EFEITO DA IRRADIAÇÃO DE VIGA ELETRÔNICA DE ALTA CORRENTE NA RESISTÊNCIA À CORROSÃO DE ÓXIDO DE SULFETO DE REVESTIMENTOS DE NI-CR-AL-Y-PLASMA

EFFECT OF HIGH-CURRENT ELECTRON BEAM IRRADIATION ON RESISTANCE OF SULFIDE-OXIDE CORROSION OF NI-CR-AL-Y ION-PLASMA COATINGS

ВЛИЯНИЕ ОБЛУЧЕНИЯ СИЛЬНОТОЧНЫМИ ЭЛЕКТРОННЫМИ ПУЧКАМИ НА СОПРОТИВЛЕНИЕ СУЛЬФИДНО-ОКСИДНОЙ КОРРОЗИИ ИОННО-ПЛАЗМЕННЫХ ПОКРЫТИЙ NI-CR-AL-Y

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RESUMO

Recentemente, o aparecimento de aceleradores de feixes de elétrons de alta corrente e poderosos lançamentos de íons contribuiu para a criação de efeitos únicos de fluxos de energia concentrados nos materiais. A melhoria dos processos de produção e o desenvolvimento de novos processos tecnológicos, tanto para fabricação de motores de aeronaves domésticos quanto para armas de aviação, continua sendo uma questão urgente. A confiabilidade dos motores depende da confiabilidade das pás da turbina, que são as peças mais carregadas, pois são expostas a cargas estáticas, dinâmicas e cíclicas e também sofrem tensões térmicas cíclicas. Portanto, o principal objetivo do trabalho foi analisar o efeito da irradiação com feixes de elétrons de alta corrente na resistência à corrosão por óxido-sulfeto de revestimentos do íon-plasma Ni-Cr-Al-Y. Para atingir esse objetivo, a irradiação por feixes foi realizada na instalação automatizada dos feixes de elétrons do complexo RITM-SP. A modificação da camada superficial do revestimento do íon-plasma SDP 2 + VSDP 16 usando feixes de elétrons de alta corrente com duração de microssegundos de acordo com o modo selecionado permitiu aumentar significativamente a resistência à corrosão por óxido-sulfeto. A análise da superfície e microestrutura das amostras após o teste de corrosão por óxido-sulfeto (SOC) permitiu determinar os diferentes efeitos do meio no revestimento das amostras, dependendo do estado da superfície das amostras. No processo de estudo da microestrutura das amostras, também foi constatado que as rachaduras individuais que estavam na superfície das amostras após a modificação não receberam seu desenvolvimento durante o teste. Verificou-se que certos tipos de crateras nem sempre são o foco do aparecimento de danos por corrosão, ou seja, a existência desses tipos de crateras e seus efeitos sobre a resistência à corrosão por óxido-sulfeto não são simples.

Palavras-chave: corrosão por óxido-sulfeto, modificação por feixes de elétrons de alta corrente, revestimentos de íon-plasma condensados, estado de fase estrutural, estudo de microestrutura.

ABSTRACT

Recently, the emergence of accelerators of high-current electron beams and powerful electron ion beams has contributed to the creation of unique effects of concentrated energy flows on materials. Upgrading of production processes and development of new technological processes of both domestic aircraft propulsion engineering and aviation arms remain topical and needed. Engine operational reliability depends on that of

turbine blades. They are the most loaded details because they are experienced to action of static, dynamic and cyclic loadings as well as are subjected to cyclic thermal stresses. Therefore the main objective of our paper is to analyze the effect of high-current electron beam irradiation on resistance of sulfide-oxide corrosion (SOC) of Ni-Cr-Al-Y-ion-plasma coatings. To achieve this purpose, beam irradiation was performed using the RITM-SP complex automated electron-beam setup. Modification of surface layer of SDP 2+VSDP16 ion-plasma coating by microsecond high-current electron beams of selected mode made it possible to increase considerably the SOC resistance. An analysis of the surface and microstructure of samples after SOC testing enabled to determine different effects of medium on sample coating depending on the state of the sample surface. When investigated samples microstructure, we found that after modification certain cracks on sample surface did not develop in the course of testing. It was found that some craters were not necessarily centers of corrosion damage origin, i.e., the existence of given types of craters and their impact on SOC resistance stability are ambiguous.

