Modification of Refractory Arc-Vacuum NiCrAlY Coatings Deposited on the Surface of Nickel-Base Alloy Blades with Intense Pulsed Electron Beams[1]

A.V. Krainikov, A.G. Paykin, V.A. Shulov, O.A. Bytzenko,
V.I. Engelko*, and K.I. Tkachenko*

Chernyshev Machine Building Enterprise, 7, Vishnevaya str., A-80, GSP-3, Moscow, 123362, Russia
Tel.: +8(495) 491-49-88, Fax: +8(495) 491-56-52, E-mail: shulovva@mail.ru
**Efremov Institute of Electro-physical Apparatus, 1, Sovietsky ave., Metallostroy,*
St. Peterburg, 189631, Russia

Abstract – The present paper reviews the results of investigations dedicated by the application of intense pulsed electron beams for surface processing of turbine blades with NiCrAlY coating. The high energy density ($w = 40–42$ J/cm^2) of these short-pulsed beams (with a diameter of $d = 6–10$ cm and an energy of $E = 100–150$ keV) exhibits a good prospect of their introduction into aircraft engine building for surface smoothing and strengthening of turbine blades from nickel alloys.

1. Introduction

Despite the latest advances in the technology of production of refractory alloy monocrystalline ingots and new developed materials (GS32, GS36, GS40, etc.) specifically containing a great amount of rhenium, the blades made of these materials cannot be used without heat-resistant protective coatings because of high turbine inlet temperature (1500–2000 °C) tending to increase in the future. Because of this, as far back as the end of the 1980s a demand arose for developing a technique of application of such coatings. In the USSR, advanced methods of application of heat-resistant coatings were developed by several laboratories of different organizations, among these are VIAM, Electric Welding Institute named after E.O. Paton, Air Force Academy named after Zhukovsky, Kuybyshev Aviation Institute, BFTI, etc. At that time, the following three methods were progressing rapidly: direct electron-beam evaporation in a vacuum, gas-phase alitizing and vacuum arc method (vacuum-plasma high-energy technology). In the USSR, the industry tested the vacuum arc method and direct electron-beam evaporation in a vacuum, while the Western States preferred the plasma technique. This, most likely, was caused by a higher level of development of powder metallurgy in these states. For the first time, the vacuum-plasma coatings were used in the aircraft engine industry to protect turbine blades from high-temperature oxidation in the air (NiCoCrAlY, NiCoCrAlY + NiCrAlY, NiCrAlY, etc.) [1]. A method of production of these coatings was developed by G.A. Mrochek and B.A. Eyzner [2, 3], the process proper was devised by S.A. Muboyagan [4, 5]. In so doing, the coating deposition rates of various materials reach 0.1–0.4 μm/min (for the MAP-1M installation). Other installations provided lower deposition rates (NNV: 0.05–0.2 μm/min; Bulat, Mir, Pusk: up to 0.15–0.1 μm/min). The increased deposition rates at installations Types MAP-1M, MAP-2M, and VIAM were achieved due to an increased content of droplet fraction (some of the fragments measured up to 10–20 μm and more). The latter – together with pure technological complications of producing the cathodes from the applied coating materials – is the major drawback of the vacuum-plasma high-energy technology. That is why the Western States preferred to employ a plasma technology using fine powders (1–5 μm) to increase the heat resistance of turbine blades. As early as 1982, at the meeting with the specialists of JSC “Samara scientific and technical Complex named by N.D. Kuznetsov” dedicated to the development of high-performance equipment for the application of heat-resistant coatings by the vacuum arc method, G.A. Mrochek, one of the leading scientists of the USSR, said (N.D. Kuznetsov wanted to give this work to the Belorussian Physics and Technology Institute because this Institute designed coatings having performance much better than that of the coatings used by VIAM): “We appreciate this important offer. However, having considered all the pros and cons, I came to a conclusion that an increase in productivity will result in a sharp fall of properties of blades with such coatings because of low adhesion and porosity. The latter is caused by the presence of dropping fraction. In this connection, I consider the introduction of the vacuum arc method into the aircraft engine industry to be unpractical and even destructive. Within 15–20 years, the industry will encounter the problem of choosing a method of application of heat-resistant coatings again. To solve this problem, a large amount of money and a lot of work will be needed. Therefore, it would be much better to begin an intensive research of appli-

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cation of the plasma technology which I consider more perspective”. Unfortunately, at the present moment there is no meaning to the question about the plasma technology development because the powder metallurgy is practically destructed. Therefore, as things now stand, it is thought to be perspective to develop and introduce high-performance methods of surface modification by the vacuum arc coatings, e.g., using high-current pulsed electron-beams to compensate some ills of the vacuum arc method.

