Uneven degradation of the material during the operation of turbine blades

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Abstract. Turbine rotor blades operate under the action of centrifugal forces, which create height-varying stresses. The temperature field of the blades is also inhomogeneous, and the value of its gradient depends on the flow parameters and the geometric dimensions of the blades. In the process of manufacturing and quality control of completed turbine rotor blades, the manufacturer uses the generally accepted state standards to determine the condition during long-term operation. It is assumed that the material of the blades should be uniform all over the volume so that the manufacturer proposes analyzing mainly the blade root. In this case, mechanical tests are carried out on large samples and the results provide only averaged data on the state of the material. Life prediction based on the results of mechanical tests can lead to a mistaken overestimation of service life. This is because this approach takes into account only the state of the internal zones of the material. However, the rupture of material occurs on the surface and in the more thermally stressed parts like the trailing edge or leading edge. As a consequence, the application of this approach is unacceptable for blades with long operating time.

To study the condition of the blade material, two turbine rotor blades were chosen: №. 1 - with a run time of 12 000 hours (not operated assigned by the manufacturer resource (25 000 hours) and №. 2 – 63 000 hours. Both blades are made of heat-treated nickel alloy ЭП800. When considering the possibility of further operation of the blades, it is necessary to conduct a comprehensive study of the material [1-3]. According to the requirements of technical documentation, the mechanical properties of the alloy at room temperature are determined on samples cut from the blade root. This approach to the analysis of the state of the material after operation is not advisable since the highest temperature is exposed to the feather part of the blade. So samples from the feather for pull test were made. The results of mechanical tests are presented in Table 1. Based on the results of the obtained values, the material of both blades correspond to stipulated standards (Table.1) and the product is still operable.

For detailed analysis, relaxation tests [4] and microstructure analysis were carried out. Studies were conducted on samples cut from the trailing, leading edges of the blades and the blade root. The results are shown in Table. 2.

From obtained results it will be obvious that the values of the yield stress (from 685 to 773 MPa) in all zones of the blade material with a lower run time corresponds to the requirements for the alloy. The yield stress of the material of trailing edge of the blade (with run time of 63000) is not consistent with standarts.
Table 1. The mechanical test results of the samples cut from the feather part of the blade.

| Object of study | $\sigma_s$ (MPa) | $\sigma_{0,2}$ (MPa) | $\delta$ (%) |
|-----------------|------------------|----------------------|-------------|
| Product specifications | $\geq 1078$ | $637-784$ | $\geq 14$ |
| Blade №1 12 000 hours | 1120 | 650 | 23 |
| Blade №2 63 000 hour | 1200 | 670 | 15 |

The microplasticity limit ($\sigma_0$) corresponds to the beginning of the microplastic flow in the material. With equal loads, an increase in $\sigma_0$ leads to a decrease in the value of microplastic deformations and, as a consequence, to an intensification of the process of plastic deformation in structural’s elements [4].

Analysis of microplasticity limit showed that the values differ little from each other for the blade material with an run time of 12 000 hours (for the feather $\sigma_0=350$ MPa, for the bucket root $\sigma_0=280$ MPa). Differences in the values of microplasticity for the feather and the blade root can be the result of changes in the microstructure like the precipitate of the strengthening phase. The value of $\sigma_0/\sigma_T$ for each zone of the blade №1 is in the range 0.40 - 0.49. For the blade material with run time of 63 000 hours, the resulting value $\sigma_0/\sigma_T$ lies in range 0.49 to 0.58. Comparing the data obtained from the relaxation tests, we have for sample (blade No. 2), is cut near the end of the crack has the smallest value of limit microplasticity $\sigma_0= 260$ MPa, with the normal value of yield stress $\sigma_T = 650$ MPa. The values of the microplasticity limit range from 320 - 450 MPa. This fact is due to the inhomogeneity of the structure and the mechanical hardening of the alloy in individual micro-sections.

