ANALYSIS OF DAMAGED TURBINE BLADES OF THE ENGINE MPM 20

Jozef Čerňan [1)*], *Marián Hocko* [1)], *Miroslava Cúttová* [1)], *Karol Semrád* [1)]
[1)] *Technical University of Košice, Faculty of Aeronautics, Košice, Slovakia*

Received: 06.05.2016
Accepted: 24.05.2016

*Corresponding author: *e-mail: jozef.cernan@tuke.sk, Tel.: +421 55 602 6153, Department of Aviation Technical Studies, Faculty of Aeronautics, Technical University of Košice, Rampová 7, 041 21 Košice, Slovakia*

Abstract
The objects of the investigation are damaged gas turbine blades of the MPM – 20 jet engine as a result of exceeding the temperature of the hot gases at the entrance of the gas turbine. On the damaged turbine blade metallographic-microscopic analysis was performed to identify aspects and consequences that accompanied the fracture. The research results showed phase changes in the structure as well as a significant oxidation along the grain boundaries, where cracks, leading to the destruction of the tip, were initiated. Toward the damage of the blades significantly contributed also the fact that higher temperatures cause higher thermal expansion and thus there was a clash of blades with an outer turbine casing. The subsequent mechanical deformation resulted in places of oxidized grains to cracking and a gradual detaching of the blade material in the form of partial fractures.

Keywords: metallography, turbine, blade material, fracture

1 Introduction
Turbine engines and steam turbines are nowadays progressive sources of kinetic energy and have also perspective future. An effort to increase their effectiveness is necessarily associated with an increase of the operating temperature of gases generated in the combustion chamber. Obviously, this aspect gives high demands on the heat resistance of the stator vanes and the rotor blades material inside the turbine, affected by the hot gases. Therefore in operation the accidents of these devices that have different causes inevitably occur. To the general causes are according to [1, 2] belong creep, thermal fatigue (low cycle fatigue), thermomechanical fatigue (high cycle fatigue), corrosion, erosion, oxidation or foreign object damage.
For steam turbines used also in power engineering are typical fatigue failures accompanied by the blade breaking, which in turn usually destroy other turbine blades [3,6]. Such failures occur in some cases also in turbine engines, even if there is an effort to avoid such fatigue fractures [4]. The fatigue damage usually accompanies the blade and their fixing parts stressed by the high centrifugal forces and thermal stresses [7]. However, there are also several documented failures of turbine locks of gas turbines in energetics [5], which were probably caused by the damage of stator vanes in the system. Therefore studies to assess the fatigue life of the blades and to reveal any insufficiencies in the design of the vanes geometry are performed using computer simulation software [2, 8, 9].
Small experimental jet engines exhibit similar problems. Especially the MPM-20 engine is particularly sensitive to changes in the thermodynamic parameters which resulted in the engine

DOI 10.12776/ams.v22i2.720 p-ISSN 1335-1532
e-ISSN 1338-1156

destruction. An explanation of the main causes of the accident of this engine is related also with the changes in the structure of the rotor blades material, which is exposed to the extreme temperatures in aggressive environment.

2 Experimental materials and methods

An experimental MPM-20 jet engine was created from the TS 20B/21turbine starter [10]. During the experiment it was tested for a variety of adverse simulated operating conditions in the Laboratory of Intelligent Control Systems of Aircraft Engines at the Faculty of Aeronautics in Košice. The purpose of the research was the determination of the compressor surge resistance by throttling of the air flow through the inlet to the compressor. The experiment finds out that the level of the air flow reduction into the compressor caused the unstable work of the centrifugal compressor. **Table 1** overviews the difference in the thermodynamic parameters of the engine operated by unthrottled air inlet and the air inlet, which is choked to 83 %. The air pressure in the room was 100 525.3 Pa and the temperature was 288.75 K.

