ANALYSIS OF THE STRUCTURAL AND MECHANICAL STATE OF HEAT-RESISTANT STEEL OPERATED IN STEAM TURBINE BLADES

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The structure and mechanical properties of the steam turbine blade steel were analyzed. It was found that the plasticity characteristics and impact toughness values of operated steel were slightly lower than the regulated ones. The corrosion-active non-metallic inclusions were revealed in the steel structure, increasing the corrosion damage of steel during operation under technological conditions.

Keywords: steel 20X13, steam turbine blades, structure, mechanical power, fractography

Introduction. The reliability of the steam turbine blade system depends on the structure and mechanical properties of the steels used for its components. During operation, these elements are exposed to high temperatures and pressures, which contribute to the occurrence of internal defects in them. The structural features and mechanical properties of the low-pressure steam turbine disk metal have been previously analyzed [1]. As for the blades, the most common causes of their damage are high cyclic loads due to vibrations [2], erosion due to the impact of the steam-water mixture drops, pitting corrosion, and stress corrosion cracking [3–6]. All these causes contribute to the component degradation. For control, the operated metal is tested for tension and impact toughness, assessing the strength, ductility of the steel, and resistance to brittle fracture. Comprehensive structural and mechanical studies of the metal used in steam turbine blades are an important condition for determining their service life at intermediate stages of operation. Fractographic studies reveal the relationship between the fracture mechanism and the structural features of steel and make it possible to identify defects that can cause blade failure.

Materials and methods. The degradation characteristics of 20X13 steel of a low-pressure steam turbine rotor blade was studied after ~129 10^3 hours of operation. According to the regulations [7], the working blades were heat-treated under factory conditions using the normalization mode with high tempering. The chemical composition of the steel was (wt.%: 0.24 C; 0.28 Si; 0.57 Mn; 0.0018 S; up to 0.0005 P; 14.11 Cr, 0.07 Mo; 0.37 Ni; 0.03 V; 0.09 Cu). Impact toughness was determined on Charpy samples, and strength and plastic tensile properties were determined on standard cylindrical samples with a diameter of 5 mm, cut along and across the blade feather. Metallographic and fractographic features of the steel were studied on an EVO-40XVP SEM.

Results. In general, the content of chemical elements in 20X13 steel blades after operation met the regulated requirements [6] with the exception of a slightly overestimated chromium content. However, this has a positive effect on the resistance of steel to high-temperature process environments.

Average values of mechanical properties of steel (strength, ductility and impact toughness as basic characteristics for assessing the technical condition of steels) are given in Table 1. The strength and ductility characteristics determined on transverse samples were lower than on longitudinal ones. After operation of the steel, its strength characteristics practically met the requirements, and the ductility characteristics became too low.

According to the results of impact tests, the values of impact toughness KCV of steel on samples of both longitudinal and transverse orientation (0.4 and 0.33 MJ/m^2, respectively) were lower than the regulated ones. According to GOST 18968-73 [7], the impact toughness of 20X13 steel (KCU) at 20 °C should be at least 0.69 MJ/m², which, when converted to KCV, corresponds to approximately 0.52–0.59 MJ/m² (Table 1).

Table 1. Mechanical tensile characteristics of 20X13 steel working blade

Sample orientation	σ_{UTS}, MPa	σ_{YS}, MPa	δ, %	RA, %	KCV, MJ/m^2
Transverse	788	649	13.6	51.3	0,33
Longitudinal	820	683	16.4	48.0	0,4
Values regulated in [7]	<670	490–655	<18	<50	0.52–0.59

The particle-dispersed structure of the steel of the analyzed blade (as a mechanical mixture of alloyed ferrite and fractional carbides) was preserved after high output and three-phase high-temperature operation morphological bond with a typical orientation for martensite packets in three directions and changes from grain to grain (Fig. 1). The structural peculiarity of steel is the number of large (up to 5–7 microns, and sometimes up to 30 microns) non-metallic inclusions, randomly distributed in both cuts of the blade. In the transverse section, their volume on a single section surface was greater in the later section (Fig. 1). Despite their smaller size, they were located more densely, which significantly weakened the transverse section of the blade feather.

