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INCREASED TEMPERATURE IMPACT ON DURABILITY OF GAS TURBINE BLADES

WPŁYW PODWYŻSZONEJ TEMPERATURY NA TRWAŁOŚĆ ŁOPATEK TURBINY GAZOWEJ*

The paper presents the research results of a microstructure of the turbine rotor blades made of nickel-based super alloys. The purpose of the research was to determine the high temperature impact on the microstructure stability of the material of the blades. The degree of advancement of the super alloy microstructure changes after the exposure to high temperature was compared to the mictrostructure condition of new blades. The research material includes blades made of EI 867 and ŻS 32 types of alloys. The microstructure research of blades subject to the high temperature impact, and the blades after operation showed the occurrence of adverse changes in relation to the microstructure of new blades. It was found that the cause of adverse changes in the microstructure was the super alloy overheating. The blade in such a condition has low heat and creep resistance. The element, in which the overheating will occur, is exposed to damage, which usually entails faulty turbine operation. This type of damage is removed during the engine major repair, which is associated with huge costs.

Keywords: *gas turbine, blade, microstructure, durability.*

W artykule przedstawiono wyniki badań mikrostruktury łopatek wirnika turbiny wykonanych z nadstopów na bazie niklu. Celem badań było określenie skutków oddziaływania wysokiej temperatury na stabilność mikrostruktury materiału łopatek. Stopień zaawansowania zmian mikrostruktury nadstopu po oddziaływaniu wysokiej temperatury porównywano ze stanem mikrostruktury łopatek nowych. Materiałem do badań były łopatki ze stopów typu EI 867 oraz ŻS 32. Badania mikrostruktury łopatek poddawanych oddziaływaniu wysokiej temperatury oraz łopatek po eksploatacji wykazały występowanie niekorzystnych zmian w stosunku do mikrostruktury łopatek nowych. Stwierdzono, że przyczyną niekorzystnych zmian w mikrostrukturze było przegrzanie nadstopu. Łopatka w takim stanie wykazuje niską żaroodporność oraz żarowytrzymałość. Element, w którym wystąpi przegrzanie jest narażony na uszkodzenie, co przeważnie pociąga za sobą wadliwą pracę turbiny. Tego typu uszkodzenia usuwa się w trakcie naprawy głównej silnika co wiąże się z ogromnymi kosztami.

Słowa kluczowe: *turbina gazowa, łopatka, mikrostruktura, trwałość.*

1. Introduction

Gas turbines are used in the energy sector in traction, marine, and aircraft engines as well as in aerospace. During operation, they are subject to variable mechanical and heat loads. The essence of low-cycle loads is a cumulative and simultaneous destructive effect of variable mechanical and heat loads of high amplitudes. These kinds of loads are especially subject to rotating blades. Along with the increasing temperature, the material strength of blades decreases. As a result of the impact of high temperature and exhaust gases with an aggressive chemical effect, the technical condition is subject to adverse changes. It results in the material overheating, its creeping and thermal fatigue [4, 17, 18, 22]. Consequently, it leads to the loss of heat and creep resistance of the material of blades.

The turbine efficiency, which is at the level of 30-45%, decreasing during the operation process, substantially depends on the exhaust gas temperature. However, the increase in exhaust gas temperature is limited by the used material properties: their resistance to creeping, microstructure change (overheating), thermal fatigue, high temperature corrosion, etc. [5, 20].

The most unreliable elements of the gas turbine include rotor blades [4, 17]. During operation, they are subject to the variable loads: mechanical ones as a result of rotation, as well as aerodynamic and heat ones from the work factor flow. In addition, the chemically aggressive exhaust gases of high temperature affect them. The reliability and durability of blades is a sum of many factors, the predominant importance of which plays the material, which they are made of. The high and stable strength properties of super alloys in structural terms constitute the proper microstructure that is not subject to weakening operational changes [2, 6, 16].

