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WEAR OF THE CONTACT SURFACES OF THE STEAM TURBINE ROTOR DISK WITH RIVETS HOLDING THE BLADES

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Abstract: Wear of contact surfaces under high specific loads is one of the most common problems for many structural components in the power, aviation, chemical, and oil refining industries. Due to inevitable overloads and fluctuations in process parameters, friction surfaces are subject to intense wear, and the gaps between them increase. The causes of damage to the peripheral section of a steam turbine rotor disk between the blade mounting holes are analyzed. The increased gaps between the friction surfaces created favourable conditions for their mutual micro-displacement under high specific loads and access to the contact zone of the process fluid. Plastic deformation of the disk surface layers due to their contact with rivets and environmental influences contributed to the initiation of fretting corrosion fatigue cracks. Their subsequent propagation between the rivet holes in the disk via a classic fatigue mechanism led to rotor shutdown. The enhancing effect of hydrogen absorbed by the preliminary operated disk steel on its susceptibility to fretting fatigue was studied.

Keywords: steam turbine rotor disk, wear, damage in contact zone, fretting fatigue, hydrogenation effect

1. INTRODUCTION

The current state of electric power generation systems, commissioned 30-40 years ago, poses significant challenges associated with the natural depletion of the service life of key equipment components, such as shafts, disks, and blades in steam turbine rotors (STRs) [1–3]. Damage to the peripheral areas of the disks is considered less critical in terms of consequences than damage to areas close to the disk seats on the rotor shafts. However, they occur significantly more frequently and pose no less of a threat to personnel, accompanied by significant financial costs for repair and restoration work and losses from unproduced energy [4, 5]. Among the main causes of damage to the blades and disks of STRs (except for those that are not caused by deviations from the requirements for their installation and operation) are high- and low-cycle fatigue, corrosion and fretting fatigue [6–8]. However, supercritical wear of contacting surfaces under challenging conditions of high-temperature process media and high specific loads precedes the implementation of precisely these mechanisms of their final failure. The relevance of this problem becomes increasingly apparent with the increasing service life of power equipment and the degradation of steel properties [9, 10]. Mechanical wear of the surfaces of components due to their sliding causes gaps between them to increase, leading to a constant increase in the amplitude of their relative displacement during operation. Consequently, the penetration of an oxidizing and simultaneously hydrogen-releasing environment into their contact zones is facilitated, accelerating the initiation of fretting fatigue cracks and their propagation throughout the entire cross-section of the components due to classical fatigue. The objective of this study is to reveal the mechanism of disk failure and demonstrate the intensifying effect of hydrogenation on the metal's endurance under fretting fatigue conditions, based on an analysis of friction and wear signs on the surfaces of the blade fixation holes on the disk crest of STRs.

2. EXPERIMENTAL

Steel 30KhN3M1FA (Wt.%: 0.3 C; 0.019 Si; 0.32 Mn; 1.67 Cr; 3.42 Ni; 0.0046 S; 0.0005 P; 0.54 Mo; 0.14 V; 0.11 Cu) was studied after $2.22 \cdot 10^5$ h of operation in a STR disk at a temperature of 400°C. Its chemical composition was determined on a SPECTROMAX LMF 0.5 spark atomic emission

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spectrometer. According to the delivery certificate, the cast disk was heat-treated using the annealing mode. The strength and yield limits, σ_{UTS} and σ_{YS}, under uniaxial tension of the steel after operation were 776 and 653 MPa, and the plasticity characteristics, El and RA, were 22 and 71%, respectively, which satisfied the requirements of the regulations [11]. Therefore, it was necessary to establish the causes of the occurrence of an abnormal situation due to the destruction of the peripheral part of the disk. To certify the technical condition of the steel, the fretting fatigue curve obtained by testing laboratory specimens in air was used. The main specimen with a cross-section of 15×4 mm made of disk steel was loaded with a symmetrical cycle according to the cantilever bending scheme at a frequency of 13 Hz. In a fixed grip of the setup, two additional specimens made of 20Kh13 steel, used in the working blades of the same rotor, were pressed against the main specimen with a constant force. The compressive stress between them reached 75 MPa. This ensured conditions for alternate partial slippage of the contacting surfaces in each half-cycle of the load. The ends of the additional specimens were rounded to a radius of 4 mm to reduce the stress concentration along the line of contact with the surface of the main specimen. Based on the test results, the number of cycles before main specimen failure N was recorded depending on the specified stress levels σ_a during cantilever bending on the line of initial contact of the specimens. Based on these data, a fretting fatigue curve was obtained for a steel disk in service. To determine the effect of hydrogen on the steel's susceptibility to fretting fatigue, specimens were electrochemically charged with hydrogen for 20 min before air tests at a cathodic polarization current density of 30 mA/cm^2 in an electrolyte with pH2 (aqueous H_2SO_4 solution + 2 g/L thiourea).

