A study of the effect of electron-beam processing on the surface of samples obtained by additive technologies from cobalt-chromium powder.

E E Dzhafarov¹, K M Erikov¹ and O A Bytsenko¹

¹ MME Chernyshev, Vishnevaya street 7, Moscow, 123362, Russia
E-mail: jafarow.emil2016@yandex.ru

Abstract. Products made of cobalt-chromium made by additive manufacturing methods are widely used in many branches of modern industry (aviation, mechanical engineering, shipbuilding and instrumentation, energy, medicine, etc.). Surface treatment with high-current pulsed electron beams (HPEB) is a promising method for further expanding the scope of these alloys. The article presents studies of the structural and phase state of the surface layer of samples before and after treatment with high-current pulsed electron beams.

1. Introduction
Developing and improving methods for surface treatment of parts and workpieces using concentrated pulsed energy flows (CPEF) has a number of advantages over classical methods of surface mechanical, chemical, and thermomechanical treatments: formation of a unique physical and chemical state of the surface layer material; achievement of record manufacturing accuracy (at the nanometer level) and surface roughness (Ra~0.05-0.06 microns); environmental cleanliness; high performance (the cross-sectional area of energy flows varies from 30 cm² to 1 m², and the pulse duration is from 10 nanoseconds’ to several tens of microseconds).

The use of CPEF has in fact only one drawback: the high science intensity of the developed technologies, due to the need to conduct long-term and expensive studies of the influence of irradiation modes on the physical and chemical state of the material in the surface layers of parts [1].

Relevance of the work. The problem of improving the performance properties of materials, in particular, cobalt-chromium alloys, is one of the most complex in modern materials science. With highly specific mechanical characteristics, it is difficult to form material from these alloys. This disadvantage can be overcome by using various types of surface hardening associated with the use of concentrated energy flows, which can be used to create nanostructured states with a high set of properties in the surface layer. One of the effective and fairly common methods of such structure modification is HPEB. The experience of using this method to date shows that its wide implementation in practice is hindered by the existing gaps in the study of the regularities of the electron-beam effect on the structural and phase state of the processed layer of the product manufactured using additive technologies and its influence on the mechanical properties of these materials. Thus, the authors of this paper chose to focus on obtaining basic knowledge about the influence of high-current pulsed electron beam processing modes on the physical nature of changes in the structural and phase states of surface layers of cobalt-chromium alloys obtained by additive technologies.
2. Materials and research methods

It should be noted that the use of innovative technologies for manufacturing parts requires a new approach to the issue of obtaining parts that have a high level of performance properties of the surface layer. In this case, it is not superfluous to consider the factor of applying technologies for modifying the surface layer using technologies similar in their mechanism to the mechanism of growing parts using additive technologies, and, in particular, SLM technology.

The research was carried out on cylindrical samples made using additive technologies from cobalt chromium powder. Before irradiation, the samples were cut into equal parts to be able to irradiate the same alloy in different modes. Processing with high-current pulsed electron beams was carried out from the outer surface, the roughness of which corresponds to the roughness after creating the samples.

Irradiation of samples was carried out on vacuum pulsed electron beam installations "GEZA-MMP" and "RITM-SP" designed for smoothing the microlief by melting the surface layer of parts and surface modification of metals by pulse hardening, at the following values of the main parameters: for "GEZA-MMP" W=27-35 J/cm², n=3-6 pulses, for "RITM-SP" W=2.3-8.6 J/cm², n=30-60 pulses.

Figure 1. Appearance of the "GEZA-MMP" installation.

Figure 2. Appearance of the "RITM-SP" installation.
At the end of the beam pulse, the heated layer is quickly cooled by the process of thermal conductivity into the depth of the material. As a result, the properties of the surface layer change:

• the microstructure changes - the grain size decreases from hundreds of microns to fractions of a micron, transition to an amorphous state and the formation of nanostructures is possible;
• the phase composition changes, and metastable phases and compounds may appear that cannot be formed under conventional heat treatment methods;
• the phase composition is homogenized, for example, carbides are crushed and uniformly distributed.

Practical consequences of these changes include increasing the hardness, corrosion resistance and wear resistance of the materials surface, reducing the coefficient of friction, increasing the dynamic strength of the products [3].

The state of the surface layers of the samples was analysed using optical microscopy, electron microscopy, electron spectroscopy, roughness measurement and microhardness measurement. Using these methods, it was possible to determine the thickness of the modified layer, obtain the microstructure of samples, determine the chemical composition of the surface layer of samples after irradiation and establish the dependence of surface roughness and microhardness on irradiation modes.