Particularly high requirements are imposed to materials used for the turbines' blades. Advances in the development of super alloys and manufacturing technology of blades resulted in a increase of operating temperature of blades almost to 1350K [8]. The improved super alloys on the turbine blades were obtained thanks to the development of alloys on the basis of nickel and cobalt. In addition, in order to increase the mechanical properties, chrome, titanium, molybdenum, vanadium, tungsten, niobium, tantalum, and other elements [1, 7, 10, 11] are added. The main component of the super alloy is the γ phase, that is Ni solid solution of a wall-centred regular structure. The composition of this phase may mainly include the elements such as Co, Cr, Mo, W and Re, which strengthen them with solution.

Due to the manufacturing methods of blades, super alloys are divided into wrought and cast ones. In the super alloys of the wrought blades, a friction of volume reinforcing with the γ' phase ranges from 20 to 45%. The blades made of these super alloys can operate to the temperature of 1173K. The further increase of the operating tempera-

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** ture of blades to about 1273 K requires an increase in the volume friction of the γ' phase in the alloy. It can be achieved by modifying the chemical composition, as well as by changing the manufacturing technology, e.g. as a result of introduction of cast super alloys. In the cast super alloys, the γ' phase volume friction is approximately 60%. In order to increase the operating temperature of blades of more than 1373K, the directional crystallization is applied [16, 18, 19]. It allows an increase in the super alloy creep resistance. The further development of super alloys was associated with the elimination of grain boundaries – monocrystalline super alloys, i.e. these are made of a single crystal with a uniform internal structure of the entire volume. Using these manufacturing technologies of the turbines' blades allowed the achievement of a fivefold increase of fatigue strength and a tenfold increase of durability at a high temperature, in comparison with the blades produced from polycrystalline super alloys [8].

Moreover, heat-resistant coatings with good thermal conductivity and high structure stability are applied on the gas turbines' blades operating in extreme temperature conditions. Thermal properties of the coatings mainly depend on the chemical composition of the material and microstructure [3, 4]. Different types of protective coatings, obtained by many methods, are used. The diffusion coatings on aluminium matrix and their variations known as modified coatings are most commonly used [9, 14, 21]. These coatings consist of a priming layer and an insulation layer. They should be characterised by very low thermal conductivity.

A further step aimed at increasing the exhaust gas temperature and decreasing the blades' temperature includes their internal cooling with air from behind the engine compressor. This allows to lower the temperature of the blade material in relation to the temperature of the circumfluent exhaust stream by over 600K [21, 22]. Furthermore, better distribution of temperature onto the blades in the turbine operation transients is obtained.

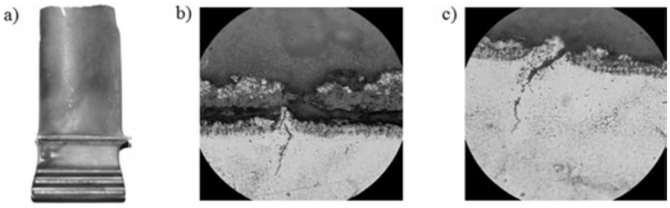

Fig. 1. The example forms of operational failures of an uncooled turbine blade made of the EI 867 type forged super alloy: a) a tip broken due to the super alloy overheating; b) stratification of heat-resistant coatings, and the super alloy crack initiation, x500; c) erosion of the heat-resistant coating and the crack penetrating into the super alloy, x500

Moreover, in order to increase durability, the complex geometric shapes of blades are designed. They are shaped in such a way, as not to create a vibration resonance during interruption of the engine operation [6]. Tip shelves at the ends or near the blade ends, which act as dampers eliminating a dangerous form and frequency of vibrations, and increasing tightness in the turbine rotor tip clearance are also applied. The minimum clearance prevents the work factor losses.

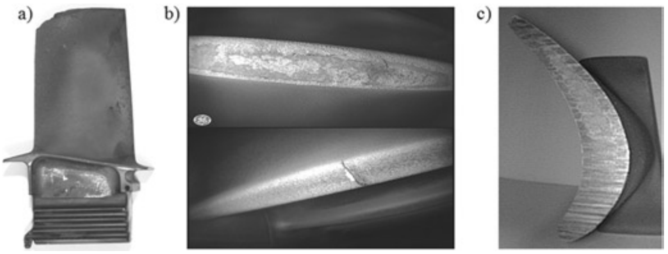

Fig. 2. The example forms of damage of the cooled turbines' blades made of the ŻS 32 type cast super alloy: a) the material overheated at the tip [2]; b) complete burning of the coating on the leading edge to expose the super alloy, and a crack on the leading edge [12]; c) blade leaf front chafing [12]

Despite using many endeavours in order to improve the efficiency of the gas turbine operation, its durability and reliability, over the long-term operation process, there are still all kinds of damages to the turbine elements, especially their blades (Fig. 1, Fig. 2). It is possible to differentiate defects being the results of material and technological faults, derogations from the quality of production and repairs. The important reasons can also include improper fuel atomization in the combustion chamber, as well as its diminished physical-chemical properties [5, 15].

