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The Investigation of Construction Materials and Protective Coatings Wear Resistance to Solid Particle Erosion

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Abstract

This article presents a description of a test rig for solid particle erosion resistance of construction materials and protective coatings investigation, as well as equipment for preparing products surfaces and protective coatings formation. The authors discuss a method of velocities and trajectories determination of solid particles that impinge on a metal surface using multiple exposure photo registration. The results of a steel 20Kh13 (X 20 Cr 13) specimen with a 2D nanostructured ion – plasma coating solid particle erosion resistance investigation are reported. It is shown that a protective coating increases resistance of blade steel 20Kh13 (X 20 Cr 13) to solid particle erosion by more than twice.

Keywords: solid particle erosion, test rig, high-speed interaction, solid particle impingement, multiple-exposure photoregistration, ion-plasma coatings, 2D nanocomposite structure

1. Introduction

During operation different components of turbomachines are undergo various kinds of wear, especially solid particle erosion (SPE), due to the interaction with entrained solid particles carried by steam. This holds true, first of all, for the first upstream rotor and stator blades of high pressure cylinders (HPC) and medium-pressure cylinders (MPC) of steam turbines (Figure1), as well as for surfaces of stop and control valves, disks and sealing strips (Truhnij & Lomakin, 2002; Kleis *et al*., 2008; Wang, 2013).

Figure 1. Deterioration of the steam turbine T-250/300-240 HPC first stage stator blades due to SPE

Due to conditions causing high rates of SPE the service life of stator and rotor blades, associated equipment and peripheral sealing of HPC's and MPC's is reduced from one to three periods between repairs; the efficiency of turbine stages is impaired because of the disturbed flow in flow channels; besides there is a risk of equipment breakdown, accidents and the increasing of the damaged components repair cost. The specific feature of SPE is its rapid development: wear necessitating the replacement of stator and rotor blades can occur in 1-3 years. According to (Truhnij & Lomakin, 2002), in case of every third overhaul of K-200-130 stator blades and associated components were damaged due to SPE. At a number of state-owned regional power plants turbines control stages rotor blades were replaced after 1600-10 000 hours of operation. According to (Kleis *et al*., 2008), SPE is the culprit with the K-300-240 double-block turbomachines efficiency reduction by 0,35% in case of normal ("nominal") operation and by 2,16% in case of operation with one boiler. According to (Truhnij and Lomakin, 2002; Kleis *et al*., 2008; Wang, 2013), after five years operation the SPE of stator blades and associated components of the 550 MW turbine HPC control stage resulted in the entire turbine efficiency reduction by 0,4%. According to estimates (Azevedo, 2009), in the USA annual damage caused by SPE to a typical turbine power generating unit amounts to 600 thousand dollars, and the nationwide total annual damage caused by SPE is about 150 million dollars.

Solid particles causing the turbines components wear are entrained products of corrosion and deposits carried by steam from the boiler to the turbine (Campos-Amezcua, 2007; Wellman, 2012; Li, 2009). The major source of solid particles is the tubes surfaces of the main and intermediate boiler steam superheaters, boiler's collectors and steam pipes, where oxide layers (and in particular layers of magnetite) are being naturally formed. During the equipment operation the oxide layer continues to grow to the critical thickness and then it begins to exfoliate. The major culprit with generation of such kind of particles is frequent to boiler starting and stopping, as it results in such conditions leading to deposits and oxide films cracking and exfoliation (Ashrafizadeh, 2012; Salman, *et al*., 1995). At present the size of solid particles cannot be regarded as exactly known. Some indirect measurements provide evidence that the symbolic diameter of solid particles is about 100 μm or less. The maximal size of particles is 300 μm and their hardness is HB (Brünell) 700÷750. The solid particles interaction parameters entrained in steam flow vary in a wide range (Azevedo, 2009; Campos-Amezcua, 2007; Wellman, 2012). The main parameters characterizing the solid particles impingement on a surface are: the impingement angle, impingement velocity, solid particles concentration and the contact surfaces temperature (Li, 2009).

The SPE problem of contact turbomachines components surfaces exists until now because active and passive methods of protection against SPE do not provide any solution, which would eliminate this problem (Dai *et al*., 2007; Shimizu *et al*., 2011; Batsh & Haselbacher, 2002).