Keywords: *sulfide-oxide corrosion, modification by high-current electron beams, condensed ion-plasma coatings, structural-phase state, investigation of microstructure.*

АННОТАЦИЯ

В последнее время появление ускорителей сильноточных электронных пучков и мощных электронных пусков ионов способствовало созданию уникальных воздействий концентрированных потоков энергии на материалы. Совершенствование процессов производства и разработка новых технологических процессов как отечественного авиационного двигателестроения, так и авиационного вооружения остается актуальным вопросом. Надежность работы двигателей зависит от надежности работы лопаток турбины, которые являются наиболее нагруженными деталями, так как подвергаются действию статических, динамических, циклических нагрузок, а также испытывают циклические термические напряжения. Поэтому основная цель работы заключается в анализе влияния облучения сильноточными электронными пучками на сопротивление сульфидно-оксидной коррозии ионно-плазменных покрытий Ni-Cr-Al-Y. Для достижения поставленной цели проводилось облучение пучком на комплексной автоматизированной электронно-пучковой установке «РИТМ-СП». Модифицирование поверхностного слоя покрытия ионно-плазменного покрытия СДП 2+ВСДП 16 с помощью сильноточных электронных пучков микросекундной длительности по выбранному режиму позволило значительно повысить сопротивление сульфидно-оксидной коррозии. Анализ поверхности и микроструктуры образцов после испытания на сульфидно-оксидную коррозию (СОК) позволил определить разное влияние среды на покрытие образцов в зависимости от состояния поверхности образцов. В процессе исследования микроструктуры образцов также было обнаружено, что отдельные трещины, которые были на поверхности образцов после модифицирования, не получили своего развития в процессе проведения испытания. Было установлено, что отдельные виды кратеров не всегда являются очагом зарождения коррозионных повреждений, т.е. существование данных типов кратеров и их влияние на стойкость к сопротивлению сульфидно-оксидной коррозии не однозначна.

Ключевые слова: *сульфидно-оксидная коррозия, модифицирование сильноточными электронными пучками, конденсированные ионно-плазменные покрытия, структурно-фазовое состояние, исследование микроструктуры.*

1. INTRODUCTION

Upgrading of production processes and development of new technological processes of both domestic aircraft propulsion engineering and aviation arms remain topical and needed. The efforts of designers and technologists who developed and made aeronautical engineering were always directed, first of all, at growth of reliability and controllability (and recently at ecological problems) of production and products as well (Baranov *et al.*, 2007; Tishkov and Firsanov, 2011; Terentyev *et al.*, 2012;

Plankovsky *et al.*, 2013; Nesterov *et al.*, 2018; Kachanov *et al.*, 2017).

One of the most important areas in growth of reliability of modern gas turbine engines (GTE) and aviation arms as well as in development of the newest construction solutions is provision of required service parameters for materials used to product especially loaded details (including GTE and primarily high pressure turbine rotor blades (Muboyajyan *et al.*, 2012; Kononov *et al.*, 2013; Budinovskiy, and Smirnov, 2015; Ivashko *et al.*, 2019). However, even at stability of strength properties of materials used for production of the

above details, the turbine blades may break in the course of operation (Cai *et al.*, 2016; Zhou *et al.*, 2017; Blesman *et al.*, 2018). One of the main reasons for that is intense material damage at high-temperature corrosion under the action of static and vibration loads.

An analysis of the performed investigations shows (Kablov, 2001; Shulov *et al.*, 2010; Shulov *et al.*, 2013; Shulov *et al.*, 2015; Kosmin and Budinovsky, 2016) that both character and intensity of turbine blade damages at high temperature corrosion are determined by the following factors: (i) anti-corrosion properties of protective coatings, (ii) level of active static and vibration loads, (iii) operating temperature of turbine blades, as well as (iv) concentration of corrosion-active substances in fuel combustion products. In some cases, high-temperature corrosion acts as an independent disturbing factor (Budinovskii and Muboyadzhan, 2003; Shejko *et al.*, 2017; Ivanov *et al.*, 2018; Braceras *et al.*, 2018). In this connection investigation of mechanisms of corrosion damage and its kinetics is one of the problems for developing new materials and coatings as well as making a system for monitoring technical condition of blades.

One of the solutions for the problem of increasing SOC resistance is the deposition of protective coatings. Application of high energy vacuum-plasma technology seems to be most reasonable for this technology (Bhat *et al.*, 2018; Chanda *et al.*, 2018; Pillis *et al.*, 2018). The MAP-type vacuum-plasma plants developed at the All-Russian Institute of Aviation Materials to deposit heat resistant coatings on turbine blades are used widely and successfully in aircraft propulsion engineering (Muboyajyan *et al.*, 2012; Kachanov *et al.*, 2017). Such plants ensured increasing service life of turbine blades to 600 hours by depositing double-layer SDP 2+VSDP16 coatings to 100 μm thick (Kononov *et al.*, 2013).