The most frequent cases of damage include the overheating of the blades' leaves (Fig. 1a, 2a). It sometimes results in the blade leaf end fracture (Fig. 1a). The destruction process of the gas turbine blade usually begins with the destruction of its heat-resistant coating (Fig. 1b c, 2b).

As a result of it, the blade material is exposed to the direct heat and chemical effect of exhaust gases. This situation mainly causes the material overheating and the formation of the blade leaf cracks (Fig. 1c, 2b). The factors affecting that phenomenon are supercritical temperature, its impact time and chemical aggression of exhaust gases. As an effect of high temperature, and high tensile stresses derived from centrifugation and time, the phenomenon of the blade material thermal expansion occurs. It significantly affects the turbine rotor tip clearance reduction. Consequently, it results in rubbing the blade front against the turbine body (Fig. 2c), which causes additional heating of the blade leaf material and adverse changes in the super alloy microstructure. The changes typical for the high-temperature creeping process with the uniaxial stress state are usually observed in the blades with a plate.

2. Increased temperature impact on degradation of uncooled blades of the EI-867 WD type super alloy

In the gas turbine operation, there are often cases of short-term heating of the material of blades above their normal operating temperature. Therefore, it is important to maintain the alloy heat and creep resistance to increased temperature at the required blade operation time. Creep resistance of super alloys for the gas turbine blades relates to the *γ'* reinforcing phase. Under the influence of a work factor with high temperature, it is subject to coagulation and dissolution in the matrix. In order to determine the increased temperature impact on the super alloy degradation of forged blades, the experimental research was carried out. In case of the research, new gas turbine rotor blades made of the EI-867 WD (HN62MWKJu) alloy – uncooled blades – were adopted. The blades' leaves were divided into four equal samples, which were chosen at random for testing and heated (three of them) at five temperature values every 100 K starting from the temperature of 1023 K. The heating and cooling of samples took place in the vacuum oven (individually) – no interference of the core on the surface of blades.

Table 1. The list of the EI-867 WD alloy basic chemical composition (% of weight)

C	Mo	Si	Cr	Ni	Co	Mo	W	Al	B	Fe
max	max	max		other					max	
0.1	0.3	0.6	9.0		14	10.3	5.0	4.5	0.02	4.0

The EI-867 WD alloy belongs to a small group of nickel super alloys that do not contain titanium. It is a super alloy of a lower chromium content, and therefore, it is sensitive to corrosion [4, 16, 20]. Accordingly, protective coatings – aluminium coatings – are applied. The TU 14-1-232-72 standard includes the requirements for the super alloy chemical composition (Table 1), heat treatment and mechanical properties.

The alloy structure is typical for nickel super alloys and is composed of: *γ*, phase, *γ'* phase, carbides and borides. The *γ'* phase is aluminium solid solution, titanium tubes in nickel. The *γ'* phase particles (Ni_3Al, Ni_3Ti) are cubical in shape [13, 16, 18]. The *γ'* phase relative volume after the alloy standard heat treatment is 31÷34%. The heat treatment includes solubilisation quenching and ageing. The cooling in air during solubilisation quenching results in precipitation of the *γ'* phase small particles, the relative volume of which is about 20%. The ageing results in further precipitation of the *γ'* phase particles and the growth of previously separated ones. Among the carbides, the relative volume of which does not exceed 2% in the alloy, $M_{23}C_6$ solid predominates. It is formed during heat treatment or it is released during operation, usually on the boarders of grains in the temperature range of 933K÷1253K. Inside the grains, there is a carbide M_6C [4, 16]. The temperature values of heating the samples cut out of the blades are associated with the temperature range, which occurs during normal and emergency operation of the exploited rotor blades. The stream temperature of the work factor at the inlet to the gas turbine, due to restrictions resulting from thermal and chemical characteristics of the materials used in the uncooled turbine blades should be within the range of 1173÷1223K [17, 20].

