https://doi.org/10.15407/ufm.21.03.345

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PROSPECTS FOR THE APPLICATION OF SURFACE TREATMENT OF ALLOYS BY ELECTRON BEAMS IN STATE-OF-THE-ART TECHNOLOGIES

Recent papers on the application of intense pulsed electron beams for surface treatment of metals, alloys, metalloceramic and ceramic materials are reviewed. The advantages of pulsed electron beam application as compared with laser beams, plasma flows, ion beams are mentioned. Promising trends of the electron-beam processing application are analysed: (1) the surface smoothing, the elimination of surface microcracks with simultaneous change in structural-phase state of the surface layer for creating the high production technologies of finishing treatment of critical metal products of intricate shape from Ti–6Al–4V alloy and titanium, steels of different classes, WC–10 wt.% Co hard alloy, aluminium; (2) the removal of microburrs being formed in manufacturing of precision moulds (SKD11 steel) and biomedical materials (Ti–6Al–4V alloy); (3) the finishing surface treatment of moulds and dies; (4) the improvement of functional properties of metallic biomaterials: stainless steel, titanium and its alloys, the titanium-nickelide-based alloys possessing the shape memory effect, magnesium alloys; (5) the treatment of medical materials and implants; (6) the formation of surface alloys for powerful electrodynamic systems; (7) the improvement of characteristics of aircraft engine and compressor blades; (8) the formation of thermobarrier coatings being applied to combustion-chamber surface; (9) the increase in fatigue service life of steels and alloys; (10) the hardening of rails' tread surface. As shown, at a correct selection of process parame-

Citation: Yu.F. Ivanov, V.E. Gromov, D.V. Zaguliaev, S.V. Konovalov, Yu.A. Rubannikova, and A.P. Semin, Prospects for the Application of Surface Treatment of Alloys by Electron Beams in State-of-the-Art Technologies, *Progress in Physics of Metals*, **21**, No. 3: 345–362 (2020)

ters, such as (i) accelerating voltage, (ii) energy density of electron beam, (iii) pulse number, and (iv) pulse length, it is possible to control thoroughly and/or to manipulate the characteristics of structural-phase state and properties of surface. As noted, the important factor for improvement of the material properties and service duration of devices manufactured from it, there is the modification of structure in order to form a submicro- and nanosize grain (or subgrain) structure.

Keywords: electron-beam processing, surface modification, alloys, prospects for application, nanosize structure.

1. Introduction

In the modern conditions of machines and structures' operation, the problems of increase in material strength, service life, survivability and durability are the main ones. The most critical and unique products, machines and structures are operated in the regimes of cyclic deformation determining the failure even at negligible loads. Their role raises especially for modern highly loaded critical products subjected to cyclic load effect.

One of the promising and approved methods of structural-phase states' modification on surface layers of metals and alloys is electron-beam processing. The application of electron beams as a tool for modification of metal and alloy surface results in the substantial change of structural and phase state of surface layers and, as a consequence, in the increase of corrosion-, wear- and microhardness resistance and fatigue durability unachievable in conventional methods of surface treatment.

Advances in the field of generation of electron beams of pulsed and continuous action [1–3], the development and mastering the corresponding equipment [4–8], the numerous studies carried out in the field of material science of metals and alloys, metalloceramic and ceramic materials processed by electron beams [5, 7, 8–16] prepared the fundamentals of application of such energy sources in various fields of industry, building industry, and medicine [5, 6, 17, 18]. These directions continue to be developed actively as evidenced by numerous papers [19–21] where it is stated that electron-beam processing is beyond doubt a promising technology having no alternative in a number of cases nowadays.

Currently, the following perspective directions of the application of electron-beam processing of metals and alloys, metal ceramic materials by pulsed electron beam are revealed:

- the surface smoothing, the elimination of surface microcracks with simultaneous change in structural-phase state of surface layer that may be used and is used, in a number of cases, for creating the high production technologies of finishing treatment of critical metal products of intricate shape from Ti–6Al–4V alloy and titanium [18, 22–26], steels of different classes [17, 19, 24, 27–32], WC–10 wt.% Co hard alloy [33], aluminium [34];

