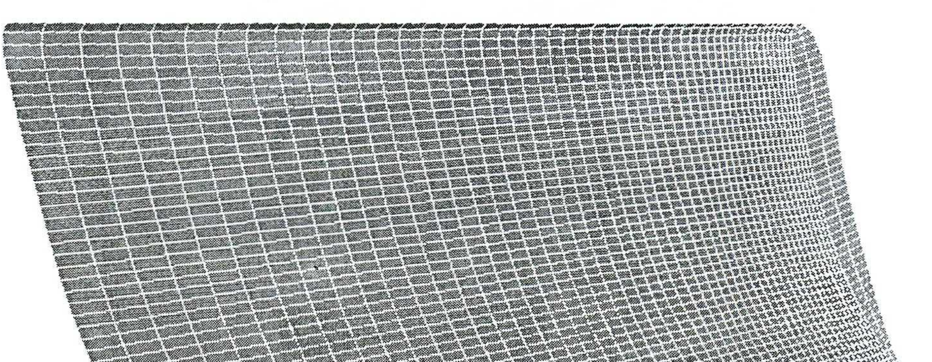

Fig. 10. The division of the blade into finite elements – view of convex part

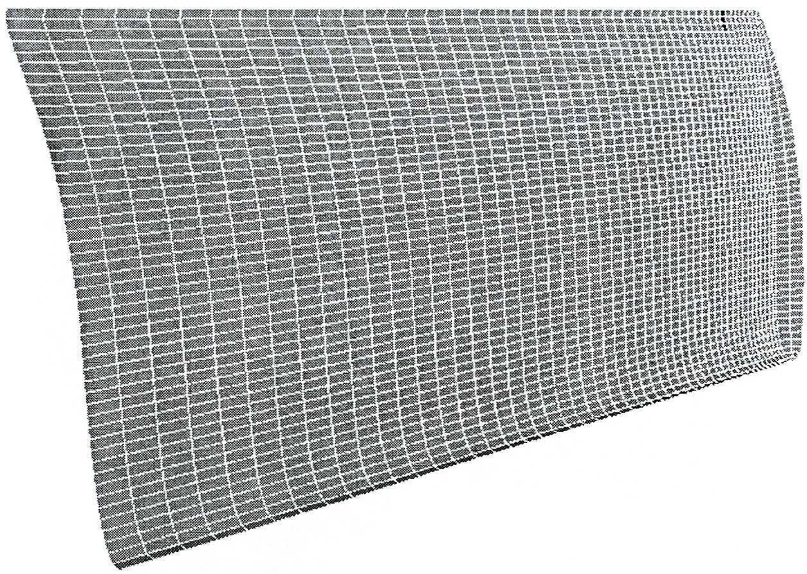

Fig. 11. The division of the blade into finite elements – view of concave part

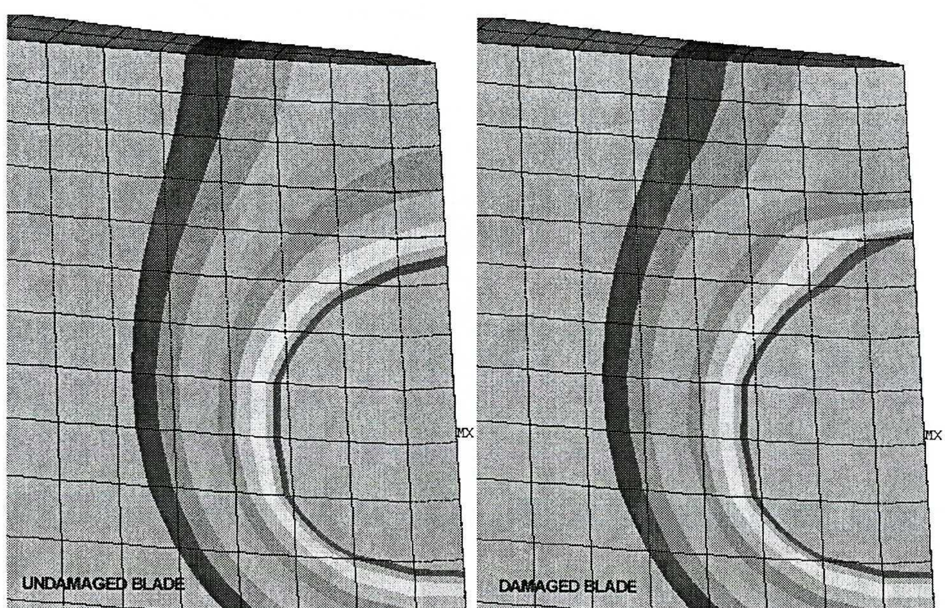

Fig. 12. The distribution of isotherms in the damaged zone of the blade, in comparison to the undamaged one

