Experimental research results of solid particle erosion resistance of blade steel with protective coating

G V Kachalin¹, A F Mednikov¹, A B Tkhabisimov¹ and L I Seleznev¹
¹ Moscow Power Engineering Institute, 111250, Moscow, Russian Federation

E-mail: tkhabisimovab@mpei.ru

Abstract
The paper presents the results of metallographic studies and solid particle erosion tests of uncoated blade steel 20K13 samples and samples with a protective coating based on chromium carbide (Cr-CrC) at a flow (air) velocity \( C_A = 180 \text{ m/s} \), flow temperature \( t_A = 25 ^\circ \text{C} \), attack angle \( \alpha = 30^\circ \) and consumption of solid abrasive particles \( G_P = 5 \times 10^{-4} \text{ kg/s} \). It was found that the coating has a granular structure, a thickness is about 11 \( \mu \text{m} \), the microhardness of the surface is \( 1520 \pm 50 \text{ HV0.05} \). Processing of the obtained data by statistical analysis methods showed that the protective coating based on Cr-CrC increases the solid particle erosion resistance of the blade steel 20kH13 by the incubation-transitional period duration more than 2.5 times.

1. Introduction
The operation reliability and the life of the power equipment depends to a large extent on the degree of structural elements functional surfaces wear that, during operation, are subject to the combined effect of various factors: corrosion, water droplet erosion, solid particle erosion, stress corrosion cracking, cavitation, high temperatures and high contact voltages.

Solid particle erosion, which affects many elements of power machines (turbines and compressors), is the process extremely difficult to study. In view of the large variety of forms of solid abrasive particles, their dimensions, velocities and attack angles, their movement is random, as well as the distribution of the particle collisions sites with the surface and the surface reaction to these disturbances. Therefore, the solid particle erosion of the surface by hard particles is a random process, and in this case the dynamics of its development can be reflected in the behavior of the this process statistical characteristics, such as: mathematical expectation \( M \) (mean value), standard deviation \( \sigma \), asymmetry coefficient \( S_k \) and kurtosis \( Ex \) of reflected particles with time as a result of their interaction with the sample surface. Earlier, it was shown in [1] that beginning from a certain moment in time such characteristics will no longer change significantly. This indicates the arrival of a steady period, and therefore, the presence of some previous stage, which is called the incubation-transition period of the solid particle erosion process, and is the main parameter of assessing the effectiveness of the material resistance to wear by solid particles increasing method.

Despite the accumulated struggle experience with various types of wear, including solid particle erosion, the problem to date remains to the end unsolved and relevant. The creation of new structural materials, protective coatings and methods of hardening functional surfaces with high wear resistance will allow modernizing technologies and equipment for the production of electricity and heat with the achievement of high energy efficiency and energy saving indicators. In this paper, the task was to study the characteristics and determine the solid particle erosion resistance of a coating based on chromium carbide (Cr-CrC), formed on blade steel 20kH13.

2 Methods of research
The process of the ion-plasma coating based on Cr-CrC formation was carried out with use of the vacuum installation "Gefest-HIPIMS of the NRU "MPEI" [2] and included the following main stages:
- preliminary preparation of sample surfaces (polishing, removal of impurities from the surface and degreasing);
- loading of samples into the vacuum chamber;
- vacuum chamber pumping out to a high vacuum with preheating;
- ionic cleaning and coating formation.

The regime parameters of the Cr-CrC-based coating formation process:
- stage duration - 30 min.;
- voltage on the substrate - 80÷150 V;
- argon consumption - 10 nl/hour;
- substrate temperature - 350÷400 °С;
- the pressure in the vacuum chamber is 3∙10⁻¹ Pa.

Coating composition determination was carried out using an X-ray energy dispersive spectrometer (EDS) X Max 50 (Oxford Instruments) of the TESCAN MIRA 3 LMU scanning electron microscope. Coating thickness was determined using a Calotest tool by ball grinding method at three points on the surface of each sample. Coated surface microhardness was measured acc.to Vickers method (GOST 9450-76) using a DuraScan 20 hardness tester.

Experimental studies of the uncoated and coated samples solid particle erosion resistance were carried out on abrasive rig of the NRU "MPEI", intended for solid particle erosion complex studies of structural materials, protective coatings and various methods of strengthening. In accordance with ASTM G76-13 [2], the abrasive rig is an jet type and allows testing at variable flow rates and attack angles of the gas-abrasive flow, as well as samples surface temperatures. The method and instrumentation of the rig allows using various criteria for estimating the solid particle erosion process intensity, also in dimensionless form. The external view of experimental rig is shown in Figure. 1.