- the removal of microburrs being formed in manufacturing of precision moulds (SKD11 steel) and biomedical materials (Ti–6Al–4V alloy) [35];
- the finishing surface treatment of moulds and dies [17, 19, 29, 30, 32, 33];
- the improvement of functional properties of metallic biomaterials: stainless steel [31, 36–43], titanium and its alloys [18, 20, 22, 23, 26, 28, 43–48], the alloys based on titanium nickelide possessing the shape memory effect [49], magnesium alloys [50–54];
- the treatment of medical materials and implants [18, 22, 55, 56];
- the formation of surface alloys for powerful electrodynamic systems [57, 58];
- the improvement of characteristics of aircraft engine and compressor blades [5, 59–61];
- the formation of thermal-barrier coatings being applied to combustion chamber surface [62];
- the increase in fatigue service life of light alloys;
- the hardening of tread surface of railroad rails.

2. Application of Electron-Beam Processing

This section deals with consideration of the examples of application of electron-beam processing of metals and alloys applied and/or recommended for using in industry.

As shown in Ref. [34], in the developed method of large-area electron beam irradiation, the high-energy density of beam may be obtained without its focusing. Therefore, the electron-beam processing of large area surface with diameter of 60 mm may be used for instantaneous melting and evaporation of material surface layer that extends the possibilities of highly effective processing of surface. However, if a billet has holes, the electron beam concentrates on the entry edge or internal wall of a hole. Thus, the difficulties emerge in smoothing the bottom surface of the hole. The performed studies showed that the effects of surface smoothing for nonmagnetic billet from alloys based on aluminium might be increased by installing the magnet block under the billet because electrons had a tendency to concentrate along magnetic lines by magnetic field. In this investigation, the smoothing of the bottom surface of the hole was experimentally tested by installing of magnet block under the working part in electron beam irradiation of large-area samples. The extension of smoothing area of bottom surface was tested by installing the through hole in the centre of magnet block. It was clarified that the wide part of a hole bottom surface might be smoothed with large-area irradiation by installing the magnet block under the billet.

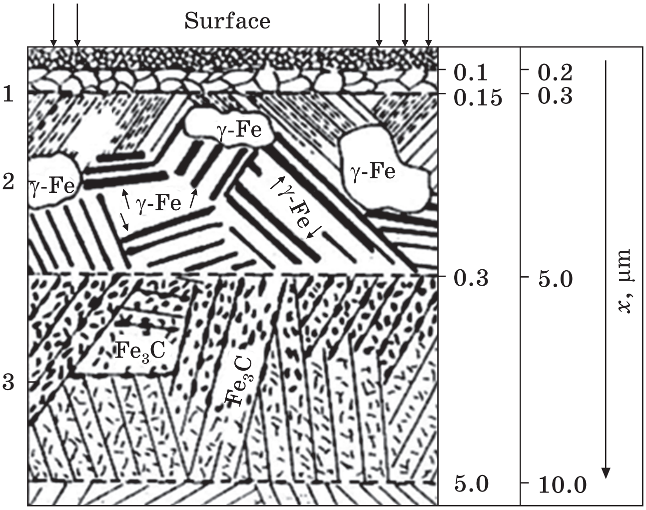

Fig. 1. Diagram of sample composition of prequenched steel 45 (electron-beam pulse duration 0.8 μs, energy density 2.2 J/cm^2) [81, 82]

The surface roughness decreased up to 3.0 μm in the surface area of a hole bottom. When the hole diameter amounted to 20 mm and the hole depth was no less than 40 mm, the 10 mm diameter smoothing area was obtained by means of magnet block. Moreover, the smoothing area was substantially extended by installing the through hole of the corresponding diameter in magnetic field.

As shown in Ref. [63], according to the results of investigation analysis published in papers [28, 51, 64–80], metals such as Al, Mg, and Ti as well as alloys on their base were preferable due to the small weight for using in applications for which the high productivity and excellent combination of specific properties were decisive. A wider application of these materials in aerospace, automobile, and biomedical branches of industry requires a significant improvement of their surface properties. Surface engineering is the economical and viable method for improvement of material surface properties such as hardness, wear- and corrosion resistance, fatigue strength, and oxidation resistance. Among different methods of surface modification, the high-energy processes based on pulsed beam application are very promising. The laser beams, plasma flows, powerful ion and electron beams refer to such methods.

