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ELECTROCHEMICAL AND CHEMICAL MECHANISMS OF THE EROSION-CORROSION PROCESS OF WET-STEAM TURBINE ROTOR BLADES DESTRUCTION UNDER THE INFLUENCE OF ELECTRIFIED MOISTURE

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This paper is devoted to the electrochemical and chemical aspects of the erosion-corrosion destruction of the surface layer of a wet-steam turbine rotor blade under the influence of an electrified working fluid. It considers a hypothesis about a complex mechanochemical-electrochemical mechanism of chromium and iron wash-out from the surface layer of the rotor blade metal during the destruction of the oxide film under the influence of a high-speed wet steam flow. Various versions of this process are analyzed for positive, negative, quasi-neutral, and neutral electrifications of wet steam. The possibility to hydrogenate the surfaces of rotor blades under the influence of negatively-charged droplets is shown theoretically. The damage to the blades in this case is similar to that from anodic etching. It is also shown that the process of blade surface hydrogenation takes place in any case both for electrically-charged droplets and for neutral ones. However, in the case of neutral droplets, the intensity of the process is insignificant. An experimental study was carried out for the erosion-damaged surface of a last-stage rotor blade from of the BK-50 LMP turbine that had exhausted its lifetime. The quantitative content of chromium was determined in the steel sample cut out from the blade. A decrease in chromium content in the erosion-damaged blade surface layer was found. To test the hypothesis about the similarity between the process of anodic electro-etching and the process of surface destruction under the influence of negatively-charged droplets, an electrochemical experiment was carried out on a model sample of 20X13 chromium steel. The reliefs of the damaged areas on the model sample after anodic etching and on the observable blade in the zone of exposure to negatively-charged droplets are shown to be similar. The experimental studies have confirmed the presence of a complex mechanochemical-electrochemical process of blade destruction. On the basis of the data obtained, recommendations for extending the useful life of turbine blades are formulated.

Keywords: electrification of steam, hydrogenation, erosion of blades.

Introduction

At present, it is considered that the leading mechanism of erosion damage to the surface of the rotor blades of wet-steam turbines is the mechanical fatigue phenomena arising under the action of Rayleigh waves. The mechanical erosion processes occurring under the influence of condensed moisture are accompanied by corrosion processes, which are considered to be secondary in importance. Corrosion damages to the blade system usually begin in the phase transition zone, spreading to the rotor blades of all the stages operating in the region of wet steam [1].

The erosion-corrosion destruction of the surface layer of a metal can be accompanied by a change in the chemical composition of the metal, primarily due to electrochemical hydrogenation. The scientific literature contains data on a significant increase (by a factor of 10 or more) in hydrogen concentration in the damaged

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surface layer of a rotor blade [2]. The influence of the active hydrogen, formed as a result of the electrochemical processes on blade surfaces, on the destruction of metal during high-speed droplet impacts is discussed [3]. An additional factor affecting the absorption of hydrogen by the metal surface can be the electric charge of the droplets and the electric fields arising in the flow path of a low-pressure cylinder in the case of electrification of a wet steam flow [4, 5].

Mechanochemical-Electrochemical Action on Rotor Blades

In our opinion, in addition to mechanical and electrochemical effects, high-speed flow exerts a mechanochemical-electrochemical effect on the rotor blade surface in a more complex configuration. Let us consider in more detail the features of this effect for various cases of the electrical state of charge of a humid-steam flow: positive, negative, and neutral with a quasi-neutral one.

In the case of positively-charged droplets striking the surface, the metal is the cathode.

The total charge of a positively-charged droplet can be represented as

$$\Sigma Q^+ = (H_2O)_n \cdot zH^+,$$

where n is the number of molecules associated with hydrogen ions; z is the number of the ions captured by the droplet.