2. Materials, equipment and research techniques

As an object of research we chose single-crystal turbine blades serially produced by Chenyshev Machine Building Enterprise. These blades are made of GS26NK alloy and have a 50 μm thick SDP-2 coating applied by the vacuum arc method at installation MAP-1. To investigate the state of material in the surface layers the following methods were used: X-ray microanalysis, scanning electron microscopy, X-ray analysis of crystal structure and polarized light optical metallography. The high-current pulsed electron-beam bombardment [6] of the targets was carried out in accelerator Geza-1. Unlike the previous installations, this accelerator provides pulses of high energy and duration as well as an increased distance between the anode and the target: electron energy: 120 keV; pulse duration: 30 μs; electron beam energy density: 40–42 J/cm^2; beam area: 40 cm^2; nonuniformity of electron beam energy density along the beam cross section: less than 10%.

3. Experimental data and discussion

It is well known that the main process parameter of the high-current pulsed electron-beam bombardment is the pulse energy density (*w*). As the energy density increases, the following processes begin in the subsurface layers of the targets made of refractory alloys: evaporation and melting of the surface layer of material, cratering and crack formation, plasma formation and ablation. These processes determine the physical and chemical state of the bombarded target surface layer material and eventually modify it properties. The results described in [6] allow to suggest that optimal modes of bombardment of samples and blades made of refractory nickel alloys and coated with the NiCrAlY system can be achieved at an energy density of 40–42 J/cm^2 when no craters are formed, strengthening γ’-phase exists and the content of an electron β-phase based on NiAl increases in the coating surface layer. In addition, this mode of bombardment allows decreasing surface roughness from 2.01–2.12 μm to 0.32–0.61 μm.

The high-current pulsed electron-beam bombardment enables to remove (partially or – in some instances – entirely) the main shortcoming of the application of protective coatings using the vacuum-plasma technology, i.e., the presence of dropping fraction in plasma. It is the presence of dropping fraction in plasma during precipitation that decreases the coating adherence and gives rise to the buildup of relatively high porosity which is the root cause of the coating degradation and premature destruction. Repeated recrystallization of the coating material having a depth of 10–20 μm (Figs. 1, 2) ensures a nonporous surface layer, but the thermal stresses arisen as a result of melting and crystallization can lead to the coating peeling off if the system of substrate and coating had low adhesion before the bombardment. Thus, the high-current pulsed electron-beam bombardment can be used as a method of checking the quality of adhesion of the coating to the surface.

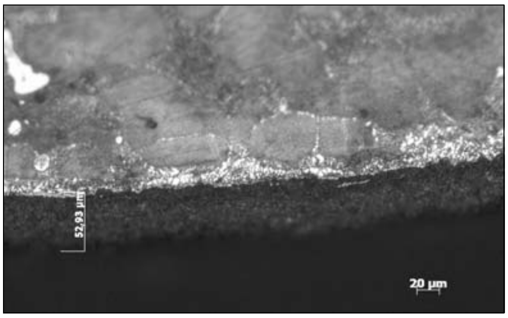

Fig. 1. Microstructure of the surface layer of serial blades made of GS26NK alloy with a NiCrAlY vacuum-plasma coating

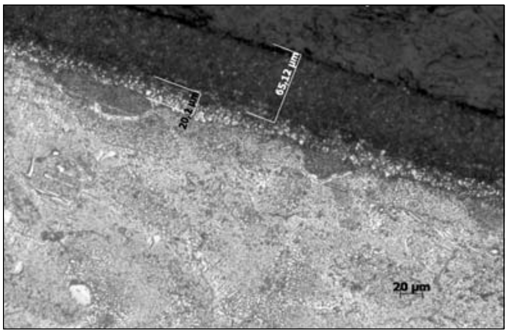

Fig. 2. Microstructure of the surface layer of serial blades made of GS26NK alloy with a NiCrAlY vacuum-plasma coating after the high-current pulsed electron-beam bombardment and vacuum annealing at 1240 °C during 2 h