The initial stage of metallographic tests was to assess the structure in order to determine the duration of the heating process of the blades' parts. The time and temperature affect the kinetics of growth and coagulation of the *γ'* phase particles. The experiment involving the heating of samples in the temperature above T_{max} (maximum temperature behind the turbine, i.e. 1223 K for 0.5h, 1h, 2h and 3h) was conducted. Therefore, the information on structural changes both of the coating and the blades' material, depending on the heating time – modification of the size of the *γ'* dispersion phase (Fig. 3) was obtained. The changes of sizes (surface) of precipitation of the *γ'* reinforcing phase in the heating time function were determined (Fig. 4).

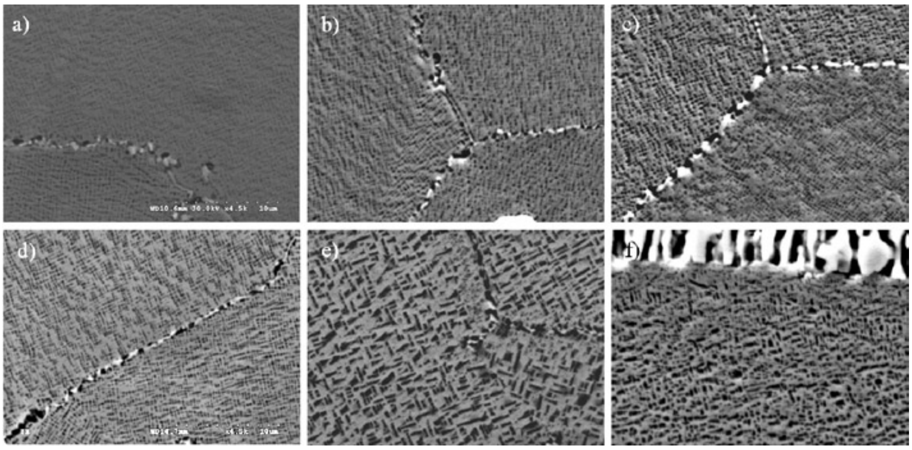

Fig. 5. EI - 867 WD super alloy subsurface microstructure: a) super alloy without heating and super alloy heated for 1 hour at: b) 1023K; c) 1123K; d) 1223K; e) 1323K; f) 1423K (surface x4500)

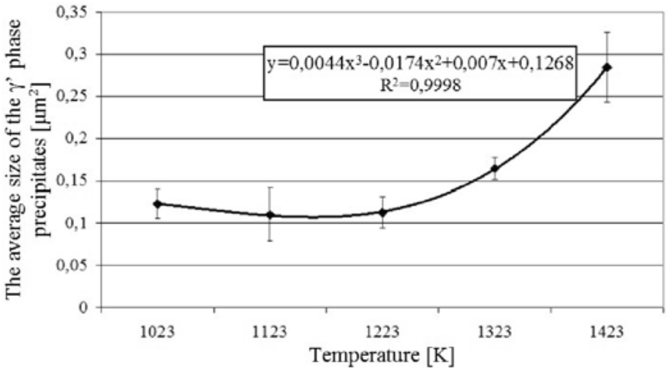

Fig. 6. Changes in the average size of the γ' phase particles in the temperature function

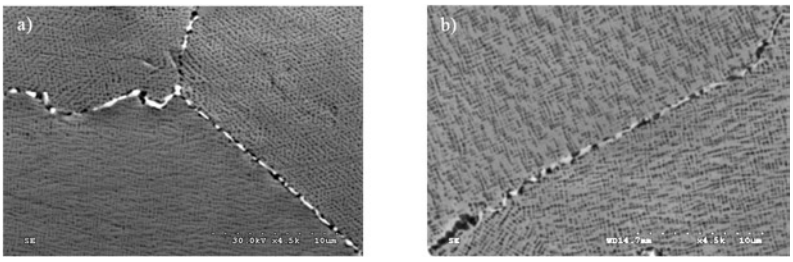

Fig. 3. Morphology of the γ' phase precipitates – heating in the temperature of 1223K for: a) 0.5h; b) 1h (surface x4500)