3. Experimental data and their discussion

Based on the previously obtained sequence of one-to-one dependencies (F (irradiation mode) ↔ G (physical and chemical state) ↔ H (properties)) for titanium, heat-resistant, and Nickel alloys produced by traditional methods, six modes of irradiation of cobalt-chromium alloys obtained by additive methods were selected at the "RITM-SP" installation. Based on the results of irradiation on "RITM-SP", the most promising mode was selected, on the basis of which the modes were selected for irradiating samples on "GEZA-MMP".

![Figure 3. Appearance of cobalt-chromium powder samples after irradiation.](image)

Redistribution of elements in surface layer usually manifests itself at low crystallization rates (several cm/min [2]). When processing HPEB, we are dealing with very high crystallization rates \(V\sim10^7\text{K/s}\). For correct interpretation of the data recorded by electron spectroscopy, it is necessary to take into account that in the case of conventional directional crystallization and conventional zone melting, the thickness of the molten zone \(L_m\) is several tens of mm. When irradiated with HPEB on the "RITM-SP", the \(L_m\) values do not exceed 5 mcm (Fig. 4,6), and on the "GEZA-MMP", the \(L_m\) values do not exceed 25 mcm (Fig. 5). Therefore, the redistribution of elements during the crystallization of the material in the molten electron beam zone is quite possible.
Figure 4. Optical microscopy of samples irradiated on the "RITM-SP".

Figure 5. Optical microscopy of samples irradiated with "GEZA-MMP".

Figure 6. Electron microscopy of samples irradiated on the "RITM-SP".
Rather specific conclusions can be drawn from the choice of the energy density in the pulse. These conclusions are based on the following considerations. When irradiating samples, it is advisable to obtain a surface that does not contain macro- and microdefects, which are stress concentrators under fatigue loading. This requirement is met by the surface of a cobalt-chromium sample irradiated in the mode \( W = 35 \, \text{J/cm}^2 \) on "GEZA-MMP" and \( W = 6,2\pm1,2 \, \text{J/cm}^2 \) on "RITM-SP". The microstructure in the surface layer of cobalt-chromium samples is shown in Fig. 7.

It is also worth noting that the study of the microstructure of the selected samples before and after irradiation with HPEB revealed the absence of cracks, which are inherent in traditional processing methods.

![Figure 7. Microstructure of the sample irradiated in the mode \( W = 35 \, \text{J/cm}^2 \), \( n=3 \) on "GEZA-MMP" and \( W = 6,2\pm1,2 \, \text{J/cm}^2 \), \( n=30 \) on "RITM-SP".](image)

In addition, it is desirable to achieve optimal redistribution of elements in the surface layer of targets. From the obtained data, processing a sample of cobalt-chromium with high-intensity pulsed electron beams in the modes \( W = 35 \, \text{J/cm}^2 \); \( n=3 \) and \( W = 6,2\pm1,2 \, \text{J/cm}^2 \); \( n=30 \) allows achieving a preferential yield to the surface of carbon, which contributes to the formation of carbides on the surface, which in turn should lead to an increase in such important performance characteristics as wear resistance, hardness, and corrosion resistance. This theory is confirmed by measurements of microhardness before and after irradiation. Microhardness of samples after irradiation increased on average by 20-25%.

| Table 1. Chemical composition of samples before irradiation |
|-----------------------------------------------------------|
| Chemical composition, %                                    |
| C  | V  | Cr | Si  | Ni | Mn | Mo | S  | P  | Co  |
| 0.01| 0.04| 17.3| 0.62| 12.6| 0.88| 2.0| 0.005| 0.011| 66.53 |
Table 2. Microhardness of samples irradiated with "GEZA-MMP" and "RITM-SP" at load P=20 g.

| № sample’s | Middle kgs/mm² | Irradiated layer kgs/mm² | Edge 1 kgs/mm² | Edge 2 kgs/mm² | Basic material kgs/mm² |
|------------|----------------|--------------------------|----------------|----------------|------------------------|
| 1.1        | 376; 356; 356  | 376; 376; 356            | 336; 402; 402  | 212; 251; 251  |
| 1.2        | 376; 402; 402  | 402; 376; 376            | 426; 446; 426  | 402; 376; 376  |
| 1.3        | 446; 446; 446  | 446; 426; 446            | 446; 426; 446  | 376; 402; 402  |
| 1.4        | 376; 402; 402  | 446; 426; 446            | 402; 376; 402  | 356; 376; 376  |
| 1.5        | 446; 426; 426  | 446; 426; 426            | 446; 446; 426  | 356; 376; 356  |
| 1.6        | 446; 426; 446  | 446; 426; 426            | 402; 376; 402  | 356; 376; 356  |
| 1.7        | 446; 489; 446  | 446; 489; 446            | 426; 446; 446  | 356; 402; 376  |
| 1.8        | 446; 525; 489  | 446; 426; 446            | 426; 489; 446  | 356; 356; 376  |
| 1.9        | 446; 446; 446  | 525; 489; 525            | 489; 525; 525  | 356; 356; 356  |
| 1.10       | 414; 446; 402  | 402; 426; 402            | 402; 402; 414  | 356; 356; 356  |
| 1.11       | 446; 446; 446  | 446; 426; 446            | 402; 402; 414  | 402; 356; 376  |
| 1.12       | 426; 446; 446  | 426; 426; 446            | 426; 446; 426  | 376; 376; 376  |