Upon contact of a droplet with the blade surface, the reaction of the discharge (neutralization) of ions in the droplet occurs



In this case, hydrogen is initially released in the atomic form H, and is absorbed by the metal, hydrogenating it, and, accordingly, deteriorating its strength properties. The process of negative influence of positively-charged droplets on the strength properties of the surface layers of blade materials is shown in detail in a number of works [4, 5, 6].

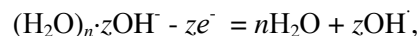
Positively-charged, as a rule, are large droplets that act on the peripheral part of a rotor blade. In this zone, the highest absorption of hydrogen is observed, and, as a consequence, intensive erosion of the blade (Fig. 1). For these reasons, stellite plates can be used as one of the common methods to protect blade surfaces from the action of coarse moisture.

Following the classical electrochemical concept, it would be logical to expect that when steam is negatively charged with respect to a metal, there will be no hydrogenation of the latter, since hydrogen cannot be released at the anode. However, as follows from the experimental data [5], when a metal is treated with a negatively-charged steam, hydrogen saturation also takes place. A purely mechano-electrochemical hypothesis cannot explain this phenomenon, and in this case the acting factors require detailed study. One of them can be the following.

The strike of a negatively-charged droplet with a full charge ΣQ^-

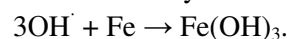
$$\Sigma Q^- = (H_2O)_n \cdot zOH^-,$$

on the blade surface, in the case of a damaged oxide film on the surface, is accompanied by a chemical reaction of the form



with the formation of the OH[·] radical.

The radical interacts with the iron atom to form hydroxide



The resulting radical is aggressive for the oxide film on the metal surface due to the following reactions:

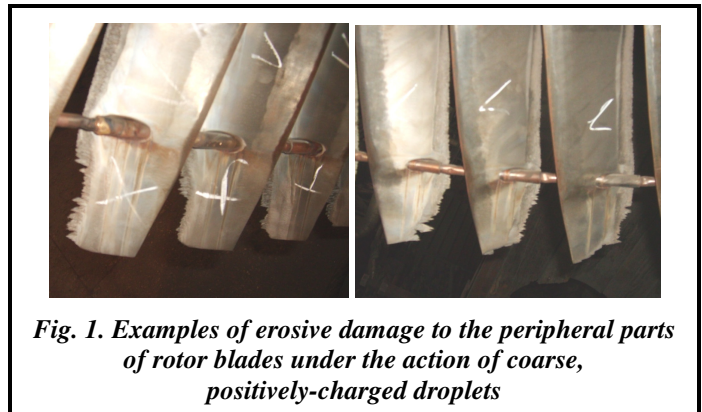
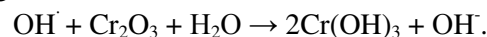
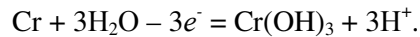
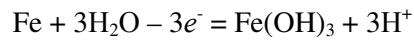


Fig. 1. Examples of erosive damage to the peripheral parts of rotor blades under the action of coarse, positively-charged droplets

As a result, the oxide film can be chemically broken down locally, and charged water droplets can react with iron and chromium atoms. In this case, a corrosion process will take place, in which free atomic hydrogen is not released, but amorphous hydroxides are formed that do not protect the active metal surface and hydrogen ions H^+



The resulting mixture of iron and chromium hydroxides does not keep on the metal surface, and is easily removed from it under the influence of condensed moisture. Thus, the metal surface is activated, and, since both iron and chromium in the galvanic series of metals are much more to the left (more active) of hydrogen, they chemically interact with water, forming atomic hydrogen



The resulting atomic hydrogen is incorporated into the metal. In this case, first of all, the most active metal, which in this case is chromium, reacts with water. As a result, the chromium content in the metal surface layer will decrease, and a corrosion process, similar to electro-etching, will develop. The same process of chemical dissolution (reaction (2), (3)) also occurs in the case of positively-charged droplets, but it is negligible in comparison with the formation of cathodic hydrogen (reaction (1)).