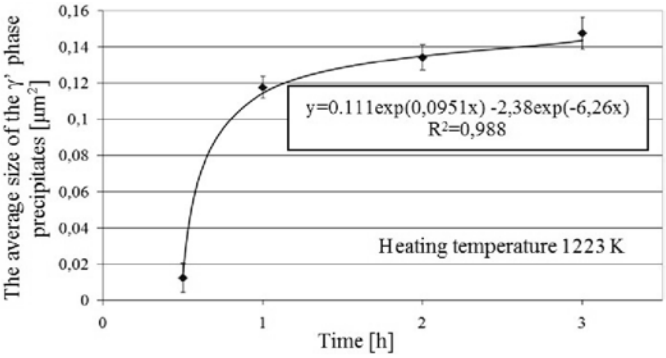

Fig. 4. Changes in the average size of the γ' phase particles depending on the heating time of samples of the blades at the temperature of 1223K

On the basis of Figure 4, the heating time, which was 1h in the research of the impact of high temperatures on the blade material, for a constant temperature, i.e. 1223K, was adopted. At that time, a sudden increase in the size of the *γ'* phase particles (an additional argument for such a choice is the aircraft task time in the operation conditions for the adopted jet engine type, which is also 1h) occurs.

The microstructure analysis of the super alloy subject to the high temperature impact was carried out, thanks to which detailed information on changes was obtained. The microstructure changes, mainly modification of sizes and distribution of the γ' dispersion phase, significantly affect strength properties. In Figure 5a÷f, the results of the super alloy metallographic test without heating and after heating for a period of 1h were presented taking into account five different temperature values.

The change in sizes of the *γ'* phase particles depending on the heating temperature was calculated (Fig. 6). It was found that the initial coagulation stage of precipitates of the *γ'* reinforcing phase, which is characterised by relatively high regularity and a large number of precipitates per are unit, occurs even at the temperature of 1123 K (Fig. 5b, c). As the temperature rises, the *γ'* phase structure becomes less regular while increasing the grain size (Fig. 6).

The initial stage of combining the *γ'* phase cubic precipitates in plates occurs at the temperature of 1223 K (Fig. 5d). At the temperature of 1323 K, a significant increase and coagulation of precipitates of the *γ'* reinforcing phase, which takes on the shape of plates, was found (Fig. 5e). The number of precipitates is much smaller, however, they are much larger than those created at 1223 K. The morphology of the *γ'* phase shows that after exceeding the temperature of 1223 K, the EI – 867 WD alloy is overheated.

3. Increased operating temperature impact on degradation of cooled blades of the ŻS 32 type super alloy

The research covered the blades cast from the ŻS 32 type cobalt and nickel super alloy. The content of basic alloy elements was presented in Table 2.

In case of the research, the new turbine rotor blades and those after increasingly long time of operation were adopted. The blades were prematurely removed from the turbine due to their overheating. In order to determine the increased temperature impact during operation on degradation of the ŻS 32 super alloy microstructure, metallographic tests were carried out.

Table 2. List of the ŻS 32 type super alloy basic chemical composition (% of weight)

