

DEGRADATION OF THE GAS TURBINE BLADE COATING AND ITS INFLUENCE ON THE MICROSTRUCTURE STATE OF THE SUPERALLOY

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Abstract

The technical condition of the blades has a critical influence on the reliability and life span of a gas turbine and an engine into which it is built in. The main causes of blade damage are overheating, creeping, thermal fatigue, high temperature corrosion, etc. It is often caused by adverse operational conditions or manufacturing defect, e.g. using insufficiently durable types of heat-resistant protective coatings or applied in an improper manner on the blade material. Reaction of coatings and blade material to mechanical and thermal loads depends mainly on the operating temperature of the turbine. Selection of a protective coating and material to manufacture a blade with an assumed strength must take into account its mechanical and thermal properties at maximum aerofoil temperature. The article presents characteristic forms of operational damages to the gas turbine blades of a turbojet aero engine. Distinguished were operational factors and their influence on the technical condition of coatings during the engine operation period. An influence of excess exhaust gas temperature on the condition of the heat-resistant blade layer was shown. Shown were also results of morphology tests of coating degradation types. Results of micro-structure tests of the blade superalloy after damage to the heat-resistant coating were also presented.

Keywords: turbine, blade, heat-resistant coating, technical condition

1. Introduction

A gas turbine is a rotor machine converting enthalpy of the work factor, also called the thermodynamic factor, into mechanical work making the rotor to rotate. Increasing turbine efficiency results in an increase of its power and a decrease of individual fuel use by the engine. That efficiency, varies from 30-45% in aero engines, decreasing during the operation process, depends substantially on the exhaust gas temperature. That is why it increased up to even 1600K over the past few years. This caused a significant improvement of the turbine's general efficiency and increased its power factor. At the same time, it affected an increase of heat stresses, of blades in particular. Moreover, exhaust fumes with an increased temperature show greater corrosion aggressiveness. Increased stress and corrosivity of the factor forced the use of heat-resistant material with better properties. However, increasing exhaust gas temperature is limited by materials used on the turbines due to their resistance to creeping, thermal fatigue, high temperature corrosion, etc. [2, 11]. That is why; it became necessary to use new, expensive alloys with a more complex composition. The turbine materials have been improved thanks to the development of

alloys because of nickel and cobalt. These materials can operate a homologous temperature, higher than 0.85 [7, 11]. In addition, to increase the properties, chrome, titanium, molybdenum, tungsten, niobium and tantalum. However, molybdenum and niobium show small fire resistance [8, 10].

Further development of heat-resistant materials is superalloys created with methods of directional crystallization and mono crystallization [11]. Using these manufacturing technologies allowed a fivefold increase of fatigue strength due to elimination of grain boundaries and a tenfold increase of durability in high temperature, in comparison to the blades produced from polycrystalline superalloys.

In order to increase durability, complex geometric shapes of blades are designed, that complicate their technological manufacturing processes. They are shaped in such a way, as not to create a vibration resonance during interruption of engine work. Sometimes, dampers are used to eliminate dangerous form and frequency of vibrations.

Meanwhile, in order to decrease the blade temperature, internal cooling with air from behind the engine compressor is used. This allows lowering the temperature of the blade material in relation to the temperature of the circumfluent exhaust stream by over 600K [2, 11]. Moreover, we gain a better distribution of temperature onto the blades in the turbine work transients.