In addition to the interaction of the OH^\cdot radical with the Cr_2O_3 oxide, another method of chemical destruction of the passive film on the metal surface can take place. Since the oxide film on the surface is not absolutely impermeable to OH -radicals and electrons, both the OH^\cdot radical diffusion under the film and its chemical interaction with chromium atoms are possible. In this case, hydroxide can be formed under the film, thus gradually accumulating, thus locally swelling and destroying it.

In the case of electrically neutral steam, the effect of condensed moisture is mainly mechanical. This also takes place in the case of a quasi-neutral steam charge (in the quasi-neutral version, the droplets have both positive and negative charges). When such droplets strike the surface, they are mutually neutralized, and, thus, hydrogen is released as a result of the chemical interaction of the metal with water only in the case of damage to the oxide film: reactions (2) and (3). For neutral and quasi-neutral steam charges, this is the only chemical process.

The results of the studies conducted have shown that under the influence of negatively-charged droplets, anodic etching of the blade surface occurs, which strongly activates (opens) the surface, and reactions (2) and (3) are accelerated. This explains the increase in the amount of hydrogen in the metal and the nature of its softening.

Experimental Part

To study the mechanochemical-electrochemical effect on the metal surface, we carried out a corresponding examination of a last-stage rotor blade of the BK-50 LMP single-cylinder turbine, which had completely exhausted its lifetime, the blade having erosive damage to the surface in its middle part up to the stellite plate, which protects the blade leading edge from destruction.

As is known from the results of experimental studies [4], the distribution of the charge sign of the steam flow along the blade length for the most common water-chemical regimes is as follows (Fig. 2): the peripheral part of the blade airfoil (approximately the upper third) is exposed to coarse, positively-charged droplets, and the rest of the airfoil, almost to the blade root is exposed to small droplets, mostly negatively charged.

The diagram in Fig. 2 suggests that the most eroded part of the observable blade (Fig. 3) was in the zone of action of large positively-charged droplets, and the middle of the blade, from which a fragment was cut for analysis, was in the zone of action of small

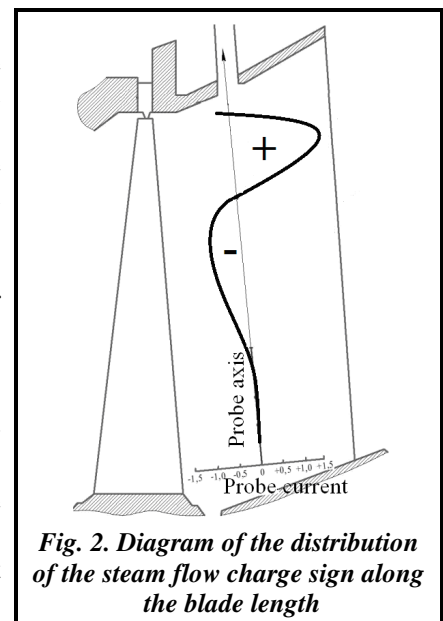


Fig. 2. Diagram of the distribution of the steam flow charge sign along the blade length

negatively-charged droplets. In this case, there was a stellite shielding plate on the peripheral part of the blade, and the area of maximum erosion was below the plate. On this part of the surface, the erosion relief is less deep, with individual damage centers resembling caverns due to electro-etching.

A detailed study of the surface revealed the similarity of the nature of destruction in the zone of exposure to negatively-charged steam with the surface destruction during the electro-etching of chromium steel (Fig. 4). To test the hypothesis about the similarity between the processes of anodic electro-etching and the processes of surface destruction under the influence of negatively charged droplets, an electrochemical experiment was carried out on a specially prepared polished electrode made of 20X13 chromium steel. The sample was subjected to accelerated anodic etching in a solution of NaCl 100 g/dm³, NaHCO₃ 20 g/dm³ at an anodic current density of 1000 A/m² with periodic nitric-acid etching to renew the metal surface in the formed pores. As can be seen from Fig. 4, the nature of the relief of the sample is similar to the blade surface relief in the zone of influence of negative drops (Fig. 3).