An EVO-40XVP scanning electron microscope was used to analyze wear marks on the surfaces of rivet holes in the STR disk crown, signs of fretting fatigue in the subsurface layers of the blade fixation holes in the disk, and on the operational fracture in the crack initiation zone.

3. RESULTS AND DISCUSSION

In the complex design of a STR, the disks and blades that transmit steam energy to the rotor shaft are among the most susceptible to damage due to contact with each other during long-term operation. The analyzed rotary utilized a complex design for connecting the forked blade roots to the rotor disk crests with rivets that penetrated through holes in these elements. Upon exiting the holes, the rivet ends were riveted. Assembling such a joint requires high-quality mechanical surface finishes and alignment of the rivet holes on both the blades and the disk crest. This is impossible without the use of high-precision technologies both during manufacturing and assembly. Both distortions and highly rough contact surfaces will necessitate the use of force-fitting rivets, which will increase stress concentrations in the vicinity of these holes and, consequently, contribute to damage to both the rotor turbine's blades and disk. However, these requirements were not met during the manufacture of the components of the analyzed STR. The surfaces of the rivet holes in both components had unacceptably rough machining marks and burrs caused by the forceful pressing of the rivets, etc. Misalignment of these holes in the disk and blades and high specific loads in the areas of their contact with the rivets caused uneven wear of the contacting surfaces and created the preconditions for an increase in the amplitude of the elements' relative slip in each high-frequency loading cycle. This contributed to the initiation of the fretting fatigue cracks from the surfaces of the holes in the disk (Fig. 1a). In the diametrical cross-section of the disk crest, these microcracks were practically parallel to the surface of the rivet hole (Fig. 1b). This indicated that, under the influence of specific operational loads, intense plastic deformation occurs in the subsurface layers near the disk holes, facilitating the formation of fretting fatigue cracks due to intense shear. Furthermore, increasing the gaps between the rotor's components also improved the conditions for fluid access to their contact zone. This, coupled with the intense plastic deformation of the surface layers of the rotor's contacting elements, only increased their oxidation. The combination of all these interacting factors contributed to the initiation of fretting fatigue cracks from holes in the rotor's disk, which then propagated throughout the entire working cross-section of the disk in the space between the holes via a classical fatigue mechanism.

Clear signs of medium access to the contact zone were observed directly on the operational fracture of the disk. Traces of intense matrix oxidation around coarsely dispersed non-metallic inclusions, with the formation of pits over 10–15 μm in size, were a key feature of the fretting fatigue crack initiation zone in the disk (Fig. 2a). The largest number of inclusions was observed directly beneath the surface of the

hole in the disk, which was considered evidence of the key role of non-metallic inclusions as structural stress concentrators during the initiation of fretting fatigue cracks in the disk.

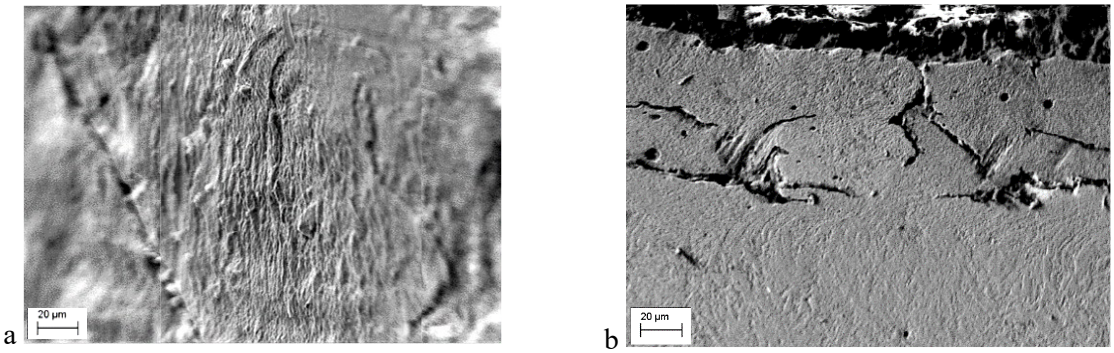

Figure 1. SEM images: a) traces of plastic deformation by sliding and nuclei of fretting fatigue microcracks on the surface of the hole, which are parallel to the fracture profile (right part of the image with insufficient sharpness) in the peripheral part of the operated disk; b) fretting fatigue cracks on a diametrically oriented section of the STR disk ridge, detected near its fracture under the surface of the rivet hole (the hole profile in the image is located at the top).