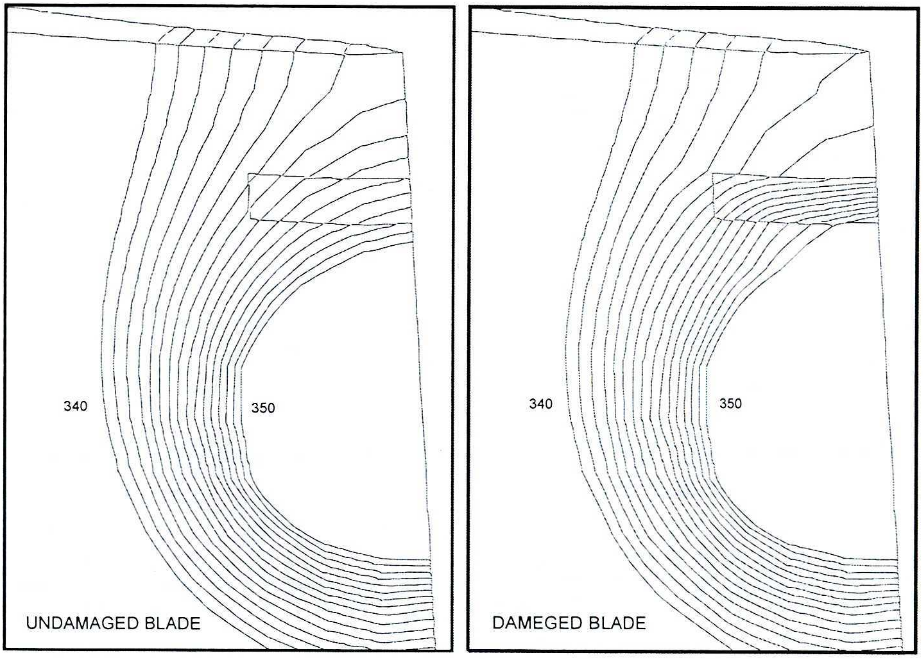

Fig. 13. The distribution of isotherms in the damaged zone of the blade, convex part

The distribution of isotherms in the damaged zone on the concave surface of the blade is presented in Fig. 14.

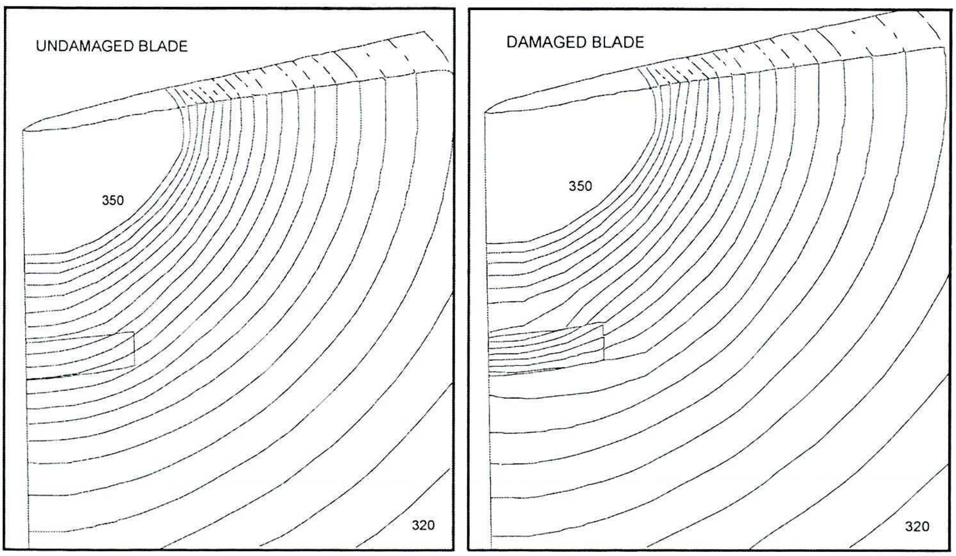

Fig. 14. The distribution of isotherms in the damaged zone of the blade, concave part

It can be seen in thermograms obtained upon the numerical calculations that there are evident disturbances of the temperature distribution in the damaged zone in comparison to the undamaged blade. This deformation of isotherm layout allows for precise localisation of damaged zone in the blade.

In diagnostic practice, the thermograph of the blade can be obtained using the modern thermovision techniques. The available thermographical apparata assure sufficient resolution and stability of the results needed for precise registration and detailed analysis of distribution of the registered temperatures. The presently popular infrared cameras can register 25 to 50 images/second with the resolution of 320×240 pixels and, furthermore, 12 to 14 bits level of information for every pixel. Inner analytical functions of the cameras allow for immediate analysis of thermographs, and the computer software cooperating with the camera allows for digital processing of the registered thermographs e.g. obtaining the profile of temperatures along arbitrary line as well as the histogram of the temperature distribution for an arbitrary measured area.

Thermovision – as a method of registration of temperature fields – combines two basic advantages i.e. contactless measurements of temperature and the possibility to observe temperature values in every point of the analysed area of the surface. It excludes the possibility of the loss of information, which would take place if the grid could not be analysed with sufficient resolution in some areas. The measurement of temperature by means of thermovision methods is fast, and the obtained images can be easily interpreted and numerically processed. The analysis of the obtained thermographs will make it possible to localize the damage and possible deviations from the normal service states of the blades.

Thermography is a comparable methodology for proper assessment of damage and its localisation. The knowledge of the temperature distribution in undamaged elements is essential; the necessity of taking into account element geometry and its design is a must, too. Proper knowledge of temperature field along with the information about the design, working conditions and technological specifications can be the first important step in the task of recognition of technical conditions of turbine blades as well as other parts of steam and gas turbines.

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Diagnozowanie uszkodzeń łopatek turbinowych

Streszczenie

W artykule opisano najczęściej spotykane rodzaje i mechanizmy uszkodzeń elementów przepływowych turbin. Na tle aktualnie stosowanych metod diagnozowania uszkodzeń zaproponowano nową możliwość lokalizowania defektów łopatek turbinowych drogą analizy rozkładu izoterm.

Niniejsze opracowanie stanowi kontynuację wcześniejszych prac autora na temat wpływu uszkodzeń na rozkład temperatur w materiałach konstrukcyjnych i dotyczy wykorzystania poczynionych spostrzeżeń do diagnozowania części maszyn.