The quantitative determination of the chromium content in the blade surface layer was carried out by X-ray spectroscopy on an X-ray fluorescence spectrometer Sprut SEF-01 with a graphite monochromator. Fig. 5 shows a model of the steel fragment cut out from the blade for analysis.

It was found that the concentration of chromium in the eroded surface layer is lower than in other areas of the metal sample. The research data are summarized below.

Place of analysis	Chromium concentration in metal, %
Smooth surface	18.53
Blade back	18.06
Eroded surface	17.64

Conclusions

On the surface of rotor blades, under the action of a supersonic flow of wet steam, electrochemical processes similar to electric etching can occur. Under the influence of a supersonic wet-steam flow on a metal, the passivating film of chromium oxide on its surface is mechanically destroyed. In this case, the metal surface is activated, and interacts with water. Negatively-charged droplets can not only have a destructive chemical effect on the

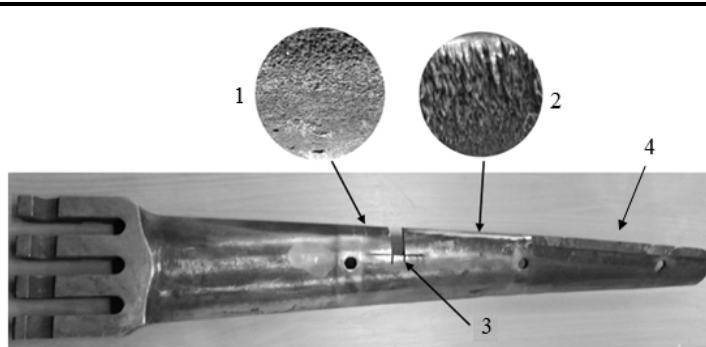


Fig. 3. General view of a damaged blade:
 1, 2 – areas of the eroded surface in the zones of influence of small negative and large positive droplets, respectively; 3 – the area of the cutout of the blade fragment for analysis;
 4 – the surface area protected by a stellite plate

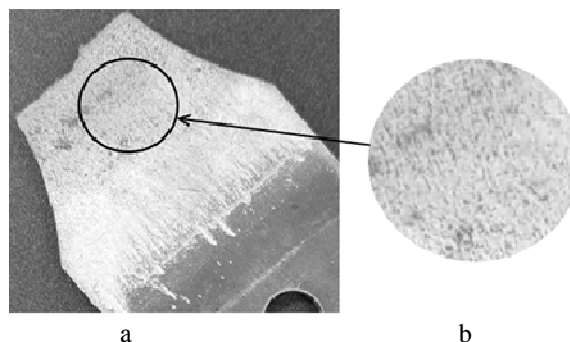


Fig. 4. Sample of 20X13 steel:
 a – a fragment of the surface subjected to electro-etching;
 b – a close-up of the etched surface relief

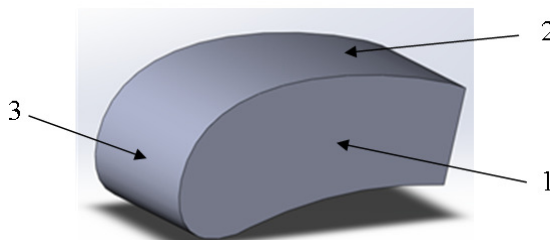


Fig. 5. Areas where the chromium content was determined:
 1 – smooth surface; 2 – blade back; 3 – eroded surface

passive oxide film, but also cause anodic corrosion of the blade surface metal, as well as mechanical removal of corrosion products. In this case, the metal surface is activated, and its chemical interaction with water is accelerated. The process of surface damage is similar to electro-etching, with the destruction of the metal occurring, but not intense. In this case, the amount of hydrogen in the metal should correlate with the amount of metal destroyed by chemical corrosion, which in this case is greater than in the reaction of the blade metal with neutral steam.