One of the steam turbines first stages SPE reduction active methods is the increase of the axial gap between the stator and rotor blades. This gap reduces the probability of solid particles impingement on the stator blades surfaces which are reflected from the rotor blades. Also it is very important to create the existence of axial gaps in shroud seals, as well as gaps in front of them so that solid particles with large tangential component of peripheral speed can be separated already in the first stage.

One of the most efficient methods of SPE reduction is the removal of oxide scale before it enters the turbine cylinders. There exist three widely used technical solutions for solid particles removal:

- solid particles separation from steam flowing in hot superheater channels by using separation devices placed in sections where the flow changes it's direction, for example, from vertically downward direction to horizontal;

- solid particles separation from steam directly at the stop valve or control valve;

- directing the solid particles concentrated in the flow channels of the HPC together with carrying steam to the external separation circuit, separation of particles from the steam and purified steam redirecting back into the circuit.

One of the more successful active method for improving SPE resistance is HPC and MPC bypassing when the power plant is being put into operation because the temperature rapid change causes exfoliation of oxide scale in the boiler steam superheaters tubes and other steam flow channels and its entrainment in the steam increases to the maximum extent. However in locally produced power-generating units HPC's are bypassed by very small steam amounts, when its velocity is insufficient for oxide scale removal from the primary steam superheater. The underlying reason is heat saving when the system is put into operation and steam dumping into the condenser minimization after the rotor turns for last stages rotor blades droplet erosion intensification prevention.

The analysis of studies results shows that in modern conditions development of both active and passive metal surfaces protection methods by using surface strengthening technologies and wear-resistant coating formation has the best perspectives for the future in terms of blade materials resistance and service life of turbine components improvement (Kachalin *et al*., 2010; Haimov, 2004; Orlik *et al*., 2008; Haimov *et al*., 2009; Haimov *et al*., 2011; Muboyadzhyan, 2012; Muboyadzhyan *et al*., 2009).

At present the ever increasing number of innovations in the world power production tends to shift towards discovery and development of new wear-resistant construction materials, new multipurpose protective coatings with unique properties and characteristics and various methods of hardening. They helped significantly increase the reliability and efficiency of highly loaded equipment components and endow contact surfaces subject to wear with new functional properties such as: heat resistance, SPE resistance, high microhardness, low friction coefficient.

The passive methods of stator and rotor blades protection against SPE include material hardening by using chemical methods and protective coatings. According to (Truhnij and Lomakin, 2002), in Japan an increase in the blade steel surface hardness up to 1500-1700 HV via boration reduced by about 40 time the SPE of 550 MW power-generating unit stator blades operated during 10000 hours. According to a Texas power company (Schofield and Johnson, 1985), chemical cleaning and washouts help combating SPE in turbines. For compressors stator and rotor blades protection one uses SPE resistant coatings produced via high velocity gas plasma spraying in vacuum. This coatings contain CrAlY and carbides layers, as well as in such coatings formation one uses nitrides (TiN, CrN, ZrN) or carbonitrides (TiSiCN, ZrSiCN).

Today the most promising passive methods of stator and rotor blades SPE resistance improvement include the universal coatings formation meeting the most stringent requirement:

- high SPE resistance;
- entire surface protection including outlet blades edges;
- lasting coatings efficiency during normal operation;
- profile and roughness of the rotating blades surface inalterability;
- absence of any influence of the coatings formation process on the protected material structure and mechanical characteristics.

One can satisfy such contradictory requirements imposed on the surfaces properties (high wear-resistance, hardness and adhesion), as well as volumetric requirements (high strength and impingement viscosity) only through creation of new materials and coatings with composite structure and layering of materials with various protective functions.

Researchers provide evidence that one of the efficient methods of stator and rotor blades surfaces protection against corrosion, fatigue wear and erosion is the coatings formation on surface via ion-plasma spraying in vacuum. This method enables homogeneous treatment of complex-shaped workpieces with high precision, repeatability of results and is rather adaptable to streamlined production and efficacious. Ion-plasma spraying ensures both high adhesion and deep diffusion of alloying elements into the material substrate. This allows creating wear-resistant multilayer coatings with nanocomposite structure which are characterized by both, high hardness and plasticity. Protective ion plasma sprayed coatings with 2D nanocomposite structure formation, in which the size of structure elements does not exceed 100 nm, on the high-loaded components surfaces is one of the most promising research lines aiming at enhancement of SPE resistance, heat resistance and thermal stability of various products (Kablov *et al*., 2008).