Table 1 Thermodynamic parameters of the MPM-20 engine during the experiment

Parameter	p_{2t} [Pa]	T_{2t}[K]	p_3[Pa]	T_{3t}[K]	p_4[Pa]	T_{4t} [K]	F_T [N]
free inlet-0 %	351178.4	459.6	351524.7	1169.3	128716.5	1039.2	732.5
choked inlet-83 %	400157.2	471.2	327326.2	1261.7	153674.3	1216.7	541.11

* p_{2t} - air pressure at the entrance of combustion chamber, T_{2t} - air temperature at the entrance of combustion chamber, p_3 – pressure of gasses at the entrance of gas turbine, T_{3t} – temperature of gasses at the entrance of gas turbine, p_4 - pressure of gasses at the outlet of gas turbine, T_{4t} - temperature of gasses at the outlet of gas turbine, F_T – thrust force of the jet engine

Throttling the air flow was carried out sequentially in 4 steps from 0 % up to 83 % in each case for about 50 seconds. During the last test a permanent damage of the turbine disc containing 27 blades around its periphery occurred. All turbine blades were destroyed by the breaking parts of the peaks as it is shown in **Fig 1a, b**.

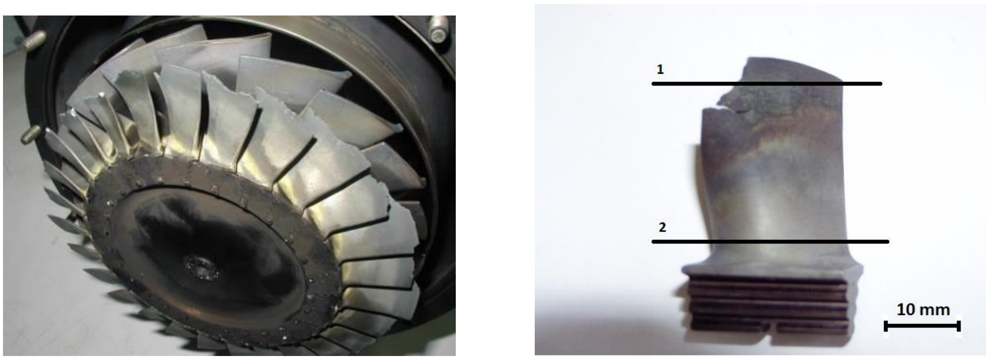

Fig. 1 a, b Appearance of the turbine disc and one destroyed blade with cutting planes (“1, 2”)

The engine was subsequently scrapped and damaged parts were removed. However it should be noted that the engine was not new. And the precise number of the hours in operation was not

DOI 10.12776/ams.v22i2.720 p-ISSN 1335-1532
e-ISSN 1338-1156

known. The analysis of the destroyed blade brings important knowledge because thanks to the prognosis of changes in the material structure and consequent adequate action taken against the negative effects of the extremely increased parameters will be valuable for the next experiments. The analysis consists of the manufacture of samples for microscopic observation by optical and scanning electron microscope using energy dispersive X-ray (EDX) chemical elemental analysis included only for the metallic elements determination. Cutting planes on turbine blade for metallographic samples preparation are visible on **Fig. 1b**. The microstructure was observed on the surface using the etchant (10g $CuSO_4$, 2.5 ml H_2SO_4, 50 ml HCl). For a better visibility of the structures on the metallographic sections during the observations using the scanning microscope, the etchant with the chemical composition 120 ml HCl, 40 ml HNO_3, 36 ml CH_3COOH, 40 ml HF, 44 ml H_2O was used.

3 Results and discussion

The metallographic-microscopic analysis was performed in the blade material section in the place of the fracture. The microstructure observed at low magnification shows the typical features of a regular dendritic structure - **Fig. 2a, b**, related to the manufacture by casting.

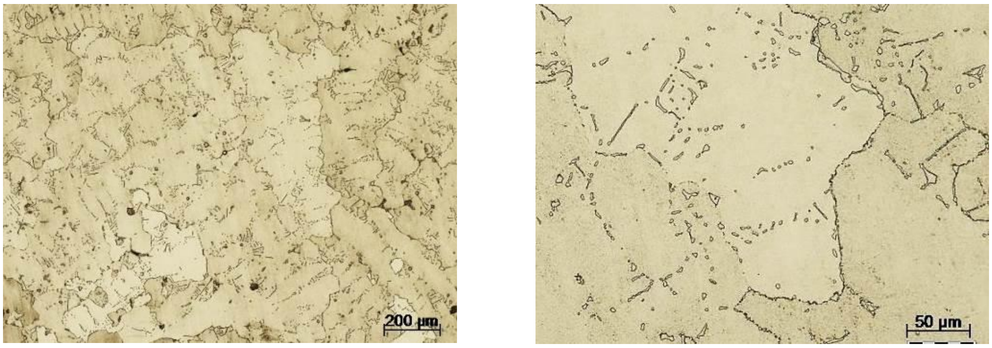

Fig. 2a,b Microstructure of the material with the feature of casting structure and in more detail