Another important conclusion about the choice of irradiation modes for samples, in particular, the conclusion about the choice of the required number of pulses, can be made based on these results. Since the surface of irradiated samples is characterized by a high heterogeneity of the structure-phase state distribution, namely, the dislocation density values, these values will not differ after the first pulse, which is associated with the loss of part of the energy for relaxation processes in the surface layer. Thus, from the point of view of the structural-phase state, the optimal number of pulses during electron-beam processing should be n>2 pulses.

The study of the microstructure of samples before and after irradiation with high-current pulsed
electron beams revealed a significant decrease in roughness. When irradiated with "GEZA-MMP", the roughness of cobalt-chromium decreased by 3 times, and when irradiated with "RITM-SP", by 1.5 times.

| № sample's | W, J/cm² | n, pulse | W, J/cm² | n, pulse | Roughness \( R_a \) after irradiation on the GEZA-MMP | Roughness \( R_a \) after irradiation on the RITM-SP |
|------------|---------|---------|---------|---------|---------------------------------|---------------------------------|
| 1          | 27      | 3       | 7.1±1.5 | 60      | 2.2                             | 2.5                             |
| 2          | 30      | 3       | 4.8±1   | 60      | 1.7                             | 2.3                             |
| 3          | 35      | 3       | 6.2±1.2 | 30      | 1.3                             | 2.2                             |
| 4          | 27      | 6       | 4.8±1   | 30      | 1.4                             | 2.5                             |
| 5          | 30      | 6       | 3.9±0.9 | 30      | 1.2                             | 2.3                             |
| 6          | 35      | 6       | 3.1±0.8 | 30      | 1.1                             | 2.1                             |

Initial | 5.8 |

4. Conclusion
The research results presented in this paper allow us to draw the following conclusions:

- The modes of irradiation of HPEB are selected, which lead to optimal redistribution of elements in the surface layer of targets. Processing of HPEB in the modes \( W=35 \, \text{J/cm}^2; \, n=3 \) on "GEZA-MMP" and \( W=6,2±1,2 \, \text{J/cm}^2; n=30 \) on "RITM-SP", allows achieving a preferential output to the surface of carbon, which contributes to the formation of carbides on the surface.
- It is shown that by irradiation with a high-current pulsed electron beam of microsecond duration it is possible to modify a surface with a thickness of 5 microns when irradiated with "RITM-SP" and 25 microns when irradiated with "GEZA-MMP".
- The influence of electron-beam processing modes on the surface roughness and microhardness of cobalt-chromium alloys obtained using additive technologies has been studied. It is shown that using high-current pulsed electron beam processing, it is possible to reduce the surface roughness when irradiated on "GEZA-MMP" approximately 3 times, and on "RITM-SP" 1.5 times. It was also possible to increase the microhardness by an average of 20-25% due to the formation of a layer of carbides on the surface of the samples after irradiation with HPEB.

The study of the microstructure of the selected samples using optical and electron microscopy, before and after irradiation with HPEB revealed the absence of cracks, which are inherent in traditional processing methods. It is shown that a high-current pulsed electron beam of microsecond duration can significantly reduce the complexity of processing parts and is a highly effective tool for modifying the surface of cobalt-chromium alloys obtained by additive technologies.

References
[1] Shulov V A, Teryaev D A, Shirvanyants G G, Engelko V I, Gromov A N and Bytsenko O A 2015 Application of high-current pulsed electron beams for the restoration of properties of the blades of gas-turbine engines Russian Journal of Non-Ferrous Metals 56:333-338 DOI:10.3103/S1067821215030190
[2] Shulov V A, Gromov A N, Teryaev D A and Engelko V I 2015 Application of high-current pulsed electron beams for modifying the surface of gas turbine engine blades University news Powder metallurgy and functional coatings (1):38-48.
[3] Belov A B, Bytsenko O A and Krainikov A V 2012. High-Current Pulsed Electron Beams for Aircraft Engine Construction (Moscow: DEEPAK publishing) 18-20 pp.