This work deals with the protective ion-plasma sprayed coatings with 2D nanocomposite structure formation and research of their SPE resistance by using coatings formation original equipment and a test rig developed at the National Research University "Moscow Power Engineering Institute".

2. Experimental Equipment and Research Methods

Testing and attestation of the developed products surface protection methods must be carried out via experimental research with determination of their efficiency and their further use for real production purposes. The experimental study of construction materials and protective coatings SPE is carried out by using special test rigs and equipment that simulate specially created conditions, at which solid particles impinge on test specimens surfaces including impingement angles and velocities variation as well as specimens surfaces temperature.

Common laboratory tests present interaction of solids flow with the sample surface. In this type of experiments, a certain amount of solid particles accelerates in the airflow using tapering nozzle and direct towards the sample surface. This type of rigs is used in many research laboratories and universities, such as Kanazawa Institute of Technology (Japan), University of Pittsburgh (USA), University of Nottingham (UK) etc.

Along with the jet-abrasive some universities, such as Cranfield University (UK), Nagasaki R&D Center, Mitsubishi Heavy Industries (Japan), Tallinn Technical University (Estonia), etc. also use the installation of a centrifugal type. In the centrifugal accelerator abrasive particles accelerate by centrifugal force. For this purpose there are radial ducts in the rotor, and the rotor is rotated by a motor.

Nowadays there are three different methods for measuring the particle velocity. In the first method, known as the photographic method, a high-speed camera is used to take pictures of the successive positions of a particle in a given period of time and thus the speed is calculated. The second method is a method of rotating disk. In this method, the rate is determined by evaluating the time of particles flight between the two discs fixed on a common shaft rotating at a specified speed. The third method uses a laser (LDV). This methodology is based on the Doppler effect.

The scientists of the National Research University "Moscow Power Engineering Institute" have developed a special test rig that simulates the conditions, at which entrained solid particles carried by steam interact with the surface of components of the power-generating equipment, in order to investigate the kinetics of the power-generating equipment contact surfaces SPE and construction materials resistance determination to SPE and efficiency of construction materials, different types of hardening and coatings (Ashrafizadeh, 2012). This test rig allows investigating the SPE resistance of construction materials and coatings in a wide range of parameters characterizing the solid particles interaction with surfaces. The developed methods and proper instrumental equipment of this rig allow using various criteria of SPE intensity estimation also in normalized (dimensionless) form.

This rig has been developed for a selected basic model according to which a flat tested specimen surface is blown over by high-speed air stream carrying a dosed quantity of entrained solid particles. The main methodological feature of such kind of research is that test rig enables the investigation of the solid particles impingement velocities and angles influence on the specimen's surface exerted on the SPE intensity in a wide range of temperatures. Another important and necessary precondition for carrying out such kind of research is the control of parameters characterizing the impingement and solid particles trajectories. This was achieved by using multi-exposure photoregistration (Tkhabisimov *et al*., 2013). This method has been selected because its use in combination with various optic schemes allows to obtain comprehensive information of the two-phase streams structure and determine the parameters characterizing the solid particles trajectories before and after impingement.

Figure 2 shows a scheme of the test rig for construction materials and protective coatings SPE researches. As varying medium one uses purified air, which is free of foreign admixtures and droplets of water; both the temperature of the air steam with entrained solid particles and the specimen surface temperature can vary from 25 °C to 600 °C. Table 1 presents the technical characteristics of the test rig.