In this case it is a pressure casting, during which the coarse structure is achieved and the grains reach the size of 400 – 600 μm. The detailed examination of the microstructure refers to the carbidic network precipitated within the grains as well as in the grain boundaries. As we already published [11] the blade material is an alloy of Soviet production, according to the GOST standards available as the ZhS-6K. The excluded carbides at the grain boundaries in the form of networks are mainly of the $M_{23}C_6$ type. The carbides within the grains may be of the MC nature with the dissolved elements such as Mo or a TiC(N) carbonitride. The used alloy also contains alloying elements for the base matrix reinforcing, such as Co, Al, Mo and W. The second group of elements, reinforcing the grain boundaries, consists of C, Cr, W, V, Ti [12, 13, 15]. The selection of individual precipitate particles and their corresponding EDX spectra are shown in **Fig. 3**.

Table 2 shows the nominal chemical composition of the standard Soviet ZhS-6K alloy and the results of EDX semi-quantitative chemical analyses corresponding to investigated base material, over-heated zone and individual selected particles depicted in **Fig. 3**. There is a noticeable change in the chemical composition of the base material comparing to the standard ZhS-6K alloy due to the structural changes during the turbine service life.

DOI 10.12776/ams.v22i2.720 p-ISSN 1335-1532
e-ISSN 1338-1156

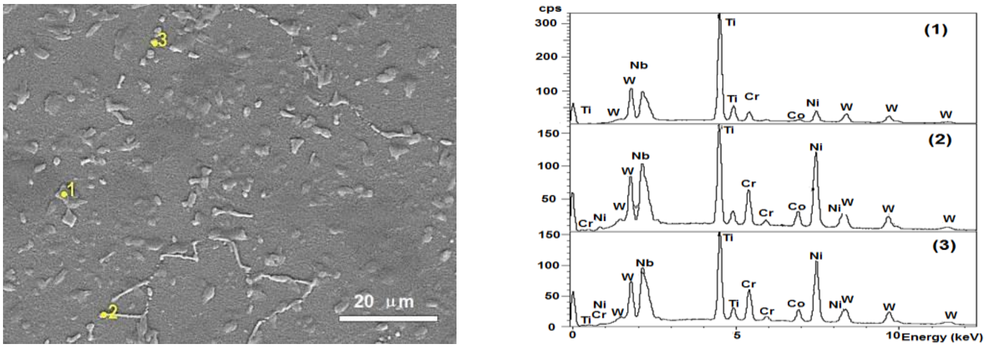

Fig. 3 Position of selected particles for semi-quantitative EDX chemical analyses and their corresponding EDX-spectra

Table 2 Chemical composition of the investigated material and chosen particles

Element	ZhS-6K (wt.%)	Base material (wt.%)	Over-heated zone (wt.%)	Particle 1 (wt.%)	Particle 2 (wt.%)	Particle 3 (wt.%)
Al	5.5	3.6	-	-	-	-
Ti	2.7	2.40	2.95	40.76	18.63	19.66
Cr	11.5	12	11.37	4.71	7.64	8.16
Co	4.5	9.67	9.78	1.11	4.35	4.12
Ni	67	64	55.32	7.00	23.84	23.17
Nb	0.1	0.1	0.1	16.13	18.55	19.03
W	5	5.63	6.40	30.29	26.89	25.87
Mo	4	3.4	3	-	-	-

Observing the fracture area of the blade in **Fig. 4** it the bright white band at the edges of the structure can be seen. Its width is related to the overheating of the blade edges. This results into the apparent recrystallization of the microstructure, whereby the original grains are divided into a number of small grains forming a fine grain structure with a different etching capability [13]. This fact also refers to the change of the composition of the alloying elements and in a loss of strength. The level of this decrease can be partially inferred by the microhardness measuring. The basic material hardness was 513 HVm and after the overheating the value was only 368 HVm.