Ni	Al	Cr	Co	Nb	Mo	Ta	W	Re
62.4	6.1	5.1	10.8	1.3	1.2	1.2	8.4	3.0

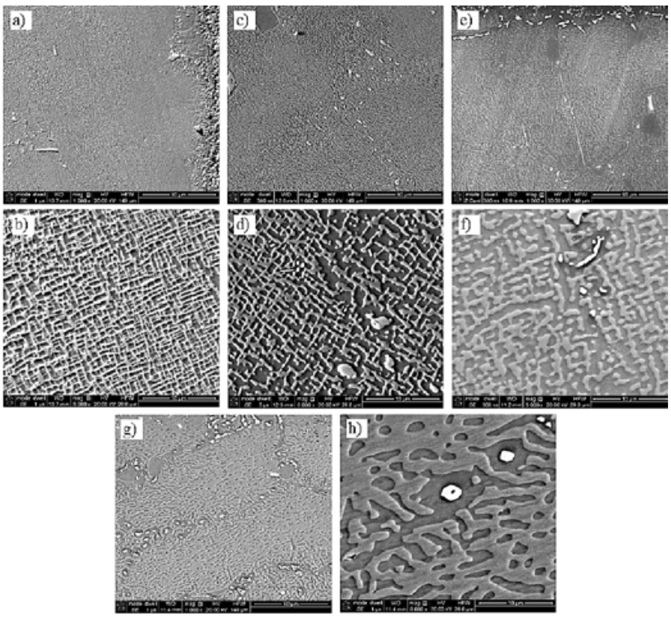

Fig. 7. The increased temperature impact on morphological changes in the cross-section of the leading edge: a, b) new blade No. 1; c; d) blade after the shortest time of operation No. 2; e, f) blade after the average time of operation No. 3; g, h) blade after the longest time of operation No. 4

On the basis of the structural observation conducted with the use of the Quanta 3D FEG scanning electron microscope, a very clear impact of the increased temperature on degradation of the microstructure of the analysed blades made of the ŻS 32 type super alloy was found. The microstructure of the tested blades consists mainly of *γ* and *γ'* phases and carbides. It was found that with the operating temperature increase and the time of operation, clear microstructural changes occur (Fig. 7). The significant changes in the morphology of the *γ'* reinforcing phase were observed. In the blade, the *γ'* phase new particles (Ni_3Al) have a cubic shape. As a result of the increased temperature impact, the change of their shape from cubic (Fig. 7a and b) to cuboidal one (Fig. 7c÷f) occurs, in order to reach an oval shape at the maximum temperature (Fig.7g and h).

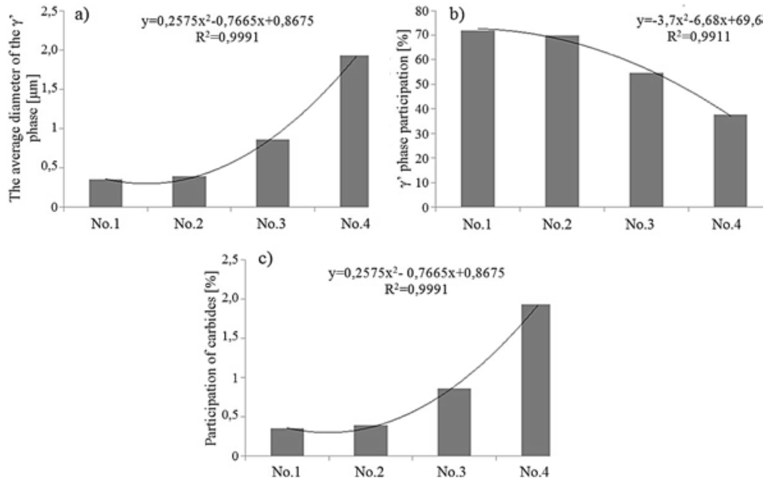

Fig. 8. The increased temperature impact on: a) the average diameter of the γ' phase, b) the γ' phase surface participation, c) surface participation of carbides

The observed changes are related to the expansion of the γ' reinforcing phase and a decrease in its participation (Fig. 8a). In case of a new blade, the average size of the γ' phase particles is approximately 0.3μm. As a result of the impact of increased temperature and operational factors, this value increases to the level of 2μm. The reported trend is also significantly reflected in the surface participation changes of the specified *γ'* reinforcing phase. It was observed that the surface participation of the *γ'* phase decreases from 70% for the new blade to 35% for the blade operated at the highest temperature (Fig. 8b). As a result of the increased temperature impact, the observed morphological changes of the *γ'* reinforcing phase are small, however, its impact on the surface participation of carbides takes place (Fig. 8c).

The surface participation of carbides in all the observed blades is at the level of 2-2.5%. Additionally, there were no significant changes in morphology of the observed carbides. However, a clear impact of the increased temperature and operating time of the tested blades on the *γ'* phase surface participation in particular zones within the cross-section of the tested blades was stated (Fig. 9). In case of the blade exposed to the highest temperature impact and the longest operation time No. 4, while measuring the surface participation of the described phase from the leading edge into the blade, it was found that the surface participation is the lowest (30%). In the distance of this blade, the participation of the described phase rises to the level of about 50%. However, no impact of the observed trend on the size changes of the *γ'* phase particles was observed in similar areas seen on the cross sections of other blades (Fig. 10).