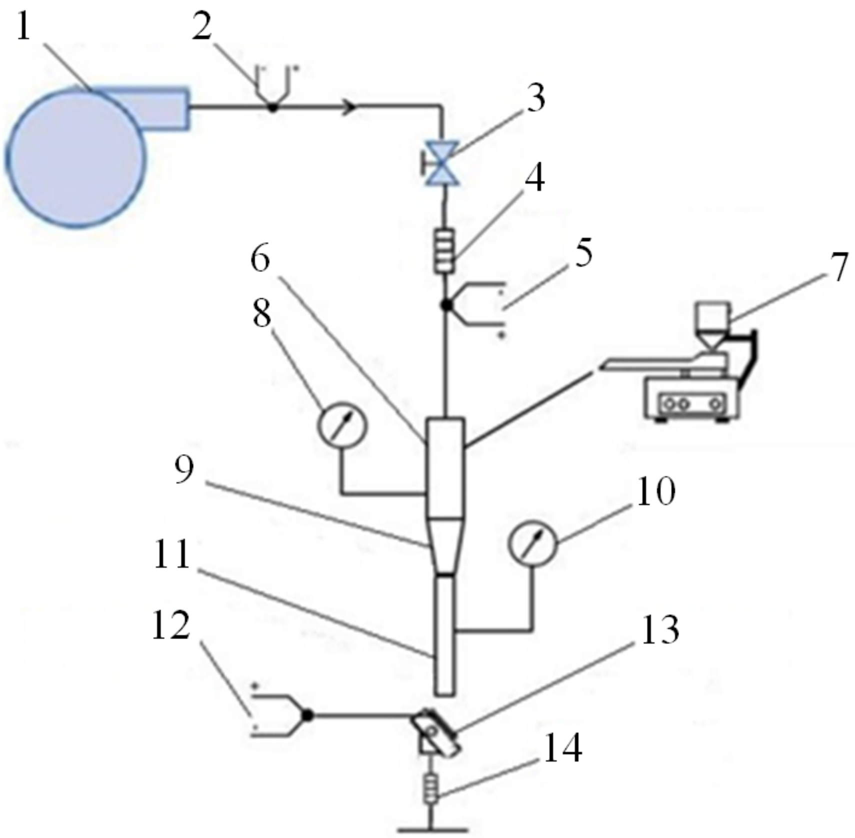
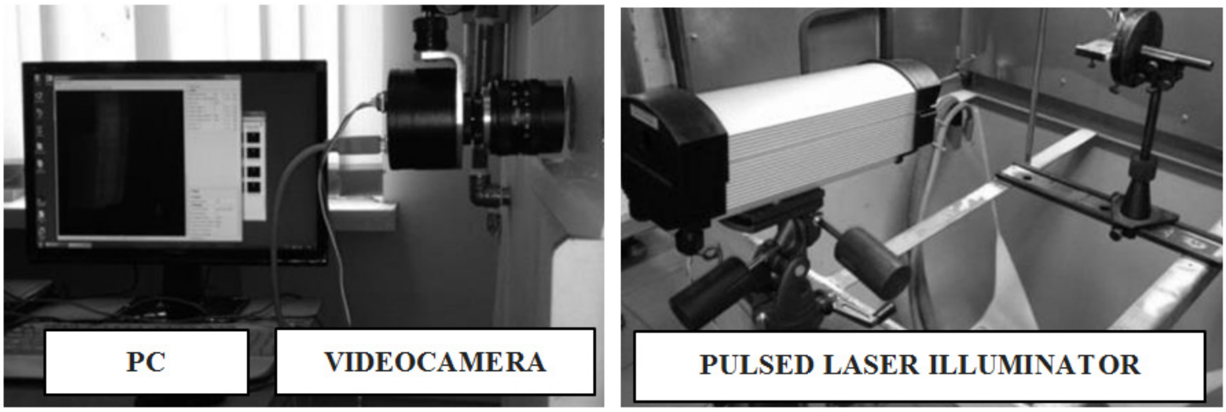


Figure 2. A scheme of the test rig for construction materials and protective coatings SPE researches. 1 – compressor; 2, 5, 12 –thermocouple-sensing element; 3 – regulating filter; 4, 14 -heater; 6 – mixing chamber; 7 – vibrating feeder; 8 – manometer (full pressure); 9 – Venturi nozzle; 10 – manometer (static pressure); 11 – accelerating tube; 13 – specimen.