The surface treatment by pulsed electron beam has some advantages as compared to other methods of surface modification. A brief comparison of surface treatment by pulsed electron beam (PEB) with other methods of the surface modifications are contained in Table [63]. The analysis of the results shown in Table [63] as well as in other papers [5–8] shows that the modification methods of structure and properties of metals and alloys, metalloceramic and ceramic materials based on pulsed electron beam application are the promising ones. These methods have noticeable advantages in comparison with other methods that facilitate the larger-area processing, considerable penetration depth along with low energy loss for material ionization. When an electron beam bombards the surface of the metal, the material undergoes the following transformations in the layers located successively in different depth: (i) the surface molten layer; (ii) the thermal effect zone; (iii) the zone of high stresses appearing under the effect of shock wave being formed as a result of material bombardment by electron beam.

Figure 1 shows results obtained in studying the cross-section of the irradiated samples of pre-quenched steel 45 (Fe–0.45C) [81, 82]. The structural analysis of cross-section of irradiated samples was carried

Table. **Comparison of the surface processing opportunities by pulsed electron beam as compared to other methods commonly applied for the surface modifications [63]**

Other Surface Modification Methods	PEB Surface Treatment
1. Chemical Processes and Conversion Coating	
Major Drawbacks (a) Use of toxic chemicals (*e.g.*, chromate solutions for magnesium-based materials) (b) Adhesion-related issues with substrates (*i.e.*, interface in coating and plating)	**Advantage of PEB Treatment** Absence of such issues
2. Friction Stir Processing	
Major Drawbacks (a) Physical contact of tool with the surface, which distorts dimensional finish	**Advantage of PEB Treatment** No physical contact with surface of the selected material
3. Pulsed Laser Beam Treatment	
Major Drawbacks (a) Low absorption depths (*e.g.*, 0.02 μm for laser pulse length ~10 to 50 ns) (b) Reflection up to 90% of incident energy (energy loss) (c) Limited to small surface area	**Advantages of PEB Treatment** (i) High absorption/melt depths (*e.g.*, 2.6 μm for the electron beam pulse length of 50 ns) (ii) Only 5% to 10% of incident energy is reflected (iii) Allows processing on large surface area (up to several 100 cm^2)
4. Pulsed Plasma Beam Treatment	
Major Drawbacks (a) Erosion of the material used for the electrode materials (b) Deposition of electrode ions on the test sample (c) Formation and presence of toxic products	**Advantage of PEB Treatment** Absence of such issues
5. Pulsed Ion Beam Treatment	
Major Drawbacks (i) Large loss in ionization (ii) Small penetration depth (0.05 to 1.0 mm at 100 to 1000 keV kinetic energy)	**Advantage of PEB Treatment** (i) Small loss ionization (ii) Large penetration depth (10 to 500 mm at 100 to 1000 keV kinetic energy)

out by the methods of transmission electron diffraction microscopy for different electron-beam pulse numbers. The analysis showed that the material has a gradient structure throughout the depth consisting of several layers (Fig. 1). At a single irradiation, *a* ≈ 0.1 μm thick nanocrystalline layer consisting of α (with b.c.c. lattice solid solution based on Fe) and γ (f.c.c. lattice Fe-based solid solution) phases in approximately equal fractions with average grain size of ≈30 nm is formed near the surface. According to the thermodynamical calculations [83, 84], the layer formed as a result of pulsed melting (the lifetime of the melt is ≈0.5 μs) and subsequent high-velocity (up to $\sim 10^{10}$ K/s) quenching from the melt. The velocity of the solidification front propagation near the surface is ≈5 m/s. An α-phase-based sublayer of ≈0.1 μm thick with average grain size of ≈200 nm is formed under the nanocrystalline layer. It follows from the thermal calculations that the sublayer emerged due to the fast ($\approx 5 \cdot 10^9$ K/s) quenching from the state characterized by the presence of solid phase islands located in the melt [85]. At the depths up to 0.3–0.5 μm, a sublayer with the mixed $(\alpha + \gamma)$ structure and retained morphology of initial martensite phase was formed. For the depths, ≥0.3–0.5 μm, a ferrite–carbide mixture characteristic of martensite subjected to high temperature tempering was observed. At the larger depths, the steel structure was similar to the initial one. In case of the multiple irradiation (up to $n = 300$ electron-beam pulses), the distinctive layer-by-layer construction of the material retained. However, the gradual increase in the initial temperature and the possible presence of pulses with the increased energy density [86] resulted to the increase in the thickness of near-surface nanocrystalline $(\alpha + \gamma)$ layer up to ≈0.2 μm and thermal effect zone up to ≈10 μm at $n = 300$ [81, 82].