The process of changing physical-chemical properties of surface layers of GTE rotor blades may be presented as the following conditional scheme: 1) destruction of protective coatings owing to erosion/corrosion damage or cracking at considerable amplitudes of thermotension; 2) formation and condensation (at blade surfaces) of sulfur-containing and other corrosion-active compounds at their penetration into engine flow part; 3) formation of Ni sulfide and Cr sulfide at the "alloy-dross" interface.

In the course of exploitation, the defects inherent in condensed multicomponent ion-

plasma coatings (presence of a micro drop fraction in plasma that leads to low local adhesion even after high-temperature diffusion annealing; no uniformity of phase components distribution over surface and depth; high roughness of coating) may lead to reduction of heat resistance of coating and its resistance to SOC. Some measures are needed for their leveling (Kahraman *et al.*, 2016; Sentry *et al.*, 2018). Therefore, it is expedient to modify surface layers of condensed ion-plasma coatings using a high-current pulsed electron beam (HPEB) (Shulov *et al.*, 2010; Shulov *et al.*, 2013; Shulov *et al.*, 2015; Bytsenko *et al.*, 2015; Kosmin and Budinovsky, 2016; Bytsenko *et al.*, 2017a).

The objective of the present work is an investigation of the effect of modifying coating surface layers on resistance to SOC by using HPEB condensed ion-plasma NiCrAlY coatings.

2. MATERIALS AND METHODS

The objects of investigation were the samples made of high-temperature JS32 nickel alloy with condensed multicomponent SDP 2+VSDP16 ion-plasma coating deposited according to the series technology (without modifying and with subsequent modifying by HPEB) (Bytsenko *et al.*, 2015; Bytsenko *et al.*, 2017b). HPE irradiation was made with a complex automated electron-beam plant "RITM-SP" using the following mode: electron energy $E = 20$ keV and pulse number $N = 10$, with further thermal treatment for two hours in a vacuum at 1050°C.

The SOC testings were performed in accordance with PI 1.2A-503-98. The testing mode was cyclic: (i) deposition of salt crust samples by sputtering solution of $\text{Na}_2\text{SO}_4 + \text{NaCl}$ salts on a hot surface; (ii) exposure at a specified temperature of 800°C for one hour; (iii) air cooling. The total testing period was ten cycles. Testing of samples (put into alundum crucibles) was performed in a chamber electric resistance furnace with air. Coating resistance to SOC was estimated before and after irradiation using the gravimetric method with analytical balance (accurate to ± 0.0002 g). To determine the kinetics of the SOC process, the samples were weighed in one, five and ten cycle intervals of testing.

The surface condition was investigated using a LEXT OLS 3100 laser confocal microscope, with further computer processing of images obtained (Bytsenko *et al.*, 2016; Bytsenko *et al.*, 2017). The investigation of the coating

microstructure was performed using a Leica DM IRM optical microscope and a VERIOS 460 scanning electron microscope with an X-MAX 80energy dispersive X-ray microanalyzer.

3. RESULTS AND DISCUSSION:

In the initial state, the coated samples have a uniform surface with single particles of drop phase (Figure 1a). For the most part, the samples with modified coating have a homogeneous shiny surface with a small amount of craters (Figure 1b). Such defects as multi-ring, adjacent and nick-like craters as well as cracks are observed at some sample surfaces after modification. They indicate the instability of irradiation conditions (Figure 1c).

For SOC testing the samples with initial coating (sample No1), defectless modified coating (sample No 17) and modified coating with defects (samples No 3 and No 15) were elected. After SOC testing the masses of samples with initial coating practically remained the same after one, five and ten SOC cycles. The mass of the sample with defect less modified coating did not change too. The masses of samples with modified coating with defects decreased by 0.0036 g for the sample No 15 after one cycle and by 0.0467 g for the sample No 3 after five cycles.

After one cycle of testing, the unmodified coating practically does not differ from the initial one (homogeneous, with single particles of drop phase). After five cycles, single areas with corrosion are observed on the sample surfaces. The corrosion-struck coating areas are of greenish tint (Figure 2a). After one cycle of SOC testing, the defect less modified coating became mat. And no corrosion nidi were observed at the sample surface after ten cycles of testing (Figures 2b, 2c). The surfaces of samples with modified coatings with defects have corrosion damages even after one cycle of SOC testing. The corrosion nidi are predominantly near defects and along the sample edge (Figures 3d, 3e). Our investigations of sample surfaces after corrosion testing performed with a LEXT laser confocal microscope (Figure 3) showed that after five cycles of testing the surface of a sample with initial coating becomes rougher than before testing. There are corrosion nidi at the sample surface (shown with arrows in Figure 3c). After ten cycles of testing, the surface roughness decreases, and corrosion is observed over the whole sample surface (Figure 3e).