Table 1. Technical characteristics of the test rig

Parameter	Value
Speed of impingement, m/sec	Up to 230
Impingement angle, degrees	From 10 to 90
Temperature of specimens, °C	Up to 600
Consumption of abrasive particles, g/minute	Up to 20

The test rig is equipped with a system for velocity measurement of solid particles entrained in the air stream based on the use of multi-exposure photoregistration. This system consists of the following: high speed video camera (see Figure 3, a), retroreflective screen, synchronizer and pulsed laser illuminator (see Figure 3, b).



a) b)

Figure 3. General view of the photoregistration camera (a) and pulsed laser illuminator (b)

The test rig operates as follows (see Figure 2). After the air passes through compressor 1 its pressure decreases down to the value set by using regulating filter 3 which controlles by the manometer. The air flows through a tube from compressor 1 to mixing camera 6. The air consumption measurement based on the difference in pressure between the mixing chamber and the test chamber. Solid particles are fed to the mixing chamber from vibrating feeder 7. The solid particles are granules of Al_2O_3 (electrocorundum, i.e. electrolytically produced corundum). The air stream with entrained solid particles is directed towards the specimen surface, whose position in respect to the stream is regulated with the use of a special clamp, which enables variation in the solid particles impingement angle on the specimen's surface.

A disk of 36 mm's diameter and 3 mm's thick was used as test specimen. For carrying out a single test one uses only one specimen, which is weighed before and after the test. The test specimen mass loss (Δm) is calculated as the difference between the specimen's initial mass and its mass after the test. As a result of initial specimens batch testing and a coated specimens batch one obtains SPE kinetic curves (mass loss (Δm) dependence on the specimen's exposure time at the test rig). The criterion of relative SPE resistance is the comparison of the incubation period characteristics of initial specimens and specimens with protective coatings.

3. Specimens Preparation and Coatings Formation

When coatings are being formed on the surface of test specimens, one has to carry out the following main procedures:

- preliminary preparation of the specimens surfaces;
- final preparation (polishing) of the specimens contact surfaces;
- inlet and outlet control of specimens parameters before and after the entire preparation cycle;
- formation of a coating with preset characteristics.

Specimens made of blade steel 20Kh13 (X 20 Cr 13) of proper geometry were used as test specimens for SPE resistance tests. After mechanical removal of dirt and degreasing, the surface of test specimens is preliminarily treated with the use of electrolyte – plasma polishing unit. The latter comprises the following: control cabinet, step-down power transformer and electrolyte – plasma polishing module. This unit is intended for polishing products made out of corrosion-resistant steels, titanium alloys, nickel-chromium alloys; it can be used for both, final surfaces polishing or surfaces preparation for galvanic treatment or coatings formation by using vacuum technologies. The operation of this unit is based on a pulsed electropolishing method providing for creation of a steam-and-gas "mantle" around a workpiece immersed in electrolyte solution and complex physical and chemical influence exerted by this mantle on the surface of the workpiece. Thanks to preliminary treatment of surfaces of test specimens their roughness decreased down to 0.6 μm. The time of treatment of each specimen did not exceed 600 seconds. The process of electrolyte-plasma polishing was carried out in a 5% water solution of ammonium sulphate at the temperature of 80 ^{0}C.

During testing the SPE resistance the protective layer with 2D nanocomposite structure was formed on the test specimens surfaces inside a vacuum unit by magnetron spraying method by using planar unbalanced magnetrons.

This unit comprises the following: a vacuum chamber, a pumping rig with three vacuum pumps, a spraying system comprising 4 unbalanced magnetrons and a planar ion source with power supply units and a bias voltage unit, a water cooling system, a heater and current leads, a planetary gear for prepared workpieces fixation and transportation, a device for measuring temperature, devices and instruments for vacuum control and a system for entire unit operation control. Figure 4 shows the general view of the vacuum unit for ion – plasma sprayed coatings formation and table 2 presents its technical characteristics.

Coatings were formed in the vacuum chamber, where vacuum pumps maintained a pressure in the range 0.05 – 0.5 Pa. Inside the vacuum chamber test specimens were fixed on the planetary gear and this enabled homogeneous coating of the entire contact surface. The coatings were formed by using a magnetron system with titanium and aluminium targets. In the process of formation of coatings the following gases were used: argon as a plasma forming gas used for creation and maintenance of electric discharges in vacuum, and nitrogen. During the process of formation of coatings the temperature of specimens did not exceed 360° C; it was measured with the use of chromel – copel thermocouple sensing element with special fixation of its tail end and sending signals from the vacuum chamber. The calibration of the entire system (temperature sensor – measuring instrument) enabled measurement of temperature with an accuracy higher than 2%.