Correct selection of the process parameters such as (a) the accelerating voltage, (b) energy density of electron beam, (c) pulsed number, and (d) pulse duration makes possible to control thoroughly and/or to manipulate the characteristics of structural phase state and surface properties. At electron-beam processing of light metals surface (Al, Mg, and Ti) as well as the alloys on their base, one of the several microstructural transformations is possible [63]:

(i) the selective enrichment with alloying elements of surface layer;
(ii) the formation of protective surface layer;
(iii) the formation of ultradisperse (nanosize) grain;
(iv) the dispersion of second phase inclusions;
(v) the formation of nonequilibrium phase due to rapid solidification;
(vi) the generation of high dislocation density at the expense of shock wave effect.

For the improvement of material properties and duration of operation of products made of this material, the main factor is a structural modification for the formation of submicro- and nanosize grains (or

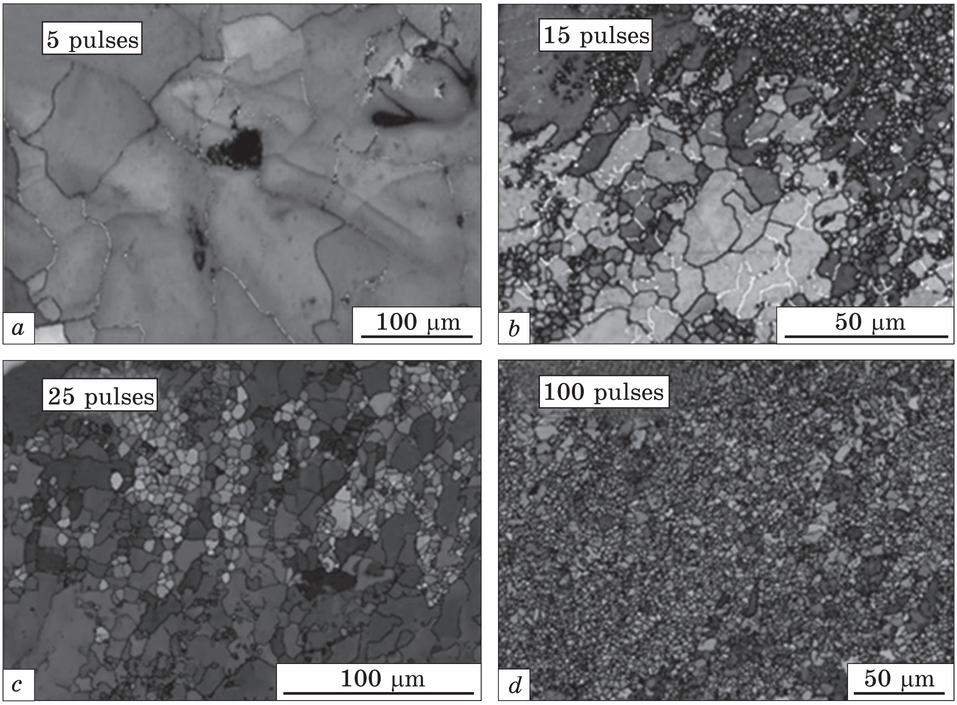

Fig. 2. Evolution of grain size in aluminium-rich zone of Al–17.5Si alloy processed by PEB for different pulse number [66]

subgrain structure) [87–93]. The surface melting and superfast solidification occurring in pulsed electron-beam processing enable the grain structure of nanosize region to be formed in material surface layer. The process may be controlled via changing the parameters of electron beam (the energy density, the duration and number of pulses) [7, 8, 11, 63].

For Al–17.5Si alloy, the formation process of nanosize grain structure was realized through increasing the pulse number of electron beam irradiation from 5, 15, 25 to 100 (Fig. 2) [66].

As established, after the pulsed electron-beam processing, the surface melted layer of Al–Si alloy contained the intermediate Al- and Si-rich zone. The thin nanosize crystals of silicon of nearly spherical shape were discovered in silicon-rich zone surrounded by α-Al. The grains of free aluminium had the cellular structure whose sizes amounted to 100 nm. The intermediate zone contained the superthin eutectic phases. As the number increases, the dimension of silicon-rich zone grows; silicon diffuses gradually to the neighbouring zone providing the places of nucleation for the formation of ultrathin grains of aluminium [66].

