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Improvement of Functional Properties of Alloys by Electron Beam Treatment

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Abstract—This article presents an overview of Russian and Western works on the application of intensive pulse electron beams for surface treatment of metals, alloys, metal ceramics and ceramic materials. Application advantages of electron pulse beams are highlighted in comparison with laser beams, plasma flows, ion beams. Promising trends of electron beam treatment are analyzed: (1) surface smoothing, elimination of surface microcracks with simultaneous modification of structural phase state of surface layer in order to develop high performance technologies of finishing treatment of critical metal items of complicated shape made of Ti–6Al–4V alloy and titanium, steel of various grades, WC–10% Co solid alloy, aluminum; (2) elimination of micro-burrs formed upon fabrication of precision compression molds (SKD11 steel) and biomedical items (Ti–6Al–4V alloy); (3) finishing surface treatment of compression molds and dies; (4) improvement of functional properties of metallic biomaterials (stainless steel, titanium and its alloys, alloys based on titanium nickelide with shape memory effect, magnesium alloys; (5) treatment of medical items and implants; (6) formation of surface alloys for powerful electrodynamic systems; (7) improvement of specifications of blades of aircraft engines and compressor blades; (8) formation of thermal barrier coatings applied onto surfaces of combustion chambers. Upon correct selection of process variables, such as boosting voltage, electron beam energy density, as well as number and duration of pulses, it is demonstrated that thorough control and/or manipulation of characteristics of structural phase state and surface properties are possible. In order to improve material properties and to increase operation lifetime of items, the important factor is the structure modification aiming at the formation of submicro- or nanoscale grain (or subgrain structure).

Keywords: electron beam treatment, surface modification, metals, alloys, steels, application prospects, nanoscale structure

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INTRODUCTION

Successes in the generation field of electron beams of pulse and continuous action [1], development and implementation of respective equipment [2], numerous studies in the field of material sciences of metals and alloys, as well as metal ceramics and ceramic materials treated by electron beams [3–5] initiated the use of these energy sources in various fields of industry, building and medicine. The intensive development of these trends continues. It is assumed in numerous works [6, 7] that treatment by electron beam is of course a promising technology, which in some cases has no alternative at present.

The main promising trends of electron beam treatment of metal, alloys and metal ceramics are as follows:

— surface smoothing, elimination of surface microcracks with simultaneous modification of structural phase state of surface layer in order to develop high performance technologies of finishing treatment of critical metal items of complicated shape made of Ti–6Al–4V alloy and titanium [8–9], steel of various grades [10, 11], WC–10% Co solid alloy [12], aluminum [13];

— elimination of micro-burrs formed upon fabrication of precision compression molds (SKD11 steel) and biomedical items (Ti–6Al–4V alloy) [14];

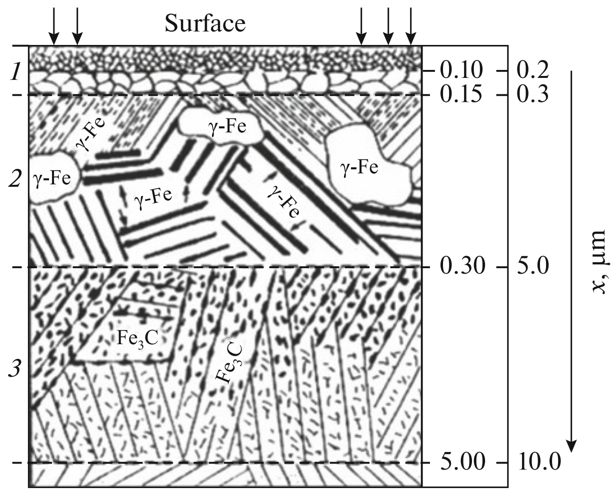

Fig. 1. Schematic view of pre-quenched steel 45 modified by electron beam (duration of electron beam pulse: 0.8 μs, energy density: 2.2 J/cm^2) [32].