Figure 4. General view of the vacuum unit for ion-plasma sprayed coatings formation

Table 2. Technical characteristics of the vacuum unit for ion-plasma sprayed coatings formation

Parameter	Value
Overall length of the product, mm	Up to 1200
Number of positions of the planetary gear	16
Number of magnetrons	4
Power supply system: bias potential, kW/V	24/up to 1350V
Power supply system: [for] magnetrons, kW/ mode	12/DC, AC, dual
Purpose: Development and introduction of new coatings compositions with 2D and 3D nanostructure coatings, treatment of medium-size and large batches of products	

4. Results

Within the framework of this article a protective coating with 2D nanocomposite structure based on TiN/AlN (see Figure 5) has been formed. The total thickness of this coating is equal to 10 μm. The new coating consists of separate layers of materials, each of them being 15-30 μm thick; its surface has a granular structure with typical grains size 60÷300 nm. The roughness of the coatings surface does not exceed 0,6 μm, thus providing evidence of the influence absence of the coating formation process on the initial surface roughness (0,6 μm). The microhardness of coated test specimens was equal to approximately 17 GPa, i.e. the microhardness is up to 5 times in comparison with uncoated test specimens.

As result of testing the abrasion resistance of a batch of uncoated specimens made out of blade steel 20Kh13 (X 20 Cr 13) and a batch of specimens with TiN/AlN-based ion-plasma sprayed coatings with 2D nanostructure the authors have obtained kinetic curves of SPE in Δm=f(t) coordinates (see Figure 6). These curves show that at the stage of the SPE process incubation period TiN/AlN-based coatings increase the SPE resistance of blade steel 20Kh13 (X 20 Cr 13) by more than twice.

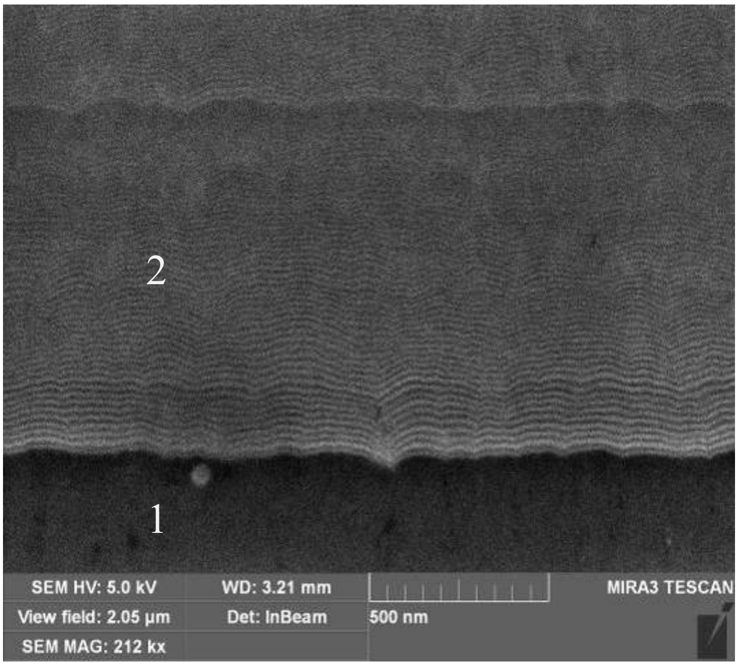


Figure 5. Transverse cross-section of 2D nanocomposite coating. 1 –substrate; 2 – coating