During the growth stage of these cracks, the fracture surface was dominated by features of ductile parallel striations characteristic of low-cycle fatigue (Fig. 2b, c). This pattern was formed as a result of the cyclic application of high specific loads in the contact zone and the resulting significant plastic deformations of the metal. The significant role of non-metallic inclusions in fracture persisted during the fracture propagation stage within the disk. Indeed, lines of corrosion pits initiated by them were observed right up to the point of fracture surface reorientation from inclined (characteristic of the propagation stage of short shear cracks) to normally oriented (characteristic of the propagation of a main crack by the classical fatigue mechanism due to normal separation). However, the longer the fretting fatigue crack, the fewer non-metallic inclusions were observed in the fracture surface. This indicated a decrease in the duration of contact between the fracture and the medium due to an increase in the crack growth rate.

The transition to a normal fracture orientation was marked by a significant number of areas damaged by contact between the crack faces (due to their small opening) with signs of friction and relief wear (Fig. 2d). All the described signs of operational disk fracture during the fretting fatigue stage indicate that intense wear of the surface metal layers near the disk hole due to their sliding relative to the rivet contributed not only to the initiation of these cracks but also to their propagation. Friction between the mating surfaces (on opposite crack faces), caused by cyclic movements, activated corrosion processes at the contact points of the protrusions on them, and initiated an autocatalytic mechanism for the formation of corrosion products. The larger volume of these products relative to unoxidized metal caused a wedging effect between the crack faces, adding a static load component to each loading cycle and thereby facilitating further crack propagation in the disk crest cross-section.

Consequently, the expert conclusion of the fractographic examination of the operational fracture of the STR disk clearly indicates that the intense wear of the surfaces of the blade retaining holes is responsible for its destruction, leading to the formation of a network of subsurface fretting fatigue cracks. Therefore, it was considered that information on the susceptibility of disk steel to fretting fatigue when in contact with blade steel and the role of hydrogen in intensifying their interaction is important for adjusting the service-life calculations of long-term STR components. After all, the intensely deformed metal of both disks and blades will inevitably absorb hydrogen during their long-term operation.

Based on the results of laboratory tests in the air of disk steel specimens loaded with cantilever bending in contact with blade steel specimens (both steels were preliminarily operated in the STR for $1.22 \cdot 10^5$ hours), a fretting fatigue curve was obtained (Fig. 3, curve 1). It is obvious that the spread in the number of cycles to failure at the same load level of the main specimens made of 30KhN3M1FA steel in their contact with two additional specimens made of 20Kh13 steel increased with a decrease in the stress level

during testing. The fatigue limit σ_{-1} of this steel in the initial state under a symmetrical bending loading cycle in air is in good agreement with the classical empirical relationship for alloy steels $\sigma_{-1} = (0.4…0.5)\ \sigma_B$ [12]. For the analyzed disk steel, its value corresponds to 310…388 MPa. The experimentally obtained value of the fretting fatigue limit of the disk steel in operation reached only 125 MPa (Fig. 3, curve 1). This value is up to 3 times lower than the fatigue threshold σ_{-1} calculated for this steel.