— finishing surface treatment of compression molds and dies [10, 11];

— improvement of functional properties of metallic biomaterials, stainless steel [15], titanium and its alloys [8, 9, 16, 17], alloys based on titanium nickelide with shape memory effect [18], magnesium alloys [19];

— treatment of medical items and implants [20];

— formation of surface alloys for powerful electrodynamic systems [21];

— improvement of specifications of blades of aircraft engines and compressor blades [22];

— formation of thermal barrier coatings applied onto surfaces of combustion chambers [23];

— treatment of rail rolling surface [24–26].

EXAMPLES OF USAGE OF ELECTRON BEAM TREATMENT OF METALS AND ALLOYS

It was demonstrated in [27] on the basis of the works [28–30] that light alloys due to low weight are preferred for operation, when high production efficiency and superior combination of specific properties are critical. Wider application of these materials in aerospace, automobile and medical industries requires for significant improvement of their surface properties. Engineering of surface is a cost efficient and viable method of improvement of such material surface properties as hardness, wear resistance, corrosion resistance, fatigue strength, and resistance against oxidation.

Analysis of the experimental results [1–3, 27] demonstrates that the modification methods of surface structure and properties of metals and alloys, metal ceramics and ceramic materials based on the use of pulse electron beams are characterized by noticeable advantages in comparison with other methods: possibility to treat higher surface areas; significant penetration depth; and low energy loss for ionization of material. Upon surface bombardment of treated material by electron beam, the transformations occur in the layers located consecutively at various depth:

— surface molten layer;

— area of thermal influence;

— area of high stresses occurring under the impact of shock wave, which is formed as a consequence of material bombardment by electron beam.

Figure 1 illustrates the results obtained during transmission electron diffraction microscopy of transversal cross section of preliminary quenched steel 45 (Fe–0.45C) [31].

Structural analysis of transversal cross section of irradiated specimens by transmission electron diffraction microscopy revealed that, irrespective of the number of influencing pulses of electron beam, the material has a gradient structure over depth comprised of several layers (Fig. 1). Upon single irradiation, a nanocrystalline layer with the thickness of about 0.1 μm is formed near the surface, which is comprised of grains of α phase (BCC solid solution based on iron) and γ phase (FCC solid solution based on iron) in approximately equal fractions with the average grain size of about 30 nm. According to thermal analysis [32], this layer is formed as a consequence of pulse melting (lifetime of the melt is about 0.5 μs) and subsequent fast (up to 10^{10} K/s) quenching from the melt. The travelling speed of solidification front near the surface reaches approximately 5 m/s. Under the nanocrystalline layer, a sublayer is formed with the thickness of about 0.1 μm based on α phase with average grain size of 200 nm.

Upon correct selection of process variables, such as boosting voltage, energy density of electron beam, number and duration of pulses, thorough control is possible and/or manipulation of characteristics of structural phase state and surface properties.

In order to improve properties of material and to increase operation lifetime of items, the important factor is modification of structure aiming at the formation of submicro- or nanoscale grain (or subgrain structure) [33]. Surface melting and extra fast solidification occurring upon pulse electron treatment allow to form grain structure of nanoscale range in the surface layer of material. This process can be controlled by varying parameters of electron beam (energy density, duration and number of pulses) [2, 3, 27].

It was established [34] that treatment of Al–Si alloy by pulse electron beam leads to formation of cellular structure. The layer thickness with the structure of cellular crystallization reaches 40 μm. The average size of cells of high-speed crystallization of surface layer is

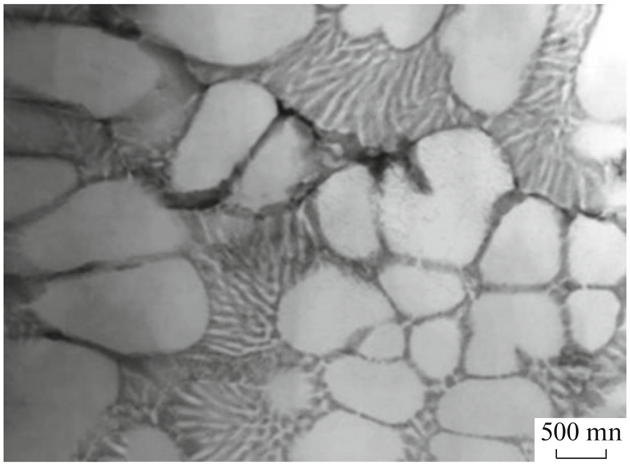

Fig. 2. Structure of silumin layer located at the depth of about 30 μm after irradiation by electron beam (25 J/cm^2, 150 μs, 3 pulses) [35].