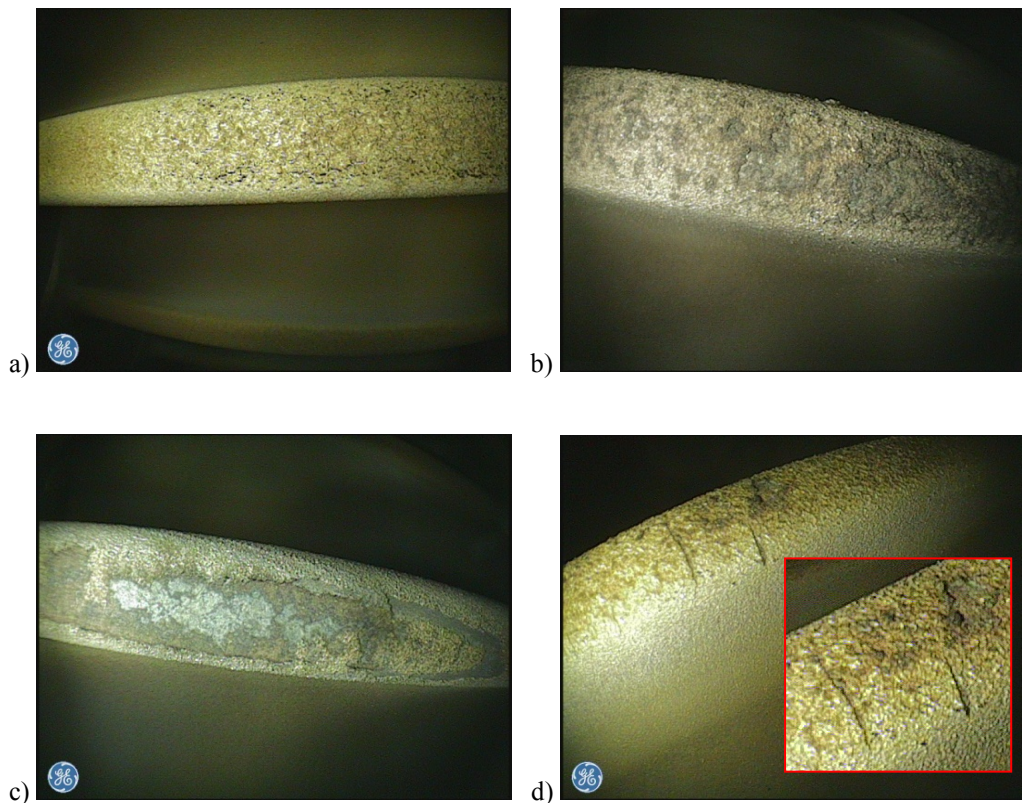


Fig. 1. Forms of damage to gas turbine blades on the leading edge: a) – coating micro-cracks, b) – partial burn out of the coating, c) – total burn out of the coating until alloy is revealed, d) – partial burn out of the coating and numerous macro-cracks [8]

On gas turbine blades working in extreme temperature conditions applied are heat-resistant coatings with good thermal conductivity and high structure stability. Thermal properties of the coatings mainly depend on the composition of the material and microstructure, i.e. grain size, porosity and impurities. Used are different types of protective coatings, obtained with many methods. Most commonly used are diffusion coatings on aluminium warp and their variations known as modified coatings [9, 12]. Coatings used on rotating blades are produced with the EB-PVD technology (electron beam physical vapour deposition) [10]. It consists of a priming layer and an insulation layer. These layers are laid with a thickness of a fraction of a millimetre.

The ground material is usually an alloy because of nickel or cobalt. That layer should be characterised by resistance to oxidation and corrosion, low tendency to form brittle transition phases and transfer of micro-deformations from the base to the insulation layer [13]. The insulation layer should be characterised by very low thermal conductivity, expressed by a temperature coefficient of thermal conductivity and by thermal diffusivity [9, 10]. That value depends on the ability of the material to scatter phonons on structural defects.

As is clear from the above analysis, despite using many endeavours in order to improve the efficiency of the gas turbine, its durability and reliability, over the work process, there are still all kinds of damages to turbine elements, especially their blades (Fig. 1). The damages can be divided into few cause groups often connected with each other. We differentiate defects being results of material and technological faults, derogations from the quality of production and repairs, operational in particular. Important reasons are also improper fuel atomization in the combustion chamber, as well as its diminished physical-chemical properties [3].

2. Testing microstructure condition

Accepted for metallographic tests were new blades and ones with different operation runtimes. The influence of degradation on micro-structural changes on the blades was tested on cut-out samples. The samples, after mechanical grinding and polishing were etched with the Kalling chemical reagent. Micro-structural tests were carried out using a scanning electron microscope Quanta 3D FEG. The observations were made on the leading edge surface and the metallographic specimens (Fig. 2). A view of the new blade surface is presented in Fig. 2a. It is characteristic for the used manufacturing process. The coating consists of the priming and insulating layers (Fig. 2b). An average coating thickness is approximately 70 μm .