In the paper [94], authors considered and summarized the results of the investigation of the formation of submicro-nanocrystalline struc-

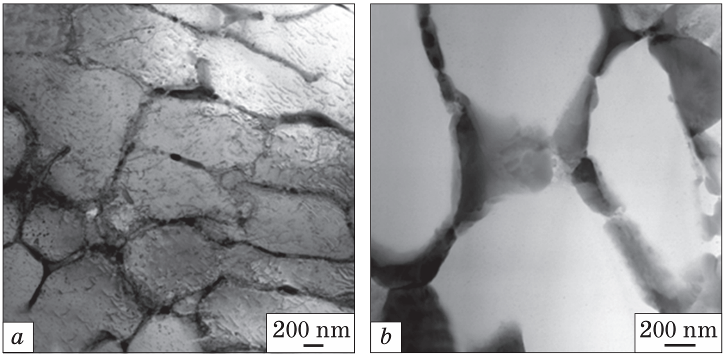

Fig. 3. Cellular crystallization structure of silumin irradiated by electron beam (parameters: 25 J/cm^2, 150 μs, 3 pulses) [94]

ture in Al–11Si–2Cu alloy irradiated by intense pulsed electron beam. The parameters [94] were as follow: the accelerated energy of electrons — 17 keV; the energy density of electron beam — 10, 15, 20, 25, 30, 35 J/cm^2; the pulse duration of electron beam — 150 μs; the pulse number — 3; the pulse repetition rate — 0.3 s^{-1}.

It has been determined that the treatment of Al–Si alloy by pulsed electron beam results in the formation of cellular-type structure (Fig. 3) [94]. The thickness of cellular crystallization structure layer reaches 40 μm. The average size of high velocity crystallization cells of the surface layer equals to 0.4±0.11 μm. With the larger distance from irradiation surface, the average sizes of crystallization cells increase, and at the lower boundary with cellular structure, they reach the values of 0.65±0.22 μm.

The surface layer of silumin with cellular crystallization structure is characterized by the presence of lamellar eutectic grains (Fig. 4). The first eutectic grains are observed in the layer located at ≈15 μm depth. When the distance from irradiation surface increases, the relative content of eutectic grains grows. The eutectic grains are located as islands or interlayers between the high velocity crystallization cells of aluminium. The sizes of eutectic grains are close to those of Al-based solid solution grains (the crystallization cells). The transverse sizes of eutectic grains vary in the limits from 25 nm to 50 nm.

The revealed microstructural modifications of silumin are helpful in the improvement of surface properties, namely, the hardness,

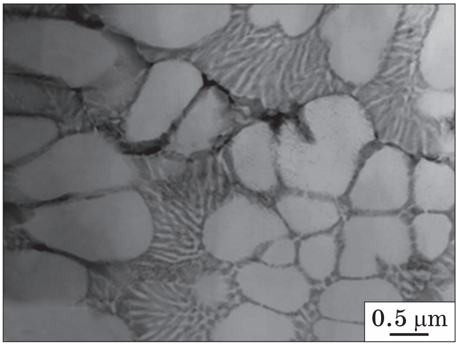

Fig. 4. Structure of silumin layer irradiated by the electron beam located at ≈30 μm depth (25 J/cm^2, 150 μs, 3 pulses) [94]

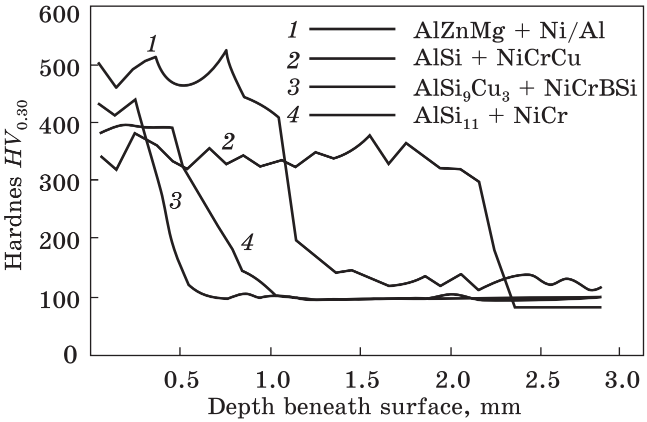

Fig. 5. Hardness profiles of Al-based alloys subjected to the electron-beam processing [101]

wear and corrosion resistance, fatigue and oxidation resistance, and many other properties sensitive to material surface state. Due to this, the properties of light metals/alloys processed by pulsed electron beams increase substantially as compared with the unprocessed analogue.

