STRUCTURE AND MECHANICAL PROPERTIES OF STEEL STEAM TURBINE ROTOR BLADES AFTER OPERATION

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Damage to the high-pressure rotor blade was due to a somewhat underestimated resistance of steel to brittle fracture, weakening of grain boundaries and interpacket boundaries by lamellar cementite particles, and overloading of the blades due to a significant number of rotor shutdowns. Under the influence of condensate formed during the operation of the rotor, all these factors contribute to the occurrence of corrosion damage to the leading edge of the blade. From these defects, cracks initiate and propagate by the mechanism of inter- and transgranular fracture, which is typical for high-cycle corrosion fatigue of such steels.

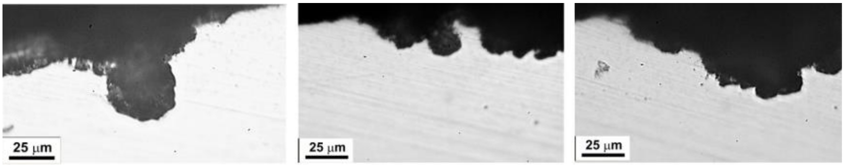
Keywords: titanium hydride, porous materials, microstructure, powders

Introduction. Accidents during the operation of steam turbines are often caused by damage to the blades, which occur due to non-compliance with the requirements for their manufacturing technology or operating conditions. In the first case, damage occurs at the beginning of the operation of the blades, while in the second – during their longer operation and is caused by non-compliance with the temperature and power conditions of the regulation (inappropriate operating temperature and steam pressure), safety requirements during turbine shutdowns and restarts, steam, and condensate quality. Non-compliance with the requirements of the regulation contributes to cavitation, erosion, and corrosion of metal, the appearance of microcracks in the blades due to fatigue and corrosion fatigue, which causes premature fracture and can disable the steam turbine rotor as a whole.

Materials and methods. The peculiarities of the degradation of steel 15Kh11MF after ~$267 \cdot 10^3$ h of operation in the high-pressure rotor blade have been analyzed. The content of chemical elements in steel (mass%: 0.16 C; 0.31 Si; 0.33 Mn; 0.008 S; 0.024 P; 10.4 Cr, 0.7 Mo; 0.38 Ni; 0.36 V;0.13 Cu) corresponded to the regulatory requirements (RD 153-34.1-17.424-2001).

To assess the current state of the operated metal, the following characteristics were used: hardness HB, strength (σ_{UTS} and σ_{YS}), plasticity (Elongation and RA), and impact toughness KCU. The hardness of blade steel was determined as the average value of 10 – 15 measurements on grinding specimens with parallel surfaces. The impact and tensile testing were carried out using standard specimens. The metallographic and fractographic features of the blade steel were studied using an EVO-40XVP scanning electron microscope.

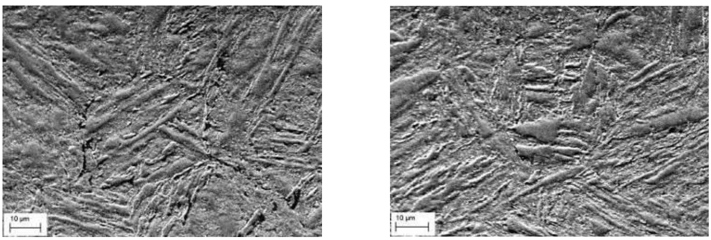
Results. Corrosion damage to different depths was found on the cross-section of the blade, located below its operational fracture surface (Fig. 1). Their maximum depth was ~50 μm. The density of these damages was less, but they were deeper near the leading edge of the blade (Fig. 1, a). Their geometry indicates the corrosive nature of their occurrence.



a b c

Fig. 1. Defects from the convex surface of the fractured blade, revealed on the cross-section at the distance 1.5 mm (a), 5 μm (b), and 8 mm (c) from the leading edge.

In the cross-section of the blade, an almost uniform structure of highly tempered martensite (type tempering sorbite) was found, the packets of which were located within the former austenite grains (Fig. 2). In the steel structure, small carbides were observed along the packet's boundaries of highly tempered martensite and somewhat larger (up to 1.5 μm) along the boundaries of former austenite grains (Fig. 2, a, b). They were considered to be a factor in weakening cohesion both between grains and between packets of highly tempered martensite. Operating conditions, namely the presence of condensate with corrosive-active impurities, rotor shutdown with blade overload, and steel hydrogenation, are contributing to the decohesion of carbides from the matrix and the formation of deep corrosion pits near the leading edge of the blades, from which could nucleation corrosion-fatigue cracks.



a b

Fig. 2. Typical structure of 15Kh11MF steel in the cross-section of the blades at the distance 1.5 mm from the leading edge near its concave (a) and convex (b) surfaces.