As a result of carried out microscopic observations of blades in use, under the destructive influence of exhaust gases, oxide layers on their surfaces were found, with their thickness of even over 50 μm and numerous thermal, and even mechanical, damages (Fig. 2 c-f). Among others, delamination between the coating and the parent material of the blade was observed. Moreover, transverse and longitudinal cracks were noticed on the layer, as well as propagation of some cracks inside the blade material to a depth of over 500 μm (Fig. 4). It was also stated, that the oxidation process, and subsequently cracking, is preferential, on dendrites or inter-dendritic spaces.

The recorded degradation of laid coatings also results in micro-structural changes that undergo within the coating itself, as well as the parent material of the blades in use (Fig. 3). An average thickness of a coating was worn down to 30 μm . On the basis of the carried out tests, it was stated that coating microstructures consist mainly of phase β , carbides and oxides (Fig. 4). A significant growth of coating structural elements was also noted. In extreme operation conditions that practically lead to a complete destruction of the microstructure and chemical composition of the coating with simultaneous intensification of the cracking and delamination processes.

Results of metallographic tests confirmed also substantial structural changes of blades in use in comparison to new ones. Found were, inter alia, significant changes in the morphology of the particles of the hardening phase γ and its share under the coating layer (Fig. 5). Observations of structural changes were carried out on transverse (in relation to the blade axis) metallographic specimens in 5, equidistant areas. Based on these observations, it was established that micro-structural changes result from, above all, operational conditions (impact of exhaust gases with extremely high temperature) (Fig. 6). It was also found that operation conditions cause the expansion of the hardening phase γ' and a decrease of its share near the surface of the laid coating. In case of a cracked blade (Fig. 3) the surface share of phase γ' near the surface decreases from 65% for a new blade (Fig. 7a) to 30% (Fig. 7d), meanwhile causing a multiple growth near the surface.

