Cracks path growth in turbine blades with TBC under thermo – mechanical cyclic loadings

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ABSTRACT. Blades of combustion turbines are extremely loaded turbojet elements, which transmit operative energy onto a rotor. Experiences of many years indicate, that cracks initiation and propagation in blades during the operation time can cause destruction not only of the engine, but sometimes an airplane. In high temperature regime, one of the most often occurring interactions in turbine engine are the time variable force fields, caused by non-stationary flowing of exhaust gas and the aerodynamics interaction of engine elements, creating degradation of blades as a result of fatigue and the creeping of material. More often Thermal Barrier Coatings (TBCs) are applied on the turbine blade surface to provide protection not only against high temperature but also against aggressive environment. The paper presents the advantages of applying the TBC layers for increase of cracks resistance to gradual degradation of the turbine blades. In particular the most efforted places of the turbine blades were selected and crack paths due to thermo-mechanical cyclic loading were determined.

INTRODUCTION

The process of thermo - mechanical fatigue [1,2,8] takes place in structural elements, working in conditions of cyclic temperature changes as well as under variable mechanical loadings. This mainly concerns for example: rotors of turbines, turbine blades, heat exchangers, pieces of nuclear reactors, heads, valves and pistons of combustion engines.

The observation of thermal fatigue process in construction is unusually complex, which results mainly from the interaction between many factors influencing the fatigue process, and also from the fact, that the visual assessment of degradation stage is possible only at the final stage.

In high temperature, one of the most often occurring interactions in turbine engine are the time variable force fields, caused by non-stationary flowing of exhaust gas and the aerodynamics interaction of engine elements, creating degradation of blades as a result of fatigue and the creeping of material. Moreover, the unfavorable influence of high temperature on durability of blades results, among others, from intensification of
processes of corrosion and erosion [4], the changes in structure of material as well as degradation of its strength properties.

To prevent phenomena such as corrosion or thermal shocks, working surfaces of blades are covered by different types of ceramic protective coatings, i.e. Thermal Barrier Coatings (TBC) [6,7,8]. Industrial application found many types of layers received, among others, by methods: gas, contact - gas, PVD and different. These layers allow for considerable raise of the heat-proof properties of working piece of blade which is shown in the present paper also by using thin ceramic layer we can get the extension of exploitation time.

THE FACTORS INFLUENCING ON FATIGUE DURABILITY OF THE TURBINE BLADE

There are three basic factors, which influence fatigue durability:

- structural,
- technological,
- exploitable

Structural factors include: shape of elements, its dimensions and local stress concentrations due to indentations or micronotches. To technological factors belong: technological operations for production of elements and improvement of property of superficial zone, state of surface as well as galvanized covering and endeavors used for finishing of surface. The exploitational factors are shaped by loading spectrum, pauses of loadings, complex loads as well as the process temperature and the presence of active environment and corroding.

Taking into consideration the third factor, superficial corrosion and the formed pitting cause local roughnesses. Their acts as local surface indentations. Depending on quantity and dimensions, activity of these defects can be treated as individual indentation or arranged in rows.

Fig. 1 presents an image enlarged under microscope in two places of blade: in half
its height and in its bottom piece. It should be noticed that blade already reached suitable service life and was excluded from exploitation. From the analysis of two points results the fact, that the bottom piece of blade is strongly subject to erosion as well as corrosive acting of combustion gases which is proved by visible pitting, creates indentations as mentioned above. Indentations situated in bottom piece of blade are more dangerous, because there occur maximum the von Mises stresses coming from bending of blade during its work, which is presented on Fig. 2.

Additional chemical analysis was executed in several points of blade in order to define proportional percentage of individual chemical elements. Their average content was showed in Fig. 3.

![Fig. 3. Chemical elements.](image1)
![Fig. 4. Grain of soot.](image2)

Altogether 13 chemical elements were detected, from which Ni, Al and Mo are the elements entering composition of alloy from which the blade was made and the total weight content is the highest. The next chemical element is carbon and it comes from burning of fuel, it often takes the form of individual grains of soot, Fig. 4. Al and O are the next two chemical elements with considerable weight content. As mentioned above Al also enters the composition of alloy from which the blade is made and together with oxygen creates chemical Al$_2$O$_3$. Aluminium like Na, Si, K, Ca, can also come from soil, for example during start or landing of a helicopter, the dust is aroused which then can be sucked into an engine. Dangerous phenomenon is presence of chlorine, which can be in relation with Na creating aggressive favorable corrosion environment.

Therefore the connection of chemical as well as electrochemical corrosion with formed pitting due to impact of solid particles as sand will enhance decrease of fatigue durability of the blade, which is proved by conducted microscopic and chemical analyses of the blade working surface.
NUMERICAL MODEL OF THE TURBINE BLADE

It is necessary to clearly point out that all theoretical investigations of the turbine blade behavior under thermo-mechanical fatigue were made for considerably higher parameters than these in which blade works normally, i.e. about 800 °C and 30000 rot/min.

Numeric study consisted of several stages:
- exact reproduction of thin ceramic layer in numerical model. The microscopic examination was used to define the thickness of individual layers, Fig. 5. Generally thermal protection structure of the turbine blade consists of: Bond Coat (BC), Thermally Grown Oxide (TGO) and Top Coat (TC),

![Fig. 5. The structure of TBC.](image)

- calculation of temperature distribution in one cycle of heating both for blade without protective layer and with TBC coating,
- simulation of the thermo-mechanical fatigue behavior to define the number of cycles leading to damage for different values of loadings.