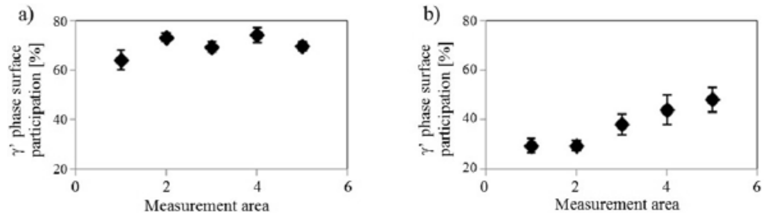

Fig. 9. Surface participation of the γ' reinforcing phase into the leading edge: a) blade No. 2, b) blade No. 4

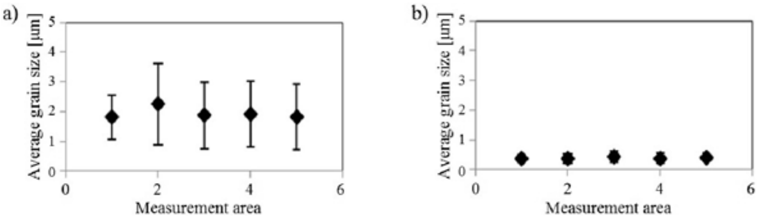

Fig. 10. The average diameter of the γ' reinforcing phase into the leading edge: a) blade No. 2, b) blade No. 4

4. Conclusion

Based on the research results, it can be concluded that both in case of new blades and the operated ones, which are subject to the increased temperature impact, there are microstructural changes in the material of blades. In case of the experiment with the EI-867 WD new blades, a high temperature and time of their impact are decisive factors. The heating time, which in testing of the increased temperature impact on the blade material was 1h, for a constant temperature, i.e. 1223 K; in that time, a sudden increase in the sizes of the γ' phase particles occurred. An additional argument for such a choice is the aircraft task time in the operation conditions for the adopted jet engine type, which is also 1h. However, the selected temperature values of heating the blades are also associated with the temperature range, which occurs during normal and emergency operation of the exploited rotor blades. The stream temperature of the work factor (exhaust gases) at the outlet from the aircraft jet engine combustion chamber, due to restrictions resulting from thermal and chemical characteristics of the materials used in the complete, uncooled turbine blades should be within the range of 1173÷1223K, as confirmed in the literature [17]. The *γ'* phase morphology shows that after exceeding the temperature of 1223 K, the EI – 867 WD alloy is overheated, and the tested blade cannot be considered useful for further operation. The obtained images of a microstructure of the EI - 867 WD alloy subject to the impact of increasingly higher temperature may be a basis for assessing the degree of overheating of the gas turbine blades.

In case of the operated blades (with different technical condition), in addition to the high temperature unstable at that time and the time of operation, there is also an important factor, i.e. aggressiveness of exhaust gases. As a result of the conducted tests of the operated blades, it is concluded that under the increased temperature influence, the chemical composition, morphology and distribution in the structure of the blade material of the *γ'* reinforcing phase adversely change. The morphology of the *γ'* phase particles depends on the mechanical stress. The tensile stress, occurring along the blade axis during the turbine rotor rotation, promotes expansion of the *γ'* phase on a plane perpendicular to the stress direction. As a result, the original cuboid shape changes into plates, whose wider walls are positioned perpendicularly to the stress direction and the narrow walls perpendicularly to other cube directions [9, 19]. These adverse changes in the super alloy microstructure exert a decisive influence on its strength properties. The *γ'* phase growth results in coagulation of precipitates, and therefore, an adverse change of its shape. Moreover, this phase percentage in the structure decreases. As a result, the heat and creep resistance of the blades' super alloy decrease. This condition significantly affects the durability of blades and has a major impact on the gas turbine premature major repair. In case of aircraft, it relates to the aircraft transition from the state of airworthiness, removal of the engine and its passing for the major repair. Although the end result are tremendous costs related to the repair due to e.g. one overheated turbine blade. However, the flight safety is an overarching principle of aircraft operation.

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