Table 2. Mechanical characteristics of relaxation tests.

| Operating time | Zone of the blade | $\sigma_0$ (MPa) | $\sigma_0$ (MPa) | $\sigma_T$ (MPa) | $\sigma_T$ (MPa) | $\sigma_0/\sigma_T$ |
|----------------|------------------|------------------|------------------|------------------|------------------|------------------|
| Blade №1 12 000 hours | trailing edge | 370 | 360 | 750 | 733 | 0,49 |
| | leading edge | 350 | 375 | 715 | 0,48 |
| | blade root | 260 | 280 | 695 | 685 | 0,37 |
| | trailing edge | 340 | 343 | 750 | 690 | 0,45 |
| | blade root | 260 | 280 | 695 | 685 | 0,37 |
| Blade №2 63 000 hour | leading edge | 450 | 450 | 630 | 0,70 |
| | blade root | 430 | 403 | 700 | 703 | 0,60 |
The conducted research of the samples’ microstructure cut from the blades with different run times showed that in the material of the blade’s trailing edge, the ageing process during operation is more intensive since it is the most loaded. The effect of the high-temperature flux leads to changes in the microstructure: changes in size and the redistribution of the hardening carbide and intermetallic phase which affects the stress-related and plastic characteristics of the material in these zones, namely, the reduction of all mechanical properties. The comparison of the microstructure of different zones (blade № 2) helped us establish the identical distribution of the hardening phases in the structure of the main material. In the nickel matrix of the base material of the feather we observed the uniform particles of the intermetallic $\gamma'$-phase (Ni$_3$Al) measuring 0.5 μm, which have a cubic shape and definite boundaries [5] (figure 1).

In the microstructure of a sample cut from the feather near the blade root (blade No. 1), a cluster of a complex carbide phase (based on chromium and molybdenum) of different dispersity distributed along the grain boundaries was observed (figure 2a).

![Figure 1. Microstructure of the feather’s material of the blade №2, x 10 000.](image1.png)

![Figure 2. Microstructure of the blade's material №. 2: a - the sample cut from the feather; b – the sample cut from the blade root, X10 000.](image2.png)

In the microstructure of the sample cut from the feather near the bucket root, a cluster of carbide phase of different dispersity at the grain boundaries was revealed. It is characteristic of the fine structure of the feather’s metal to have a small increase in the size of the large $\gamma$ phase’s particles and the loss of their definite boundaries. They were also found to be partially merged. The size of the strengthening intermetallic phase in the material of feather and root of the blade ~ up to 0.5 microns, carbides ($\text{Me}_{23}\text{C}_6$) ~ up to 3 microns (In the microstructure of a sample cut from the feather near the blade root (blade No. 1), a cluster of a complex carbide phase (based on chromium and molybdenum) of different dispersity distributed along the grain boundaries was observed (figure 2b). Both primary
(large) carbides and secondary (small) carbides were found out in the structure of the material of the blade root.

Conclusions
The application of relaxation tests using mini-samples to determine the mechanical properties of the blade's material made it possible to analyze the state of the ЭП 800 alloy in local stressed zones. The local analysis of the microstructure confirmed that the degradation of the material, which manifests itself as a change in morphology and volume of strengthening phases during operation, occurs non-uniformly over the body of the blade and is most pronounced in the region of the trailing or leading edge of the feather. These methods of microanalysis can be used to analyze the state of both new blades and blades after operation.

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Reference
[1] L.B. Getsov. Materials and durability of gas turbines. Rybinsk: Gazoturbinnye tehnologii. 601p. (2010).
[2] A.V. Logunov Heat-resistant nickel alloys for blades and disks of gas turbines Rybinsk: Gazoturbinnye tehnologii, 854 p. (2017).
[3] Yu.P. Tarasenko, V.A. Sorokin, O.B. Berdnik Vestnik of Samara university. Aerospace and Mechanical engineering.- Samara No. 3 (19), pp.110-117 (2009)
[4] V.A. Skudnov, M.K. Chegurov Relaxation of stresses in metals and alloys - N.Novgorod: methodical manual. NNSTU, - P. 30 (2010).
[5] S. V. Kirikov, V. N. Perevezentsev Yu. P. Tarasenko VESTNIK of Samara University. Aerospace and Mechanical Engineerin. Vol. 15. No. 4 pp. 216-223 (2016).