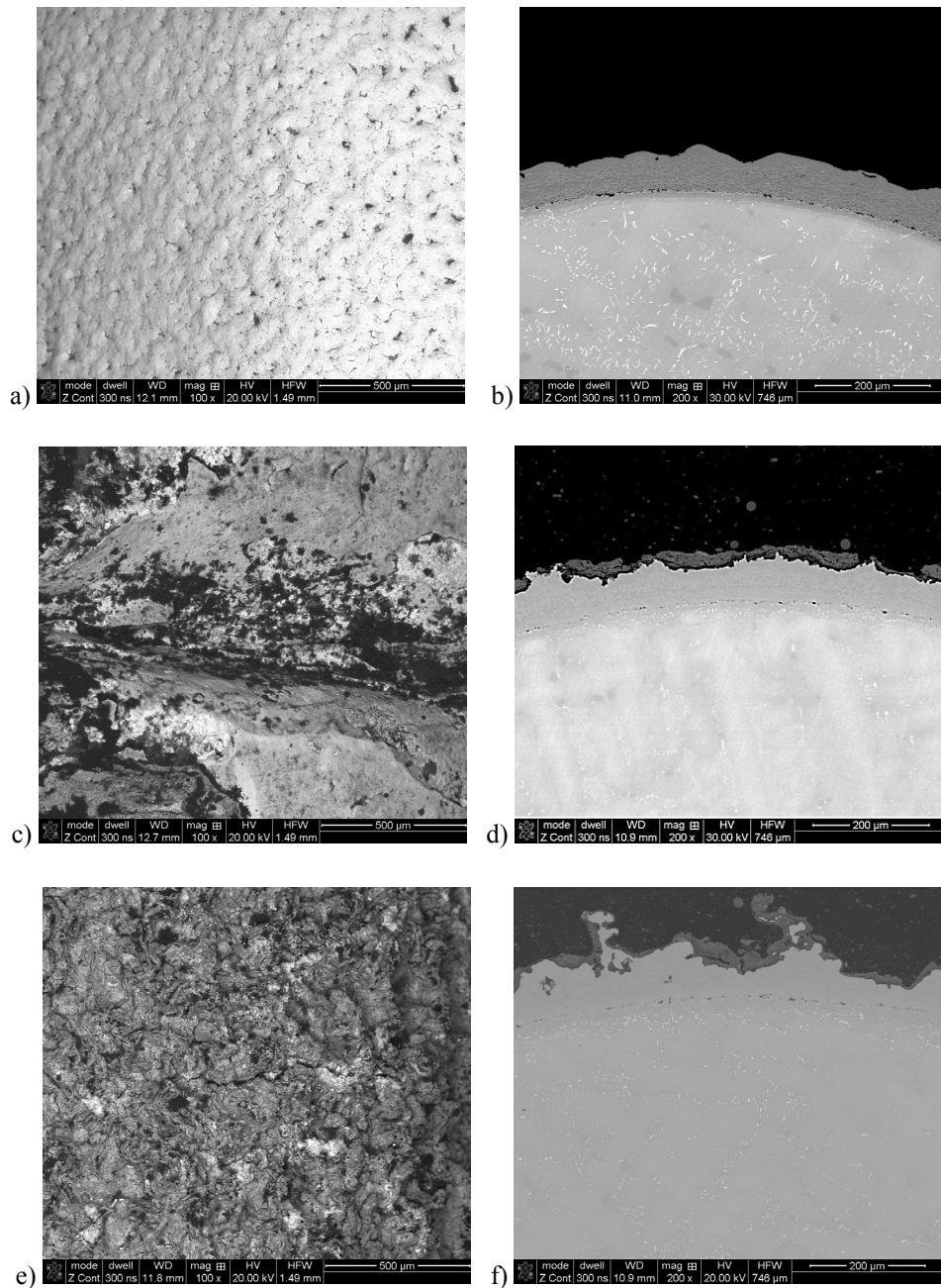


Fig. 2. Coating morphology in the cross-section of the leading edge: a-b) new blade; c-d and e-f—blades after a respectively longer operation period