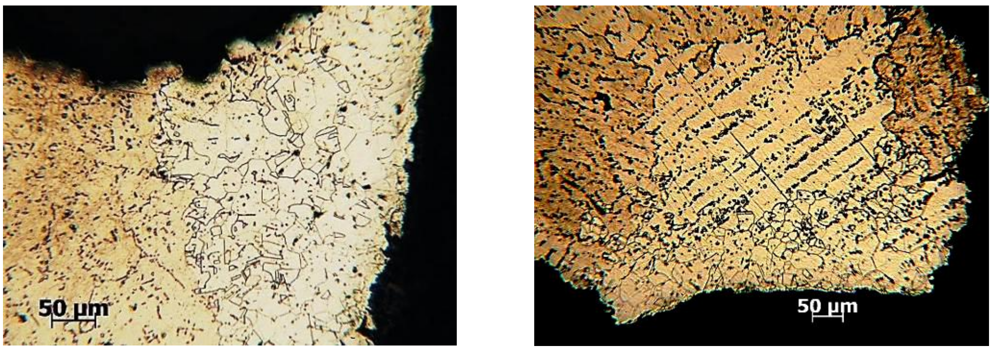

Fig. 4 a, b Recrystallization zone at two locations of the blade tip

DOI 10.12776/ams.v22i2.720
p-ISSN 1335-1532
e-ISSN 1338-1156

In addition to this effect at higher temperatures, there was a rapid reduction of the gap between the blade tip and the casing of the turbine. There occurred a friction and also to the deformation of the blade tip. This contributed to a further increase in the overall stress of the blades and to the cracks formation. Formation of these cracks was extensively supported by the intensive penetration of the oxygen into the grain boundaries, mainly due to its high affinity to carbides at the grain boundaries - **Fig. 5**. From a macroscopic point of view this phenomenon logically seems like the decarburization [14].

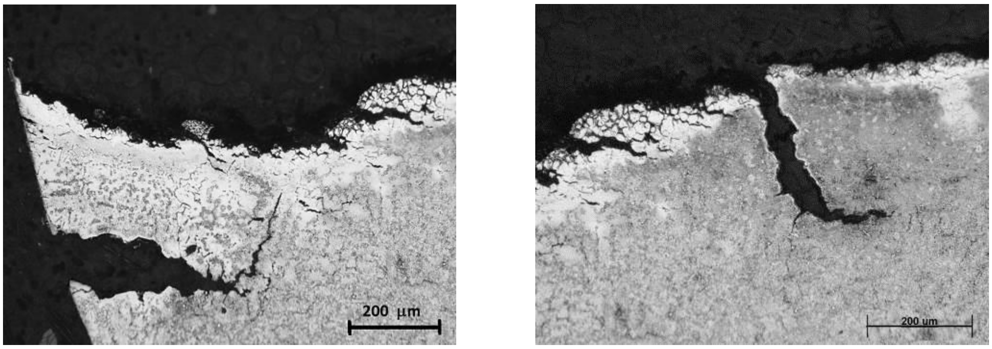

Fig. 5 Recrystallization zone and effects of the oxygen penetration into the grain boundaries

A significant contribution to this fracture has the fact that the blade was in its weakened tip during the collision with the inner casing of the gas turbine deformed. This is an explanation of the fact, that all the blades are damaged in this part. The fact is that the formation of the cracks and their distribution into the over-heated zone was apparently easier due to the deformation. In the rest of the blade, with no recrystallized microstructure the crack propagation can occur only by the path of the least resistance, that is, through the grain boundaries - **Fig. 6 a, b.**