0.4 ± 0.11 μm. At higher distance from the irradiated surface the sizes of crystallization cells increase and at lower bottom of the layer with cellular structure reach 0.65 ± 0.22 μm.

The surface layer of silumin with the structure of cellular crystallization is characterized by the grains of lamellar eutectics (Fig. 2). The first eutectics grains are detected in the layer located at the depth of about 15 μm. While moving away from the irradiation surface, the relative content of the eutectics grains increases. The eutectics grains are located as islands or interlayers between the cells of high-speed crystallization of aluminum. The sizes of the eutectics grains are close to those of the grains of solid solution based on aluminum (crystallization cells). The transversal sizes of the eutectics lamellas vary in the range from 25 to 50 nm.

The revealed microstructural modifications of silumin promote improvement of surface properties, namely: hardness, wear resistance, corrosion resistance, fatigue resistance, resistance against oxidation, and many other properties, sensitive to the state of material surface. Thus, the properties of light metals and alloys treated by pulse electron beams are significantly improved in comparison with untreated analogs [34].

An exceptionally important feature of modification of rail rolling surface by low energy high intensity electron beams is the absence of expressed interface between the modified layer and the bulk of material, which determines good damping properties of material during mechanical and temperature external impacts, prevents early formation and propagation of brittle cracks from the surface to the main bulk of material, which leads to destruction [24–26].

The regime of irradiation by high intensity electron beam (energy density of 25 J/cm^2) was detected, which allows to increase the fatigue lifetime of rail steel by 2.5 times. It was demonstrated that the predominant place of formation of stress concentrators in the electron beam irradiated steel is the interface between the high-speed crystallization layer and the thermal impact layer (molten bath bottom). It was established that the increase in fatigue lifetime of the electron beam irradiated steel is stipulated by formation of acicular profile of interface, which leads to dispersion of stress concentrators and promotes more homogeneous flow in the substrate [24–26].

CONCLUSIONS

This brief analysis of the published experimental results regarding the impact of electron pulse beams on the surface layer's structure and properties of metals and alloys makes it possible to conclude that treatment of commercial materials by electron pulse beams is the basis of future modification technologies aiming at engineering of surfaces of items and products within a wide range of critical applications.

REFERENCES

1. Ozur, G.E. and Proskurovskii, D.I., *Istochniki nizkoenergeticheskikh sil'notochnykh elektronnykh puchkov s plazmennym anodom* (Source of Low-Energy High-Current Electron Beams with Plasma Anode), Koval', N.N., Ed., Novosibirsk: Nauka, 2018. doi https://doi.org/10.15372/Sources2018OGE
2. *Evolutsiya struktury poverkhnostnogo sloya stali, podvergnutoi elektronno-ionno-plazmennym metodam obrabotki* (Evolution of Surface Layer Structure of Steel Subjected to ElectronIonPlasma Treatment), Koval', N.N. and Ivanov, Yu.F., Eds., Tomsk: Izd-vo Nauchn.-Tekh. Literatury, 2016.
3. Ivanov, Yu.F., *Elektronno-ionno-plazmennaya modifikatsiya poverkhnosti tsvetnykh metallov i splavov* (Electron-Ion-Plasma Modification of Surface of Non- Ferrous Metals and Alloys), Tomsk: Izd-vo Nauchn.-Tekh. Literatury, 2016.
4. Gromov, V.E., Ivanov, Yu.F., Vorobiev, S.V., and Konovalov, S.V., *Fatigue of Steels Modified by High Intensity Electron Beams*, Cambridge: Int. Science Publ, 2015.
5. Uno, Y., Okada, A., Uemura, K., and Raharjo, P., Method for surface treating a die by electron beam irradiation and a die treated thereby, US Patent 7049539, 2006.
6. Murray, J.W., Kinnell, P.K., Cannon, A.H., Bailey, B., and Clare, A.T., Surface finishing of intricate metal mould structures by large-area electron beam irradiation, *Precis. Eng.*, 2013, vol. 37, no. 2, pp. 443–450. https://doi.org/10.1016/j.precisioneng.2012.11.007
7. Goriainov, V., Cook, R.B., Murray, J.W., Walker, J.C., Dunlop, D.G., Clare, A.T., and Oreffo, R.O.C., Human skeletal stem cell response to multiscale topography induced by large area electron beam irradiation