Air is used as a carrier medium in the rig, cleaned of foreign impurities and moisture; The flow temperature (ambient temperature) is kept constant, and the sample temperature can vary from ambient temperature to 600 °C. As the abrasive material are the particles of Al₂O₃ (electrocorundum).

The air-abrasive jet is directed to the sample flat surface, the angle of it’s position relative to the jet is regulated by means of a special bracing. The exposure time of the samples ranged from 1 to 36 minutes. Images of captured particles were obtained using a TESCAN MIRA 3 LMU scanning electron microscope.

In assessing the composition, a statistical analysis of the captured reflected particles sizes was carried out on several partial selections, each of which contained 200 to 500 captured particles. Estimates numerical values of mathematical expectation \( \bar{M} \), standard deviation \( \sigma \), asymmetry coefficient \( Sk \), and kurtosis \( Ex \) were calculated by formulas 1-4.
\[
\bar{M} = \frac{\sum_{i=1}^{n} x_i}{n}
\]

where \( n \) is the number of captured reflected particles, \( x_i \) is the linear dimension of the \( i \)-th particle.

\[
\sigma = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{M})^2}{(n-1)}}
\]

\[
S_k = \frac{\sum_{i=1}^{n} (x_i - \bar{M})^3}{n \sigma^3}
\]

As applied to the present studies, a change in the value of the asymmetry coefficient \( S_k \) over time will indicate the following:
- positive values of \( S_k \) - a decrease in the estimate of the mathematical expectation \( \bar{M} \), i.e. displacement of the particle lengths towards the small-dispersed component;
- negative values of \( S_k \) - an increase in the estimation of the mathematical expectation \( \bar{M} \), i.e. displacement of the particle lengths toward the large-grained component.

\[
E_x = \frac{\sum_{i=1}^{n} (x_i - \bar{M})^4}{n \sigma^4} - 3
\]

For the purposes of this research, a change in the value of the kurtosis \( E_x \) over time will indicate the following:
- positive values of kurtosis \( E_x \) - less "fuzziness" of the distribution density due to the absence of large fraction particles crushing;
- negative values of kurtosis \( E_x \) - large "fuzziness" of the distribution density due to small-dispersed fraction particles crushing.

Based on the obtained numerical values of \( \bar{M} \), \( \sigma \), \( S_k \) and \( E_x \), were determined the functional dependences of these quantities on the exposure time \( t \) at the rig for blade 20kH13 steel samples without coating and with Cr-CrC coating.

3. Results and discussion

Figure 2 shows the images of the cross section and the distribution profiles of elements along the sample surface layer depth after the coating formation, obtained with an optic-emission spectrometer of a glow discharge.

![Figure 2](image)

**Figure 2.** The image of the cross-section (a) and the profile of the layer-by-layer elements distribution (b) in the protective coating on a blade steel 20kH13 sample

Coating microhardness H0.05 on the samples on the average is 1520 HV at a thickness of 11 \( \mu \)m. It was revealed that the coating has a granular structure with a characteristic grain size in the range up to 50÷100 nm. Elemental analysis of the coating composition showed that the chromium content in the carbide layers is about 95.2%, with 4.8% carbon. The results of the solid particle erosion tests are shown in Figures 3 and 4. Analysis of the obtained dependences shows that the considered coating increases the resistance of the blade steel 20kH13 to solid particle erosion by the duration of the incubation-transitional period at least in 2.5 times.

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Figure 3. Behavior of the $M$ (a) and $\sigma$ (b) estimates of the reflected particles after interaction with the surface of 20kH13 uncoated steel (1) and 20kH13 steel with a coating based on Cr-CrC (2).

Figure 4. Behavior of $S_k$ (a) and kurtosis $Ex$ (b) estimates of the reflected particles after interaction with the surface of 20kH13 uncoated steel (1) and 20kH13 steel with a coating based on Cr-CrC (2).

4. Conclusions
As a result of the work, was formed an ion-plasma coating based on Cr-CrC and was carried out a complex of studies of its properties, including solid particle erosion resistance. It is established that the proposed coating composition increases the blade steel 20X13 wear resistance by solid particles no less than 2.5 times.

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References
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