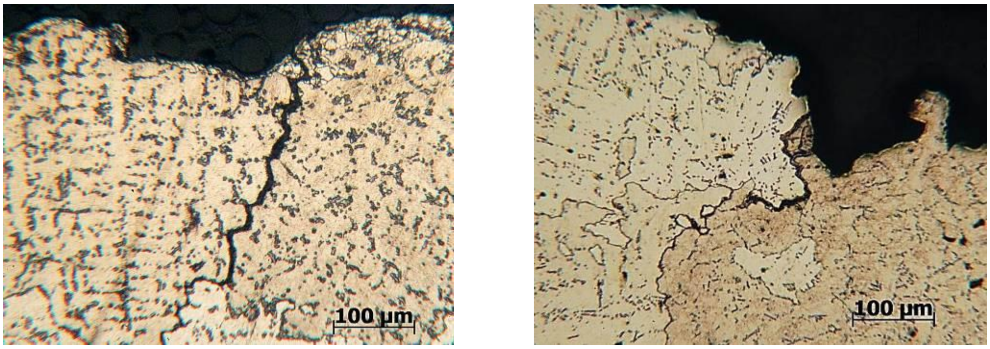

Fig. 6a,b Intergranular cracks in the microstructure of the blade near the fracture

In addition to these aspects directly related to the fracture, in the microstructure were recorded also places where there was an evident disintegration of the original Ti-type carbide particles the size of 40–80 µm. These, have been divided due to the high temperature into the large number of small particles with the size of 5–15 µm. These locations are shown in **Fig. 7a, b**.

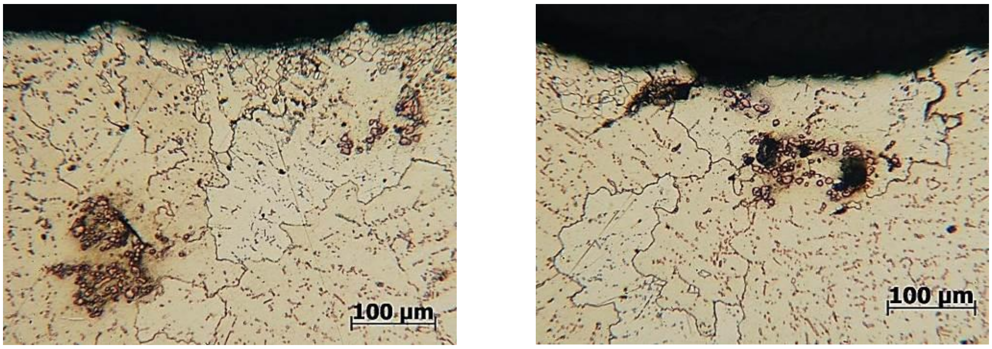

Fig. 7a,b The disintegration of titanium carbides in the blade microstructure

Such disintegration of these particles was observed just around the heat affected zone with the recrystallization of the original microstructure. It is evident that their role in the precipitation hardening was eliminated and the substantial weakening of the microstructure had to occur.
Also, the observation using the scanning electron microscopy revealed the differences in the microstructure of the base material and the material in the heat affected zone. This is evidenced by the following images in **Fig. 8a, b.**

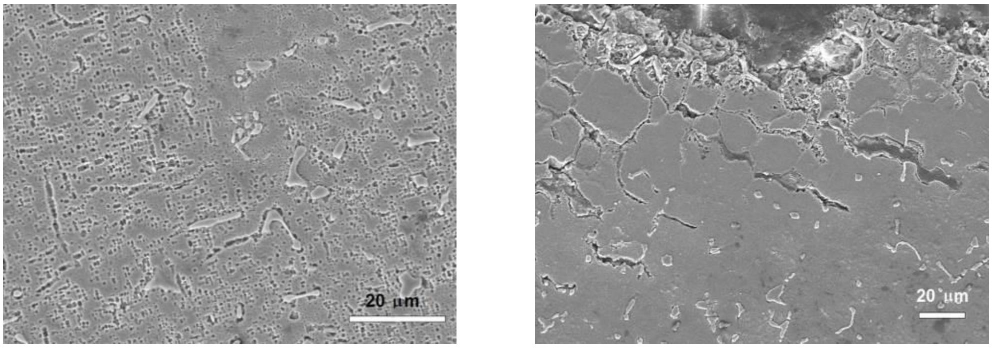

Fig. 8a,b Non-affected microstructure and heat affected area of the microstructure