surface treatment, *Front. Bioeng. Biotechnol.*, 2018, vol. 6, p. 91.
https://doi.org/10.3389/ fbioe.2018.00091

8. *Manufacturing Techniques for Materials. Engineering and Engineered*, Srivatsan, T.S., Sudarshan, T.S., and Manigandan, K., Eds., Boca Raton, Fla.: CRC Press, 2018.
9. Okada, A., Uno, Y., Yabushita, N., Uemura, K., and Raharjo, P., High efficient surface finishing of bio-titanium alloy by large-area electron beam irradiation, *J. Mater. Process. Technol.*, 2004, vol. 149, nos. 1–3, pp. 506–511.
https://doi.org/10.1016/j.jmatprotec.2004.02.017
10. Tokunaga, J., Kojima, T., Kinuta, S., Wakabayashi, K., Nakamura, T., Yatani, H., and Sohmura, T., Large-area electron beam irradiation for surface polishing of cast titanium, *Dental Mater. J.*, 2009, vol. 28, no. 5, pp. 571–577.
https://doi.org/10.4012/dmj.28.571
11. Uno, Y., Okada, A., Uemura, K., Raharjo, P., Sano, S., Yu, Z., and Mishima, S., A new polishing method of metal mold with large-area electron beam irradiation, *J. Mater. Process. Technol.*, 2007, vols. 187–188, pp. 77–80.
https://doi.org/10.1016/j.jmatprotec.2006.11.080
12. Okada, A., Okamoto, Y., Uno, Y., and Uemura, K., Improvement of surface characteristics for long life of metal molds by large-area EB irradiation, *J. Mater. Process. Technol.*, 2014, vol. 214, no. 8, pp. 1740–1748.
https://doi.org/10.1016/j.jmatprotec.2014.02.028
13. Okada, A., Kitada, R., Okamoto, Y., and Uno, Y., Surface modification of cemented carbide by EB polishing, *CIRP Ann. Manuf. Technol.*, 2011, vol. 60, no. 1, pp. 575–578.
https://doi.org/10.1016/j.cirp.2011.03.107
14. Shinonaga, T., Okada, A., Liu, H., and Kimura, M., Magnetic fixture for enhancement of smoothing effect by electron beam melting, *J. Mater. Process. Technol.*, 2018, vol. 254, pp. 229–237.
https://doi.org/10.1016/j.jmatprotec.2017.11.024
15. Okada, A., Yonehara, H., and Okamoto, Y., Fundamental study on micro-deburring by large-area EB irradiation, *Procedia CIRP*, 2013, vol. 5, pp. 19–24.
https://doi.org/10.1016/j.procir.2013.01.004
16. Zhang, K., Zou, J., Grosdidier, T., Dong, C., and Yang, D., Improved pitting corrosion resistance of AISI 316L stainless steel treated by high current pulsed electron beam, *Surf. Coat. Technol.*, 2006, vol. 201, nos. 3–4, pp. 1393–1400.
https://doi.org/10.1016/j.surfcoat.2006.02.008
17. Rotshtein, V.P., Gyuntsel', R., Markov A.B., Proskurovskii D.I., Fam M.T, Rikhter E., and Shulov, V.A., Surface modification of a titanium alloy with low-energy high-current electron beam at elevated initial temperatures, *Fiz. Khim. Obrab. Mater.*, 2006, vol. 1, pp. 62–72.
18. Zhang, X.D., Hao, S.Z., Li, X.N., Dong, C., and Grosdidier, T., Surface modification of pure titanium by pulsed electron beam, *Appl. Surf. Sci.*, 2011, vol. 257, no. 13, pp. 5899–5902.
https://doi.org/10.1016/j.apsusc.2011.01.136