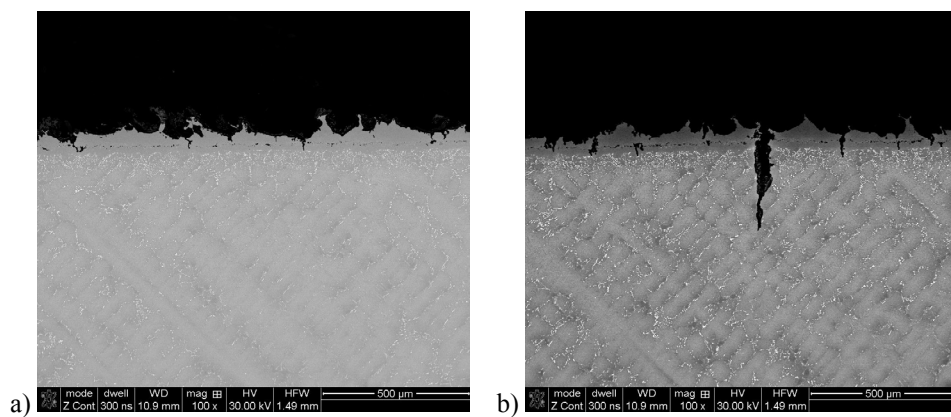


Fig. 3. Morphology of a blade working with a crack on the leading edge

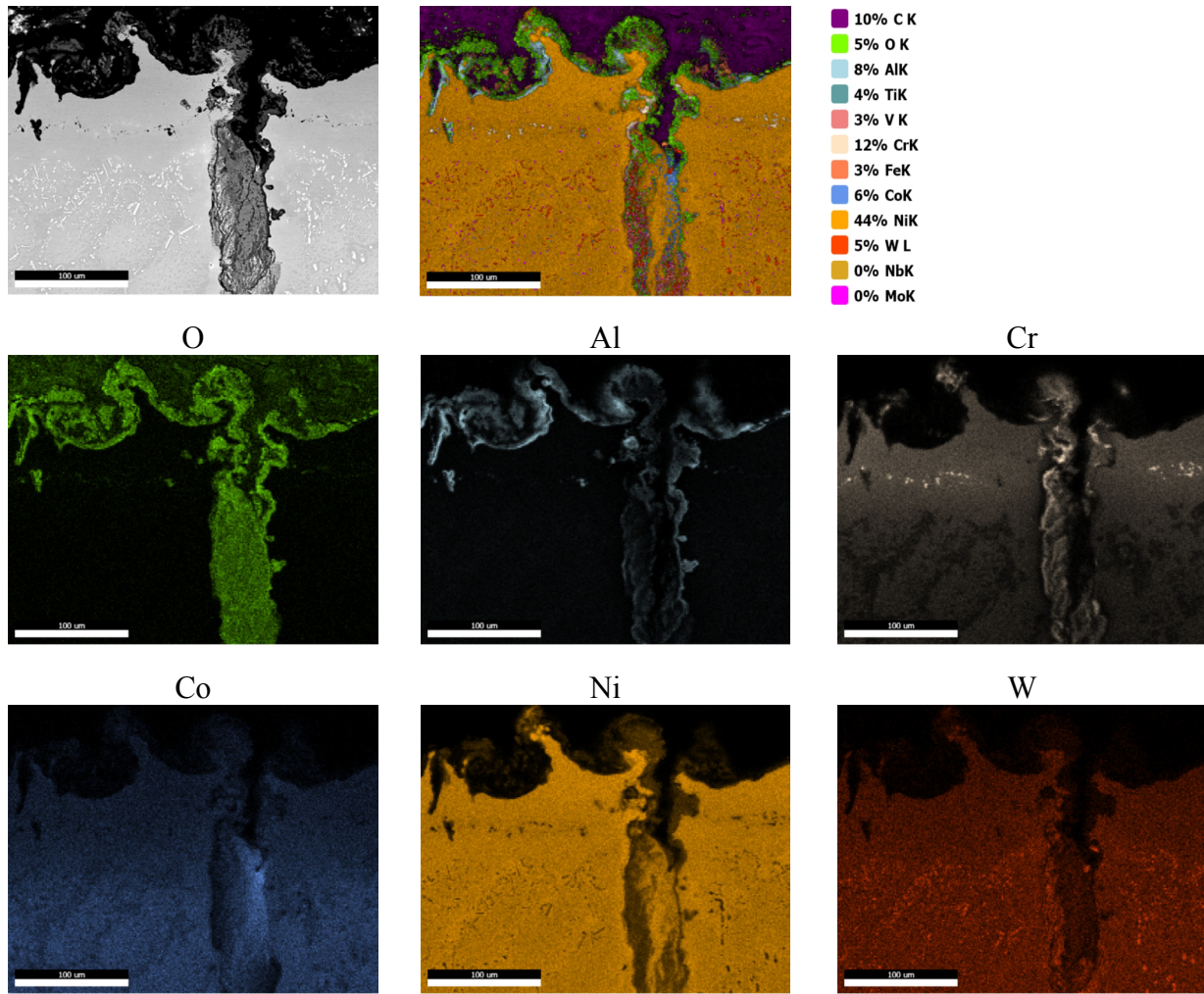


Fig. 4. Surface distribution of elements of a blade working with a crack on the leading edge