Basic microstructure in **Fig. 8a** has the clearly visible carbides of various types and sizes inside the grains as well as at the grain boundaries. These carbides are in the heat affected zone of the microstructure hardly noticeable. However, the fine grain microstructure of the heat affected strip is well visible. The grain boundaries are surrounded by the intergranular cracks. The nature of the damage of the blades can be understood by studying the features of the fractographic fracture of the surfaces using the scanning microscope. **Fig. 9a** shows appearance of the whole width of the fracture. From the picture it is obvious that not a single fracture mechanism took place. It has all of the fractographical fracture features.
For example **Fig. 9b** shows a characteristic nature of the brittle fracture, in **Fig. 10a** there is an obvious fatigue character with visible striation facets and **Fig. 10b** shows a typical ductile fracture. It has to be noted that all of these fractographical features are marked by the fact that they took place at the increased temperature.

DOI 10.12776/ams.v22i2.720 p-ISSN 1335-1532
e-ISSN 1338-1156

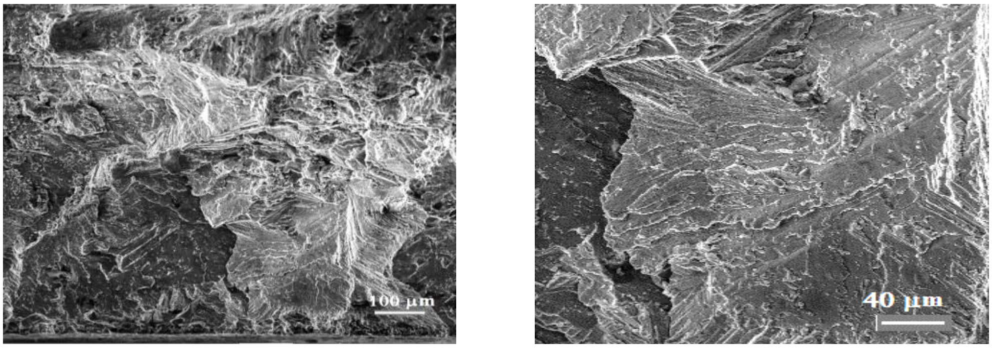

Fig. 9a,b The entire width of the blade fracture and brittle nature of the fracture

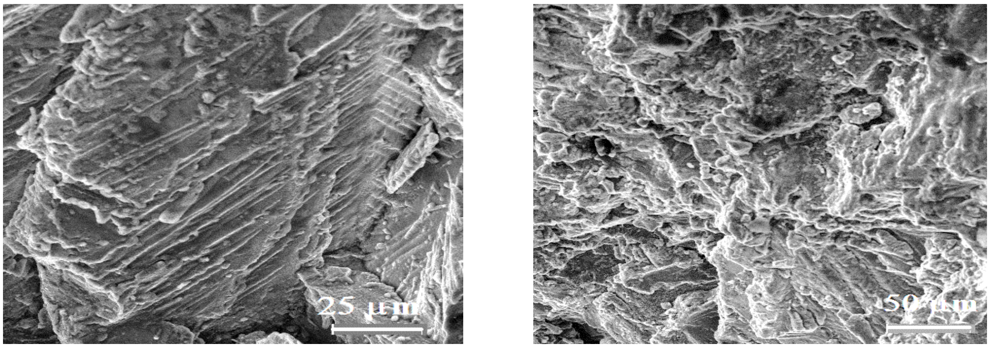

Fig. 10a,b Fatigue fracture character and ductile nature of the fracture

Typical application areas of the ZhS-6K alloy is casting of stator vanes and rotor blades of small turbines or small integrally casted rotors operated up to the 900 °C. If alitation takes place, the components can be in the operation in temperature ranges from 950 to 1050 °C [15]. However, also short time during which the temperature is exceeded will result in the destruction of the turbine blades manufactured from this material. But in our case the cause was a combination of more factors, not purely the exceeding of the operating temperature of the blades. One of the factors is the construction of the turbine. Analysis of the damaged parts of the engine showed that the overheating of the entire turbine disc occurred, which led to the expansion of the diameter, as a result of the thermal expansion. It happened in such extent that the collision of the blades with the inner wall of the abrasive ceramic-metallic casing of the turbine occurred. This resulted in the deformation and fracture of the profiled blade tips weakened by the local overheating in a combination with the high-temperature oxidation. It resulted in the irreversible changes of the microstructure.