![Fig. 6. Single blade.](image)  
![Rys. 7. Segment of rotor.](image)
Therefore simulation was conducted in two steps. In the first step the blade was heated to appropriate temperature. The second stage concerned the use of direct cyclic step in ABAQUS, which is less expensive in comparison to transient simulation and is perfectly suitable to quasi–static problem connected with cyclic loadings of structure with regard to nonlinearity of materials incorporating internal damage.

The assembly consisted of single blade (Fig. 6) as well as a segment of the rotor (Fig. 7). The compiled geometry required the use of 4-node linear tetrahedron elements. 31891 elements C3D4 type were used for segment of rotor meanwhile for blade 48658 elements type C3D4 were used. Additionally, for model with the TBC layer 22329 elements type C3D6 were used.

The blade and a segment of the rotor were loaded by rotational body force depending on the rotator speed. The constraints of tie type were used for fixing the blade to the segment of the rotor. The side surfaces of the rotor segment had all degrees of freedom taken away. They have possibility of displacement in direction of centrifugal force. The mechanical and thermal loadings grew linearly to maximum value and after that they diminished to initial value. There was no shift in phase between mechanical and temperature cycle. Similarly as in [3] we do not take into account aerodynamics pressure, which influence on loading of the blade is small and calculations are expensive [5].

**Material used for modeling of the turbine blades**

For our investigation we assumed that the turbine blades material is a casting heat-resistant alloy with nickel matrix. This material is widely used for production of the stator, guide vanes and turbine blades of first and second stage of air-engine (e.g. TWD 10B and PZL 10W). The mechanical features of the heat-resistant alloys in the range of temperatures 20-500°C change insignificantly (Fig. 8). In range of temperatures from 500°C to 700°C the small increase of the yield limit was observed in comparison with the room temperature. For the temperature above 700°C a decrease of mechanical properties of alloy is visible.

![Fig. 8. Mechanical properties of material.](image)
The numerical model of the core material of the turbine blades includes internal ductile damage when a critical value of plastic deformations is reached, whereas the fracture energy criterion was taken into account for description of damage evolution. It was also assumed that the TBC was made of zirconia partially stabilized by yttria (ZrO$_2$/7\%Y$_2$O$_3$) with properties specified in [6,7].

**NUMERICAL RESULTS**

Fig. 9 presents the temperature distribution of the blades without and with TBC after the same period of time starting from the beginning of engine ignition. One can notice, that the thin TBC layer with thickness 0.3mm very effectively prevents influence of highly active exhaust gas. The heat outflow from working piece of the blade proceeded to the rotor, which is cooled by air from a compressor. The temperature of combustion gases was equal to 1300$^\circ$C and it made up about 160\% value of real working temperature.

Curves presented in Fig. 10 show dependence between quantity of damaged elements related to the whole model and the quantity of cyclic thermo – mechanical loadings. With steady rotator speed of 35800 rot/min and maximum amplitudes of temperature 1000$^\circ$C as well as 1300$^\circ$C the damage was initiated at 60 and 30 cycles. Below the value of 1000$^\circ$C the blade could work infinitely long without any visible damage. Total separation of blade into two pieces (Fig. 12) took place respectively at 180 and 130 cycles.
As mentioned above, below temperature of 1000\(^\circ\)C and the rotator speed of 35800 rot/min the damage caused by thermo – mechanical fatigue did not occur. Thus, the situation was examined when the blade was heated cyclicly to temperature 900\(^\circ\)C and then its rotator speed was raised. The fatigue began occurring only after the speed of 42970 rot/min was achieved which considerably exceeds the nominal value. Fig. 11 presents correlation between relative quantity of elements with damage and number of thermal cycles.

The development of damage in dependence of number of thermal cycles for blade without TBC barrier

Fig. 12 shows the bottom piece of blade for different quantities of cyclic thermo – mechanical loadings.
High temperature causes that material properties $R_m$ as well as $R_{0.2}$ significantly decrease (Fig. 8) and plastic deformations in the material are much higher. Together with the increase of cycle numbers the plastic deformations grow and lead to the damage increase due to material fatigue. The presented above results concern maximum amplitude of temperature 1300°C and the rotator speed of 35800 rot/min.

**Conclusions**

1. All investigations were conducted in conditions considerably exceeding the parameters of blade working conditions. There still exists large reserve of durability of the blade in case of unexpected resonance or higher temperatures. For example, with the increase of rotator speed by 19% it is also necessary to raise the temperature of combustion gases by about 25% in order to initiate damage resulting from fatigue.

2. Occurrence of pitting on the blade surface due to corrosion or erosion caused solid particles impacts requires constant monitoring of service life of the engine. The use of protective layer TBC can therefore extend the working time of the blade. It will be the subject of next investigations.

3. The use of protective the TBC layer has significant influence on the level of temperature during thermal shocks which occur during starting of airplane engine. Application of the TBC allows for decreasing of the working temperature about 15% in reference to blade without covering, after the same time of heating. It leads to considerable increase of the turbine blade safety due to reduction or elimination of plastic deformations and excluding plastic damage initiation and further growth.

4. The limiting parameters for the blade without TBC layer causing damage formations as a results of thermo – mechanical fatigue were established. For the rotator speed equal to 35800 rot/min the fatigue of material damage can take
place for the temperature higher than 1000°C. In the working temperature equal to 900°C the failure due to thermo-mechanical fatigue can appear for the rotator speed of about 42970 rot/min.

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References:


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