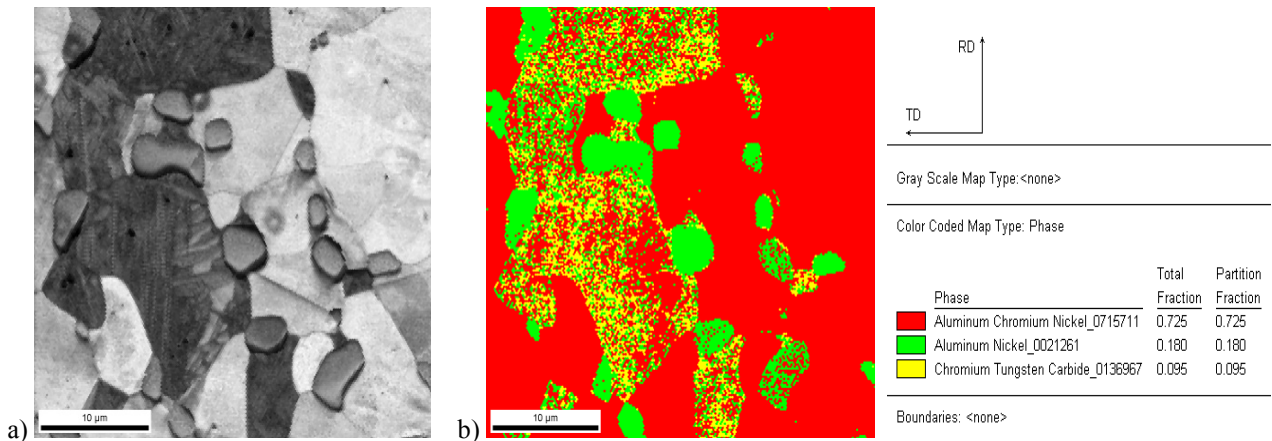


Fig. 5. Topographic orientation results in a new blade; a) microstructure, b) surface distribution of phases occurring on a presented area of a blade in use

Morphology of phase γ' particles depends on the mechanical stress. Tensile stress, occurring along the blade axis during the rotation of the turbine rotor, promotes expansion of phase γ' on a plane perpendicular to the strain direction [2, 11]. As a result, the original cuboid shapes (Fig. 6a) changes into tiles (Fig. 6c, d), with wider walls, being positioned perpendicular to the strain direction and the narrow walls perpendicular to other cube directions.

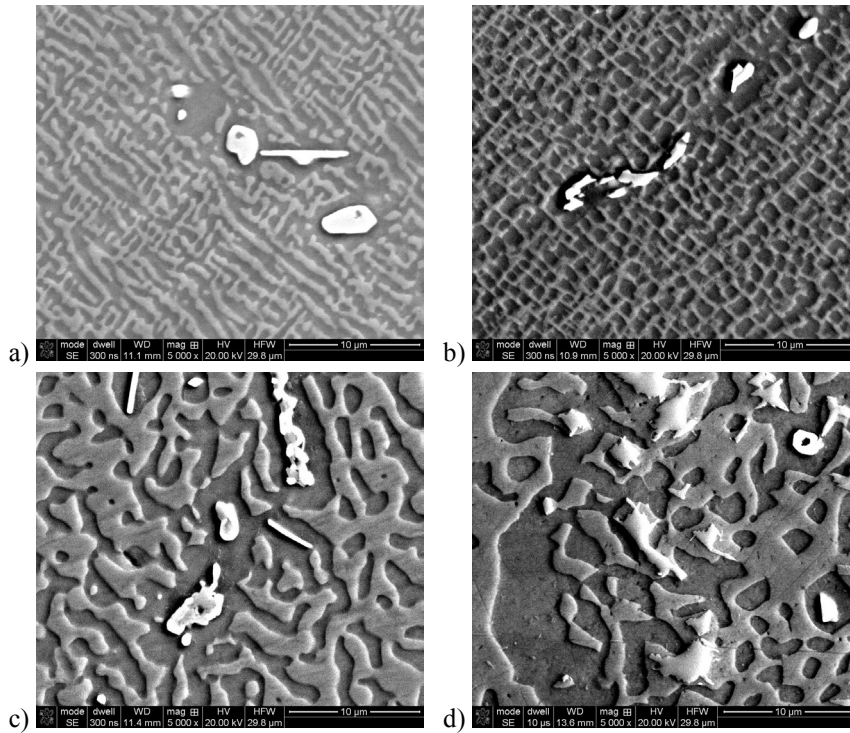


Fig. 6. Blade material microstructure – leading edge: a – new blade; b, c, d – blades with a respectively longer operation runtime

The expansion of the phase γ' particles lead to the loss of their stability, resulting in coagulation of some particles and dissolving of other. That process occurs above a certain, characteristic for a given phase, temperature and the time of exposure to exhaust gas temperature. After exceeding the temperature of 1223K and even after a relatively short exposure time, there is an intensive expansion of phase γ' exudations what leads to the loss of shape stability and the creation of tiles [2, 11].