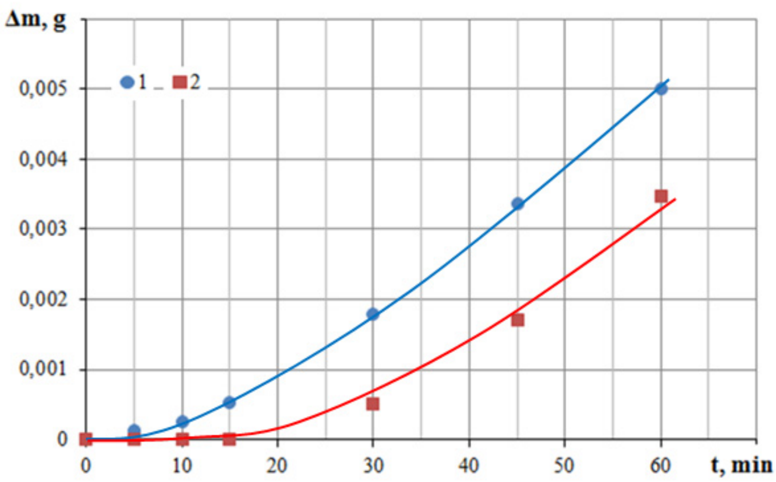
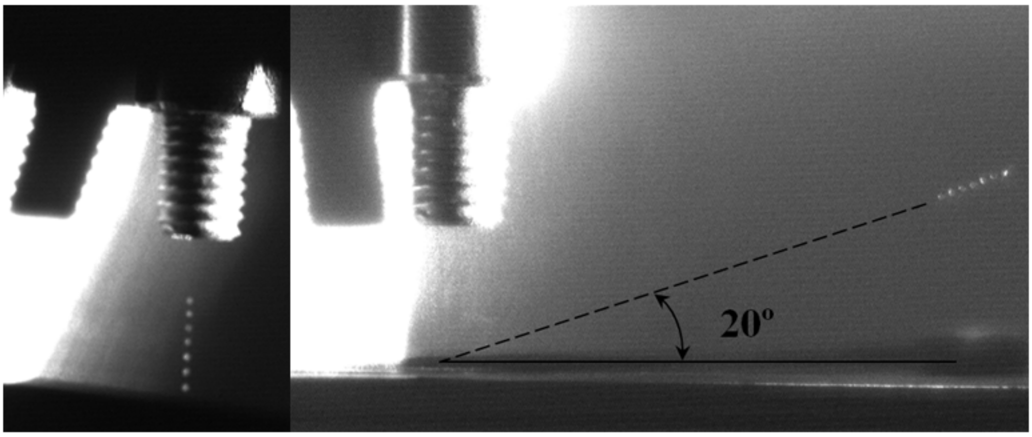


Figure 6. Kinetic curves of SPE of uncoated steel 20Kh13 (X 20 Cr 13) (1) and steel with 2D nanocomposite coating (2)

The developed system of solid particles velocities and trajectories measurement enabled obtaining high-quality images showing the interaction of solid particles with test specimen metal surface. The velocity of a particle is measured via its calculation based on the length of its trajectory during the known exposure time, the trajectory ("track") of the particles being registered by the chamber as a series of bright points because the particles reflect brief bursts of light ("flashes") produced by the laser illuminator (see Figure 7, a). The laser illuminator produced bursts of light with duration less than 1 μs in the form of a flat beam, which is about 10 mm wide in the horizontal plane and is about 50 mm high in the vertical plane. The camera's line of sight was perpendicular to the plane of illumination. Therefore were registered those particles that travelled in the plane of the pulsed illumination and this enabled the measurement of their velocity [speed and direction of motion] (see Figure 7, b), in case of further tests it also enabled particles' trajectories estimation for varying conditions (impingement angle, roughness of the surface, etc.) at which they impinged on test specimen surface.



a) b)

Figure 7. Image of a solid particle "track" (a) and its trajectory after interaction with the specimen surface (b)

5. Discussion

In order to study the SPE resistance of construction materials and protective coatings in a wide range of parameters characterizing the impingement the scientists of the National Research University "Moscow Power Engineering Institute" have developed and continue to use a special test rig, which simulates the conditions, at which the contact surfaces of turbomachines suffer SPE. Using this test rig one can test and attest the developed coatings and hardening of various types, as well as carry out fundamental research into the kinetics of the construction materials SPE mechanism and proper methods of protection. The results obtained within the framework of this study devoted to the determination of the influence of ion-plasma sprayed coatings with 2D nanocomposite structure on the SPE resistance of blade steel 20Kh13 (X 20 Cr 13) provide evidence of good perspectives for their future use and development as turbomachines components passive protection against SPE. The results reported in this work show the efficiency of ion-plasma sprayed coatings with complex laminated structure for enhancement of blade steel SPE resistance and the necessity to carry out further research. The following materials have good perspectives in terms of new types coatings creation: titanium, aluminium, chromium, zirconium, molybdenum, etc., as well as their compounds with nitrogen and oxygen.

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