Thus, it must be stated that the hydrogenation of the blade material takes place under the impact of the droplets in any case – whether they are charged or neutral, the only difference being in the intensity of the process. The most negative effect on the blade is exerted by a positively-charged steam flow, the negative flow has a damaging effect to a lesser extent. Compared with positively- and negatively- charged steam flows, neutral and quasi-neutral ones have the least, predominantly mechanical, damaging effect. And it is this (neutral) electrophysical regime of the working fluid that can be recommended to be maintained in humid steam turbines to extend the life of the blades, which is achieved through a rational choice of the water-chemical regime, by neutralizing the flow and using other methods.

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Електрохімічний і хімічний аспекти ерозійно-корозійного процесу руйнування робочих лопаток вологопарових турбін під дією електризованої вологи

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Стаття присвячена електрохімічному та хімічному аспектам ерозійно-корозійного руйнування поверхневого шару робочої лопатки вологопарової турбіни під дією електризованого робочого тіла. Розглянуто гіпотезу щодо комплексного механо-хіміко-електрохімічного механізму вимивання хрому та заліза з поверхневого шару металу робочої лопатки під час руйнування оксидної плівки під дією високошвидкісного потоку вологої пари. Теоретично показана можливість наводнювання поверхонь робочих лопаток під дією негативно заряджених крапель. Пошкодження лопаток в цьому випадку подібне пошкодженню від анодного травлення. Також показано,

що процес наводнювання поверхні лопатки має місце в будь-якому випадку і для електрично заряджених крапель, і для нейтральних. Однак в разі нейтральних крапель інтенсивність процесу незначна. Проведено експериментальне дослідження поверхні робочої лопатки з ерозійним пошкодженням з останнього ступеня турбіни ВК-50 ЛМЗ, яка відпрацювала свій ресурс. Визначено кількісний вміст хрому у вирізаному з лопатки зразку сталі. Виявлено зменшення вмісту хрому в пошкодженому ерозією поверхневому шарі лопатки. Для перевірки гіпотези про схожість процесу анодного електротравлення з процесом руйнування поверхні під дією негативно заряджених крапель проведено електрохімічний експеримент на модельному зразку хромової сталі 20Х13. Показано, що рельєфи пошкоджених ділянок на модельному зразку після анодного травлення і на досліджуваній лопатці в зоні дії негативно заряджених крапель подібні. Проведені експериментальні дослідження підтвердили наявність комплексного механо-хіміко-електрохімічного процесу руйнування лопатки. На основі отриманих даних сформульовані рекомендації щодо продовження ресурсу лопаток турбомашин.

Ключові слова: електризація пари, наводнення, ерозія лопаток.

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OPTIMAL DESIGN OF SINGLE-LAYERED REINFORCED CYLINDRICAL SHELLS

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This paper discusses the application of the random search method for the optimal design of single-layered reinforced cylindrical shells operating in a neutral environment. When setting a mathematical programming problem, the minimum shell weight is considered as an objective function. The critical stresses are determined according to the linear theory in the elastic region of the material. As the constraints imposed on the feasible region, the constraints on the strength, general buckling and partial buckling of a shell are accepted. The aim of this paper is to study the weight efficiency of various types of shell reinforcements and the influence of an optimum-weight shell on the parameters of an axially-compressed one. A numerical experiment was carried out. Dependencies of shell weight, wall thickness, and reinforcement parameters on the magnitude of a compressive load were investigated for shells with different types of reinforcement. As a result of the numerical experiment performed, it was found that with an increase in compressive load magnitude, there is a tendency to an increase in the wall thickness of an optimal shell, with an increase in the thickness of longitudinal stiffeners (stringers) and a slight decrease in the number of ribs. In addition, it should be noted that the general case of buckling and the first special one turned out to be decisive in choosing optimal shell parameters.

Keywords: reinforced cylindrical shell, optimal design, random search method.

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