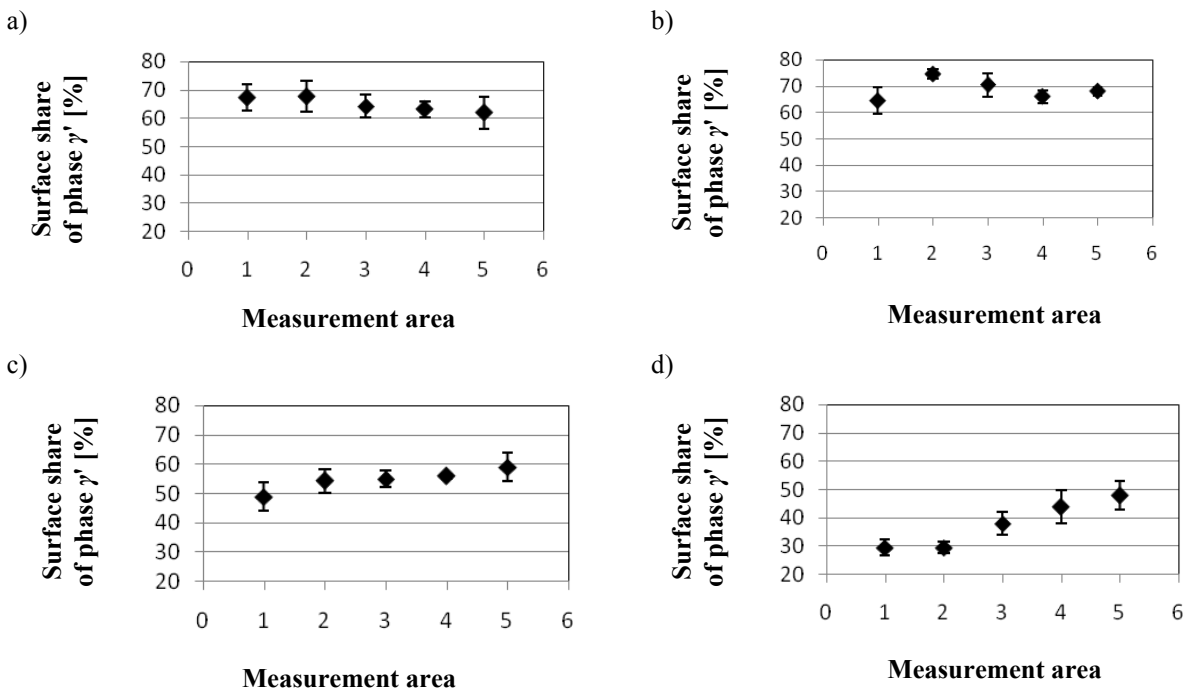


Fig. 7. Surface share of the hardening phase γ' inside the leading edge, in individual blades; a) new blade, b, c, d – blades after a respectively longer operation runtime

The kinetics of phase γ' exudations depends on the super-saturation with alloy elements of phase γ . Exudation shape depends on the degree of mismatch between their grid with the warp grid. Hardening phase γ , with mismatch of the grid $\Delta a = 0.2\%$ exudes in spheroid shape, at $\Delta a = 0.5 - 1\%$ takes the cuboid form and at $\Delta a = 1.2\% -$ tile form. The exudation hardening theory shows that the factors deciding the hardening degree are diameter of phase γ' particles and distance between them. These parameters depend on the rate of growth and coagulation of those particles [2, 11].

3. Summary

The destruction process of a gas turbine blade starts with the damage to its heat-resistant coating. As an effect, the material of the blade is exposed to direct thermal and chemical impact of the exhaust gases. Such a situation causes, primarily, the blade material to overheat, which is manifested in adverse changes of the microstructure. The factors affecting that phenomenon are supercritical temperature, its impact time and chemical aggression of exhausts. Chemical composition, morphology and distribution of phase γ' exudations in the structure of the blade material have a decisive influence on the strength properties of the superalloy. Growth of that phase leads to coagulation of exudation and changes in the shape from cuboid to tile. Moreover, its percentile share in the structure declines. As a result, the heat-resistance and heat-strength of the superalloy decreases.

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