A finishing heat treatment (annealing at $p_{res} < 10^{-5}$ mm Hg) after the high-current pulsed electron-beam bombardment of samples and blades made of GS26NK alloy improves (according to [6]) the fatigue and corrosion resistance if the duration of the heat treatment is 2 h and the thermal exposure temperature achieves the operation temperature. Fig. 3 and Table 1 show the results of analysis of the blade surface layer physical and chemical state after bombardment using X-ray microanalysis and scanning electron microscopy. The data presented above show the following: some serial single-crystal blades have fairly large grains of 100–200 μm formed by liquation and segregation processes during casting and high-temperature annealing; practically all the blades have polycrystalline layer formed in the area of adhesion between the coating and the substrate as a result of sand blasting during preparatory treatment of the surface before coating and the high-temperature annealing after deposition; the coating formed by the vacuum-plasma high-energy technology is characterized by a high degree of phase and element nonuniformity, this coating has vast areas of low concentration of aluminum and noticeable presence of the heat-resistant alloy components; the last explains the poor heat resistance of the vacuum arc coating; the electron-beam bombardment provides a uniform nonporous layer 12–14 μm in depth with an aluminum concentration of 8.9–9.0 mass % ensuring a higher level of the performance of bombarded blades as compared to that of serial ones [6].

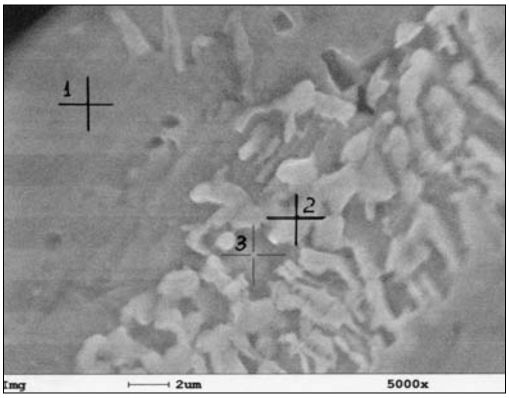

Fig. 3. Microstructure of the surface layer of serial blades made of GS26NK alloy with a NiCrAlY vacuum-plasma coating after the high-current pulsed electron-beam bombardment and vacuum annealing at 1240 °C during 2 h

Table 1. Composition according to X-ray analysis of crystal structure (mass percent) in different points (Fig. 3) of NiCrAlY vacuum-plasma coating after the high-current pulsed electron-beam bombardment and vacuum annealing at 1240 °C during 2 h

No.	Al	Cr	Ni	W	Co	Y
1	8.9	17.5	base	1.0	1.5	0.3
2	4.2	17.0	base	10.0	4.3	0.3
3	11.9	16.0	base	7.0	6.0	0.4

The data presented above show the following: some serial single-crystal blades have fairly large grains of 100–200 μm formed by liquation and segregation processes during casting and high-temperature annealing; practically all the blades have polycrystalline layer formed in the area of adhesion between the coating and the substrate as a result of sand blasting during preparatory treatment of the surface before coating and the high-temperature annealing after deposition; the coating formed by the vacuum-plasma high-energy technology is characterized by a high degree of phase and element nonuniformity, this coating has vast areas of low concentration of aluminum and noticeable presence of the heat-resistant alloy components; the last explains the poor heat resistance of the vacuum arc coating; the electron-beam bombardment provides a uniform nonporous layer 12–14 μm in depth with an aluminum concentration of 8.9–9.0 mass % ensuring a higher level of the performance of bombarded blades as compared to that of serial ones [6].

4. Conclusion

On the basis of the research conducted, a processing procedure of electron-beam modification of the surfaces of the gas turbine engine blades made of GS26NK heat-resistant alloy with NiCrAlY protective vacuum-plasma coating was devised. A fifty blade set was prepared that now undergo a test on a production machine according to an experience certificate (by now, the time of operation is 300 h).

References

[1] E.N. Kablov, *The casting blades of gas turbine engines*, Moscow, MISiS, 2001, pp. 1–632.

[2] Gh.A. Mrochek, B.A. Eizner, and V.I. Ivanov, *The oxidation resistance coatings*, Leningrad, Nauka, 1990, pp. 173–176.

[3] Gh.A. Mrochek, B.A. Eizner, and V.I. Ivanov, EOM **6**, 13 (1989).

[4] A.A. Muboyadghan, Ya.A. Pomelov, and S.A. Budinovskiy, *Aviation materials*, Moscow, VIAM ONTI, 1988, pp. 95–99.

[5] A.A. Muboyadghan and S.A. Budinovskiy, *in Proc. 6th Int. Conf. on Modsification of Materials with Particle Beams and Plasma Flows*, 2002, pp. 561–563.

[6] A.G. Paikin, V.A. Shulov, A.B. Belov et al., Strengthening Technologies and Coatings **2**, 32 (2005).