After five cycles, a sample surface with defect less modified coating is less affected with

corrosion than unmodified one and partially preserves the initial condition (see highlights in Figure 3d). After ten cycles, corrosion occurs uniformly over the whole sample surface; no corrosion nidi (pits) are observed (Figure 3f).

After HPEB irradiation and five cycles, a coated sample No3 with defects (as well as that with defect less modified coating) partially preserves the initial (prior to testing) surface condition (Figures 3g, 3h). When comparing with the defect less modified coating, the given sample demonstrates strong corrosion near defects and along its edges. After SOC testing, the microstructure of sample surfaces was studied by the methods of optical and scanning electron microscopy (Figures 4 and 5). It was found that corrosion damage of unmodified coating is uniform (Figure 4a). The corrosion-struck depth increases with the number of cycles (five and ten) from $\sim 6.0\ \mu\text{m}$ to $\sim 25.0\ \mu\text{m}$ (Figure 5a). After ten cycles, single deeper corrosion damages of coating are observed. A uniform corrosion damaging of surface is also observed for a sample with defect less modified coating (Figure 4b). The depth of corrosion damaging is $\sim 1.0\ \mu\text{m}$ at five cycles and $\sim 10\ \mu\text{m}$ at ten cycles (Figure 5b). For the sample No3 with defects of modified coating, corrosion damaging after five cycles is $\sim 5.0\ \mu\text{m}$ deep; the sample coating is partially damaged near the sample edge and defects.

An analysis of sample surfaces and microstructure after SOC testing showed different effect of medium on sample coatings depending on the condition of sample surfaces. The reason for such different conditions of surface layer after SOC testing at samples No 3 and No 15 with modified coating is the presence of defects after coating deposition and further irradiation. The appearance of damage centers due to SOC is related to coating peeling after irradiation owing to poor adhesion of coating to substrate. Another cause is the instability of irradiation modes. This is indicated by the presence of the following crater types: multi-ring, adjacent and nick-like. It is known (Shulov *et al.*, 2015) that craters of such types are the most dangerous with respect to corrosion resistance (Figure 6).

4. CONCLUSIONS:

It should be noted that multi-ring and adjacent craters not necessarily served as centers of origin of corrosion damages, i.e., presence of craters of such types and their effect on SOC resistance tolerance are not too

unambiguous. When investigating the microstructure of samples No3 and No15, it was found that after modifying some cracks on the sample surfaces did not grow in the course of SOC testing.

When analyzing the data obtained, one can conclude that HPEB modification of the surface layer of the SDP 2+VSDP16 coating by the chosen mode made it possible to considerably increase SOC resistance. The corrosion damage of unmodified coating was from ~6.0 μm to ~25.0 μm (at five and ten cycles) while that of modified defectless coating was ~1.0 μm at five cycles and ~10 μm at ten cycles (i.e., 2.5 times smaller).

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Figure 1. Condition of sample surfaces before SOC testing (x7): a) initial coating; b) modified coating; c) multi-ring crater at the modified coating surface

Figure 2. Condition of sample surfaces after SOC testing (x7): a) initial coating after five cycles of testing; b) defectless modified coating after five cycles of testing; c) defectless modified coating after ten cycles of testing; d) modified coating with defects (sample No15) after one cycle of testing; e) modified coating with defects (sample No 3) after five cycles of testing

Figure 3. 3D images of sample surfaces (x500): a) unmodified coating in the initial condition; b) defectless modified coating in the initial condition; c) unmodified coating after five cycles of testing; d) defectless modified coating after five cycles of testing; e) unmodified coating after ten cycles of testing; f) defectless modified coating after ten cycles of testing; g) modified coating with defects (sample No3) after five cycles of testing; h) modified coating with defects (sample No15) after five cycles of testing

Figure 4. Microstructure of surface layer after SOC testing (x200): a) unmodified coating after five cycles of testing; b) defectless modified coating after ten cycles of testing; c) modified coating with defects after five cycles of testing

Figure 5. Coating microstructure after SOC testing (x2000): a) unmodified coating after ten cycles of testing; b) defectless modified coating after ten cycles of testing

Figure 6. Effect of SOC on the surface of sample with crater-like defects (x20): a) condition of a nick-like crater after five cycles of testing; b) condition of a multi-ring crater after five cycles of testing