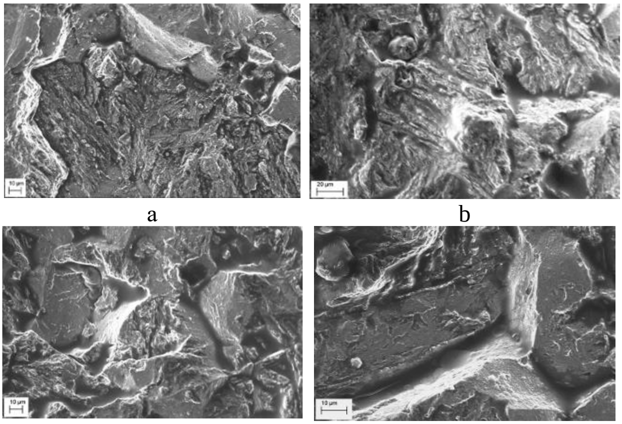
Hardness measurements are an accessible and cheap method of steel control, which is widely used to assess their current technical condition. Using measurements of the hardness of steam turbine blades, it was established that its values varied in the range from 285 to 306 HB, and the average value was 297 HB. It turned out that this is a somewhat slightly high value, since according to the requirements of RD 153-34.1-17.424-2001, the hardness of the blades should not exceed (241...285) HB.

Impact toughness (like hardness) is also a basic characteristic for evaluating the technical state of heat-resistant steels. According to the operational history of the rotor, it has experienced a significant number of shutdowns, which usually cause dynamic loads of the blades. According to the results of impact tests, the values of impact toughness of 15Kh11MF steel varied in the range from 0.33 to 0.48 MJ/m^2, while the regulated value of KCU should not be lower than 0.39 MJ/m^2. The values of impact toughness at different distances from the blade fracture surface were analyzed and established their decreased with the approach to it. The lowest value KCU = 0.33 MJ/m^2 was obtained for a sample cut at a distance of 30 mm from the fracture surface. The presence of condensate with corrosion-active impurities and low resistance to brittle fracture of steel create favorable conditions for the initiation of corrosion-fatigue cracks from corrosion pits as the stress concentrators.

The strength and ductility characteristics of the blade steel at different distances from the fractured blade were analyzed. The properties of the steel were practically the same along the entire length of the blade, and their average values were: σ_{UTS} = 884 MPa, σ_{YS} = 753MPa, Elongation = 16.6 %, RA = 58 %. According to the regulated document RD 153-34.1-17.424-2001, all characteristics of blade steel did not exceed the established limits.

However, despite the compliance of the strength and ductility characteristics with according to the regulatory requirements, the high-pressure rotor blades still failed. The somewhat overestimated hardness HB of the blades (297 HB) could even increase the steel's ability to resist the occurrence of cavitation damage but made it more sensitive to the influence of stress concentrators. In addition, its resistance to brittle fracture was also lower than acceptable, as evidenced by the lower values of the impact toughness of the steel samples cut at a distance of 30 mm from the fracture surface. Consequently, changes in the exploited steel occurred at the local level, and macro characteristics (strength and ductility) are not sensitive to them.

Micro fractographic analysis of the operational fracture of the blade revealed that several cracks initiated from corrosion damage on the concave surface near the leading edge of the steam turbine blades. They extended to the entire cross-section of the blade during high-cycle corrosion fatigue and formed typically for such steels an inter- and transgranular relief fracture (Fig. 3, a). The connection of the intergranular relief of fracture surface with the structure of steel was noted (Fig. 2, Fig. 3, b). As the propagation of fracture over the entire cross-section of the blade, the role of grain boundaries increased, which was manifested by an increase of the area of the intergranular fracture. The intergranular fracture was observed within large grains with unfavorably oriented (relative to the main direction of corrosion fatigue crack growth) packets of highly tempered martensite. At a higher resolution, secondary cracking along the grain boundaries was observed, which clearly outlined intergranular facets (Fig. 3, c, d). It was found that the farther from the convex surface into the body of the blade, the brighter these features were. A mixture type was preserved throughout the further propagation of the fracture in the blade cross-section until the appearance of fatigue macro marks on the fracture, concentrically located relative to the leading edge of the blade.



a b

c d

Fig. 3. Peculiarities of the fractures surface relief in the centers of initiation of blades fracture from their convex surface.

Therefore, the fracture of the rotor blades is due to the corrosion-fatigue crack growth from the leading edge of the blade with its propagation into its entire cross-section due to high-cyclic fatigue.

Conclusions. It was confirmed that the strength and ductility characteristics of 15Kh11MF steel after ~$267 \cdot 10^3$ h of operation in the blades of a high-pressure rotor steam turbine corresponded to regulatory requirements. There was only an increase in the hardness and a slight decrease in the brittle fracture resistance of the steel. The carbides along the grain boundaries and the boundaries of high-tempered martensite packets were fixed. Under the influence of steam condensate with impurities of aggressive salts, these structural features contribute to the formation of corrosion damage near the leading edge of the blades. Cracks nucleated from them and propagated to the entire blade cross-section according to the mechanism of inter- and transgranular fracture, which is characteristic of high-cycle corrosion fatigue of such steels.