4 Conclusions

Based on the analyses of the damaged turbine blades the following conclusions can be stated:

- The damage was located at the top of the profiled blade, and was characterized by the fracture accompanied by the local deformation.
- The analysis showed in the fracture the operational temperature range of the alloy was locally exceeded and led to the microstructure recrystallization.

DOI 10.12776/ams.v22i2.720 p-ISSN 1335-1532
e-ISSN 1338-1156

- In the recrystallization areas the local over-heating led to disintegration of original coarse Ti-rich precipitates to increased amount of smaller particles
- The recrystallized region showed different etching ability and also the chemical composition compared to the base microstructure, which was proved by the EDX analysis.
- Only the intergranular crack propagation from the fracture places to the base material was observed.
- The overheating of the turbine blades as well as of the turbine disc occurred. Due to the thermal expansion the turbine disc increased in its diameter and caused the collision of the turbine blade tips with the inner turbine casing.

Operation of the engine in future has to be treated so to avoid exceeding of the applicable temperature ranges of the turbine blades. This can be ensured by the limitation of the operational parameters, or by the constructional modification of the blade cooling.

References

[1] T. J. Carter: Engineering Failure Analysis, Vol 12, 2005, p. 237–247, DOI: 10.1016/j.engfailanal.2004.07.004
[2] H.E. Wettstein: ASME Turbo Expo 2013: Turbine Technical Conference and Exposition, GT 2013; San Antonio, Tx; United States; 3 June - 7 June 2013, Vol. 7 A, 2013, Article number GT2013-94221, DOI: 10.1115/GT2013-94221
[3] N. Vardar, A. Ekerim: Engineering Failure Analysis, Vol. 14, 2007, p. 743–749, DOI:10.1016/j.engfailanal.2006.06.001
[4] V.V. Artamonov, V.P. Artamonov: Russian Journal of Nondestructive Testing, Vol. 49, 2013, Issue 9, p. 538-542, DOI: 10.1134/S1061830913090027
[5] E. Poursaedi, M.R. Mohammadi: Engineering Failure Analysis, Vol. 15, 2008, p. 847–855, DOI:10.1016/j.engfailanal.2007.11.015
[6] H. Wanzek: Practical Metallography, Vol. 49, 2012, Issue 9, p. 588-596, ISSN: 0032678X
[7] Wu, X.-Y., Li, X., Shi, Y., Zhang, C.-H., Du, Z.-N: Journal of Aerospace Power, Vol. 29, 2014, Issue 5, p. 1177–1183, DOI: 10.13224/j.cnki.jasp.2014.05.025
[8] J. Hou, B. J. Wicks, R. A. Antoniou: Engineering Failure Analysis, Vol. 9, 2002, p. 201–211, DOI:10.1016/S1350-6307(01)00005-X
[9] P. Gašparovič, M. Čarnogurská: Journal of Applied Science in the Thermodynamics and Fluid Mechanics, Vol. 2, 2008, No. 1, p. 1-6
[10] K. Ratkovská, J. Černan, M. Cúttová, K. Semrád: ASME Turbo Expo 2015: Turbine Technical Conference and Exposition, GT 2015; Montreal; Canada; 15 June - 19 June 2015, Volume 8, 2015, DOI: 10.1115/GT2015-42374
[11] J. Čerňan, D. Rodziňák, K. Semrád, M. Cúttová: Advances in Military Technology, Vol. 11, 2016, Issue 1, p. 1-10
[12] J. Belan: Materials Engineering - Materiálové inžinierstvo. Vol. 18, 2011, p. 121-128
[13] ASM Handbook comitee: Metallography and microstructures, Volume 9, ASM Handbook, ASM International, 2004, p. 2733.
[14] A. Chyrkin et al.: Corrosion Science, Vol. 96, 2015, p. 32-41, DOI: 10.1016/j.corsci.2015.03.019
[15] ASM Specialty Handbook: Nickel, Cobalt, and Their Alloys, ASM International 2000. p. 442 ISBN: 978-0-87170-685-0

DOI 10.12776/ams.v22i2.720 p-ISSN 1335-1532
e-ISSN 1338-1156