As it has been noted above, the electron-beam processing of metal and alloy surface is accompanied by high and even super-high (up to 10^9 K/s) rates of cooling contributing to the formation of silumin structure with Al grains (the high velocity crystallization cells) of 250–600 nm and silicon crystals within the 100 nm in size. They have a round shape and are randomly distributed in the modified volume of the alloy [94–96]. In the paper [97], the technique based on the application of the above-mentioned fact has been developed. It has been shown that the high cooling rate ($6 \cdot 10^2$ K/s) of AlSi7Mg0.3 alloy provides a significant refinement of eutectic silicon particles (to 2–3 scale divisions of 6 stage Chai–Bäckerud scale) immediately after pressure application (about 100 MPa) at solidification of the casting with forced melt flow. The similar spheroidizing heat treatment not only increases the properties of castings but also gives the economic advantages due to the possibility of heating temperature shortening for quenching.

As noted in References [98–101], the industrial application of electron-beam processing of products made of aluminium and Al-based alloys is especially promising in automobile industry, *viz.*, in a wide range of surface technologies. It is mentioned that electron-beam processing is successively used for the decrease in porosity of cast aluminium alloys (silumins), porous layers obtained by spraying and sintered materials. The good, reasonable, and adequate results of effective application of electron-beam processing are obtained in alloying, dispersing of structure or plating of alloys based on iron, aluminium, titanium, and magnesium. Figure 5 shows the results illustrating the effect of surfacing treatment through electron beam on the mechanical properties of alloys based on aluminium.

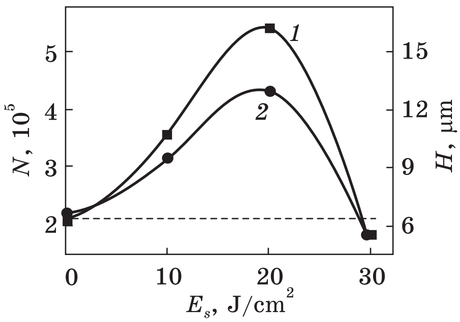

Fig. 6. Dependences of cycle number to failure N (curve *1*) and surface layer thickness H separated by micropores from the base (curve *2*) on energy density of electron beam E_S. Dotted line marks the fatigue life value of steel in the initial state (before electron-beam processing) [111–113]

As shown in series of papers [76, 78, 102–108], the silumin surface irradiation by high-intense pulsed electron beam (with the parameters of 20 J/cm^2, 150 μs, and 5 pulses) allows enhancement of silumin fatigue life in 3.5 times. It is detected that the main reasons of the increase in fatigue life of silumin irradiated by intense pulsed electron beam are the formation of polyphase submicro- and nanosize structure in the surface layer, the refinement of large silicon plates to nanosize state. The electron-beam processing (EBP) of silumin in the regime of 20 J/cm^2, 150 μs, and 5 pulses provides the maximum increase in fatigue life. Such EBP regime allows (i) 2-fold increase in critical crack length thereby increasing the service life of material working capacity, (ii) 1.6-fold increase in safety factor of material operation, (iii) 2.7-fold decrease in crack step in one cycle of fatigue loading that results in a higher resistance to fatigue crack propagation.

For commercially pure titanium, the electron-beam processing with energy density of 25 J/cm^2 results in 2.2-fold increase in cycles' number to failure [109–110]. The physical reason of the increase in fatigue life of commercially pure titanium of VT1-0 grade irradiated by intense pulsed electron beam is the formation of lamellar substructure initiated by high-velocity crystallization of titanium surface layer and the decrease in average dislocation density $\langle p \rangle$.

The substantially important feature of tread surface modification of railroad rails by low-energy high-intense electron beams is the absence of the pronounced interface between the modified layer and material bulk. It determines the good damping properties of the material under mechanical and temperature external effects by preventing the premature nucleation and propagation of brittle microcracks leading to fatigue [111–113] from the surface to the main material bulk.