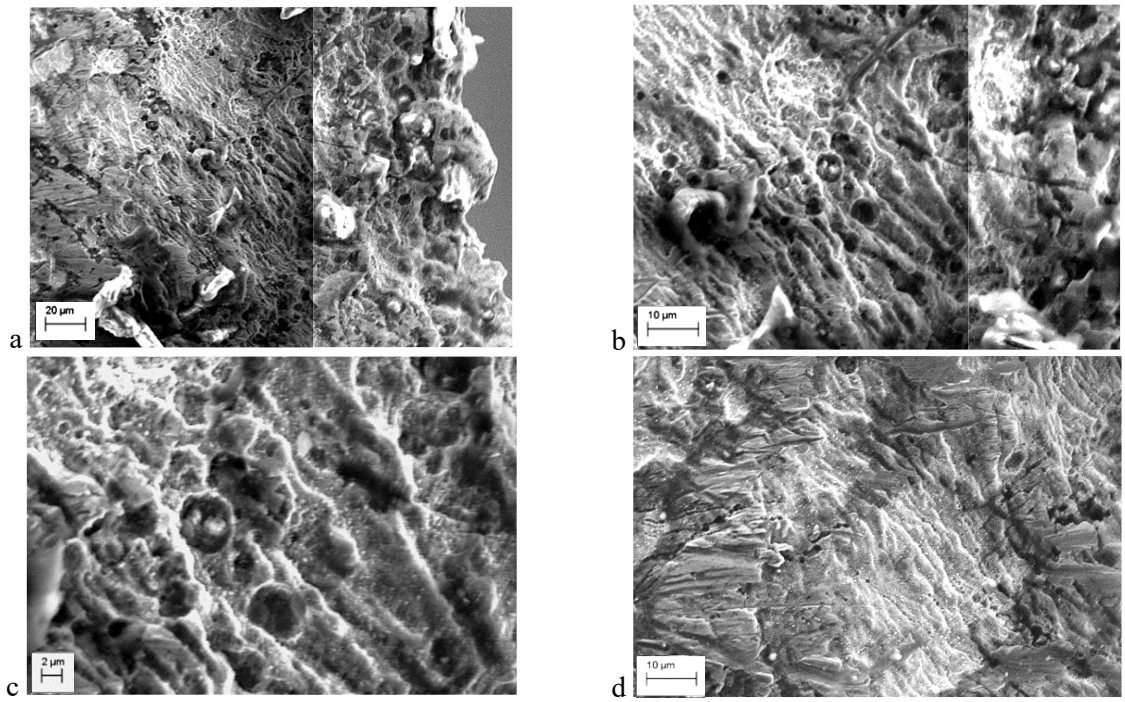

Figure 2. SEM fractograms at different resolutions of the fracture surface between adjacent holes in the peripheral part of a working disc at the initial stage of a fretting fatigue crack growth from the surface of a rivet hole in the disc crest. The edge of the surface of the rivet hole in the disc is located in the images on the right.

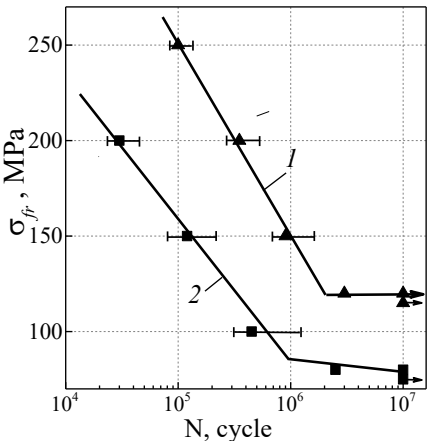

Figure 3. Fretting fatigue curves σ_{fr} – N, obtained in air for 30ХН3М1ФА steel in contact with 20Х13 steel (both steels were pre-exploited for $1.22 \cdot 10^5$ h in the disk and rotor blades of the STR): 1 and 2 – curves correspond to steel without and after additional electrolytic hydrogenation. Loading scheme – cantilever bending, symmetrical cycle (R = –1), frequency 13 Hz, compressive stress in the contact zone of the main and additional specimens – 75 MPa. At least three specimens were used for each selected σ_f level. The N ranges indicate the spread of these data.

The observed reduction in the fatigue limit due to fretting is, of course, a consequence of the combined negative effects of both steel degradation in service and fretting fatigue due to high specific loads.

Considering the relatively short service life of the steel in the STR before disk failure, it was believed that its poor performance was predetermined by the disk steel's high susceptibility to fretting fatigue. This is consistent with the fractographic analysis of the causes of operational damage in the disk. Considering the key role of non-metallic inclusions in the steel structure (as potentially active sources of hydrogen absorption of steels during service due to their electrochemical interaction with the process environment), the effect of hydrogen absorption on the fretting fatigue curve of 30KhN3M1FA steel in service was assessed (Fig. 3, curve 2). It was believed that the deterioration in the fatigue strength of hydrogenated steel at all levels of specimen load during fretting fatigue tests and a significant additional reduction in its conditional fretting fatigue limit were mainly caused by the action of hydrogen absorbed by the steel.

4. CONCLUSIONS

In summary, the obtained results revealed that the performance of the STR disk is largely determined by a number of factors, including:

Violation of the requirements for mechanical processing and installation of components on the rotor using force pressing; excessive surface roughness between the disk and the STR rivets; intense wear of the components in the contact zone due to sliding friction, which increased the gaps between them and, as a result, contributed to an increase in the amplitude of their relative movement in the zone of high specific loads;

Presence of corrosion-active non-metallic inclusions in the structure of 30KhN3M1FA steel, detected on a real fracture of the STR disk, the contact of, which can cause local dissolution and hydrogenation of the metal in their vicinity upon contact with the process medium;

High susceptibility of 30KhN3M1FA steel to fretting fatigue in a pair with 20Kh13 steel leads to a decrease in the frictional fatigue limit to 70% of the σ_{-1} value calculated for it;

Hydrogenation of steel before fretting fatigue tests, which cannot be avoided during long-term operation of STR elements, additionally significantly reduced the fretting fatigue limit of steel, which is important to take into account when calculating the service life of rotors.

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