Micro-X-ray spectral analysis established that these are corrosion-active non-metallic inclusions (wt.%: 33.89 C; 23.96 O; 4.79 Al; 0.99 Si; 0.56 Ca; 10.64 Cr; 25.17 Fe), which are dangerous during operation in hydrogen-containing environments, since they can increase the rate of local dissolution of the matrix in their vicinity by orders of magnitude. These inclusions significantly worsen the corrosion resistance of steels and increase their susceptibility to pitting (as potential foci of fatigue crack initiation). The role of this dangerous aspect of structural degradation of steel will constantly increase with increasing service life and will worsen the performance of blades during their operation. After all, due to the loss of cohesion of these inclusions with the matrix in the blade cross-section, a developed network of cavities was formed as structural stress concentrators. Under the influence of high cyclic loads during the operation of the blades in the turbine, the membranes between these cavities will collapse, which will inevitably result in the destruction of the entire blade cross-section. Therefore, when justifying the loading parameters of the blades, it is important to conduct an input control of the structural features of the steel for its compliance with the requirements for the presence of non-metallic inclusions.

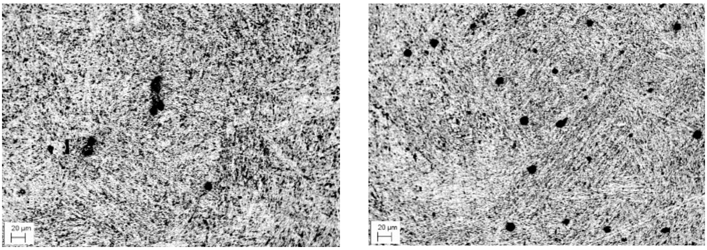

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Fig. 1. Microstructure of steel 20X13 working blade at the longitudinal (a) and transverse (b) sections of the blade.

In addition, the presence of cavities formed in the metal will contribute to the accumulation, molization and increase in hydrogen pressure in them. This aspect of operational degradation must be taken into account to ensure the calculated resource of the blades. After all, the negative impact of hydrogen absorbed by the metal is dangerous due to the occurrence of brittle and therefore difficult to predict fractures.

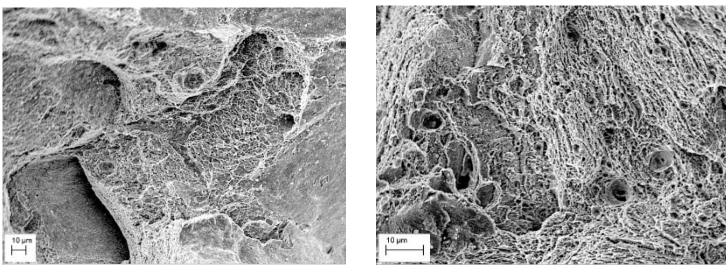

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Fig. 2. Microfractograms of the fracture of a smooth specimen made of blade metal, tested by tension in air.

Fractographically, on the fractures of smooth samples from the blade, tested for tension in air, against the background of large areas of small dimples of detachment formed on carbides in the steel structure, significantly larger ones (10–15 μm in size) were found, which were attributed to those formed on non-metallic inclusions (Fig. 2). Often in their vicinity were observed areas of brittle quasi-cleavages, which were considered evidence of the embrittlement effect of hydrogen accumulated in the cavities around large inclusions (Fig. 2b).

Conclusions. The main negative factors influencing the performance of steam turbine rotor blades include an unacceptably high density of non-metallic inclusions in their structure. It is shown that, by composition, they should be classified as inclusions with increased corrosion activity. When they come into contact with the process environment (steam), prerequisites will be created for active dissolution of the matrix around them with the formation of a developed network of structural defects that will contribute to the origin of damage and accelerate the destruction of the blades. Their presence in the steel used is confirmed fractographically, by detecting large dimples against a background of smaller areas, usually initiated by carbides. It was believed that the combined effect of high cyclic loads and hydrogenation will intensify both the growth of these defects and the destruction of the membranes between them, until the destruction spreads across the entire cross-section of the blade.

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