The fatigue tests of steel have revealed the dependence of material life on the energy density of electron beam E_S (Fig. 6, curve *1*). It is clearly seen that the maximum effect (≈2.5-fold increase in fatigue life of steel) is observed at E_S = 20 J/cm^2.

It has been detected that fatigue failure of steel is accompanied by the formation of ≈10 μm thick sublayer. On the interface of this sublayer with the main material bulk, there are the micropores. The circumstance permits one to suggest that fatigue failure of steel is initiated in a subsurface layer.

The process of pore formation is manifested the most brightly in studying the failure surface of steel processed by electron beam at energy density of electron beam of 10 J/cm^2. In this case, the pore sizes vary in the limits from 1 to 6 μm. In a steel processed by electron beam at a larger energy density of beam (20–30 J/cm^2), the pore sizes are substantially smaller (0.3–1.0 μm). The lines being formed by the pores are pronounced less clearly and locate at a definite distance from irradiation surface correlating with the change in fatigue life of steel (Fig. 6, curve *2*).

It has been shown that the primary site of stress concentrator formation in steel irradiated by electron beam is the interface of high velocity crystallization layer and thermal effect layer (the bottom of the melt bath). It has been determined that the increase in fatigue life of steel irradiated by electron beam is caused by the formation of acicular profile of the interface leading to the dispersion of stress concentrators and contributing to a more homogeneous plastic flow in the substrate [111–113].

3. Conclusion

We carried out brief review of the available results published in the articles dealing with the study of the effect of pulsed electron beams on structure and properties of surface layer of metals and alloys. The analysis of the published papers allows suggesting that the treatment of industrial materials by pulsed electron beam will be implemented progressively in order to become the basis of the future modification technologies for surface engineering of parts and products for wide spectrum of critical applications.

Acknowledgements. The research was supported by Russian Research Foundation grant (project no. 19-79-10059).

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Received 17.04.2020;
in final version, 03.07.2020

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ПЕРСПЕКТИВИ ЗАСТОСУВАННЯ ПОВЕРХНЕВОГО ОБРОБЛЕННЯ СТОПІВ ЕЛЕКТРОННИМИ ПУЧКАМИ В СУЧАСНИХ ТЕХНОЛОГІЯХ

Оглянуто останні роботи щодо застосування інтенсивних імпульсних електронних пучків для поверхневого оброблення металів, стопів, металокерамічних і керамічних матеріалів. Зазначено переваги використання електронних імпульсних пучків порівняно з променями лазера, потоками плазми, йонними пучками. Проаналізовано перспективні напрями використання електронно-пучкового оброблення: (1) вигладжування поверхні, позбавлення від поверхневих мікротріщин із одночасною зміною структурно-фазового стану поверхневого шару для створення високопродуктивних технологій фінішного оброблення відповідальних металевих виробів складної форми із титанового стопу Ti–6Al–4V і титану, криць різноманітного класу, твердого стопу WC–10 ваг.% Co, алюмінію; (2) видалення мікрообшарів і мікрозадирок, що утворюються при виготовленні прецизійних прес-форм (криця SKD11) і біомедичних виробів (стоп Ti–6Al–4V); (3) фінішне оброблення поверхні прес-форм і штампів; (4) поліпшення функціональних властивостей металічних біоматеріалів: неіржавійної криці, титану та його стопів, стопів на основі нікеліду титану, що виявляють ефект пам'яті форми, стопів маґнію; (5) оброблення виробів медичного призначення й імплантатів; (6) формування поверхневих стопів для потужних електродинамічних систем; (7) поліпшення характеристик лопаток авіаційних двигунів і лопаток компресорів; (8) формування термобар'єрних покриттів, що наносяться на поверхню камер згоряння; (9) підвищення утомного ресурсу криць і стопів; (10) зміцнення поверхні катання рейок. Показано, що при правильному виборі параметрів процесу, таких як (а) пришвидшувальна напруга, (б) густина енергії пучка електронів, (в) кількість імпульсів і (г) тривалість імпульсу, можливий ретельний контроль і/або маніпулювання характеристиками структурно-фазового стану та властивостей поверхні. Зазначено, що для поліпшення властивостей матеріалу та тривалости експлуатації виробів з нього важливим чинником є модифікування структури з метою формування субмікро- та нанорозмірного зерна (або субзеренної структури).

Ключові слова: електронно-пучкове оброблення, модифікування поверхні, сплави, перспективи застосування, нанорозмірна структура.