19. Zhang, K.M., Yang, D.Z., Zou, J.X., Grosdidier, T., and Dong, C., Improved in vitro corrosion resistance of a NiTi alloy by high current pulsed electron beam treatment, *Surf. Coat. Technol.*, 2006, vol. 201, no. 6, pp. 3096–3102.
https://doi.org/10.1016/j.surfcoat.2006.06.030
20. Li, M.C., Hao, S.Z., Wen, H., and Huang, R.F., Surface composite nanostructures of AZ91 magnesium alloy induced by high current pulsed electron beam treatment, *Appl. Surf. Sci.*, 2014, vol. 303, pp. 350–353.
https://doi.org/10.1016/j.apsusc.2014.03.004
21. Uvarov A., Uemura K., Alexandrov S., Murayama H., Soba R., Molecular properties characterization of PTFE films deposited by hot wire CVD, *Session Report. 16th Symp. on High Current Electronics and 10th Conference on Materials Modification, Tomsk, 2010*, Tomsk, 2010, pp. 500–503.
22. Batrakov, A.V., Onischenko, S.A., Kurkan, I.K., Rostov, V.V., Yakovlev, E.V., Nefedtsev, E.V., and Tsygankov, R.V., Comparative study of breakdown strength of vacuum insulation in gaps with electron-beam polished electrodes under pulsed DC and microwave electric fields, *Proc. 28th Int. Symp. on Discharges and Electrical Insulation in Vacuum*, 2018, vol. 1, pp. 77–80.
https://doi.org/10.1109/deiv.2018.8537014
23. Proskurovsky, D.I., Rotshtein, V.P., and Ozur, G.E., Use of low-energy, high-current electron beams for surface treatment of materials, *Surf. Coat. Technol.*, 1997, vol. 96, no. 1, pp. 117–122.
https://doi.org/10.1016/S0257-8972(97)00093-5
24. Cai, J., Lv, P., Guan, Q., Xu, X., Lu, J., Wang, Z., and Han, Z., Thermal cycling behavior of thermal barrier coatings with MCrAlY bond coat irradiated by high-current pulsed electron beam, *ACS Appl. Mater. Interfaces*, 2016, vol. 47, no. 8, pp. 32541–32556.
https://doi.org/10.1021/acsami.6b11129
25. Ivanov, Yu.F., Gromov, V.E., Grishunin, V.A., Teresov, A.D., and Konovalov, S.V., Surface layer structure and fatigue life of rail steel irradiated by a high-intensity electron beam, *Fiz. Mezomekh.*, 2013, vol. 16, no. 2, pp. 47–53.
26. Ivanov, Yu.F., Gromov, V.E., Grishunin, V.A., and Konovalov, S.V., Rail steel treated by electron beam, its phase composition, structure, and fatigue life, *Vopr. Materialoved.*, 2013, vol. 73, no. 1, pp. 20–30.
27. Gromov, V.E., Ivanov, Yu.F., Grishunin, V.A., Raikov, S.V., and Konovalov, S.V., Scale levels of the structure-phase states and fatigue life of rail steel after electron-beam treatment, *Usp. Fiz. Met.*, 2013, vol. 14, no. 1, pp. 67–80.
28. Gao, B., Hu, L., Li, S.-W., Hao, Y., Zhang, Y.-D., Tu, G.-F., and Grosdidier, T., Study on the nanostructure formation mechanism on the hypereutectic Al–17Si alloy induced by pulsed electron beam, *Appl. Surf. Sci.*, 2015, vol. 346, pp. 147–157.
https://doi.org/10.1016/j.apsusc.2015.04.029
29. Gromov, V.E., Ivanov, Yu.F., Glezer, A.M., Konovalov, S.V., and Alsaraeva, K.V., Structural evolution

of silumin treated with a high-intensity pulse electron beam and subsequent fatigue loading up to failure, *Bull. Russ. Acad. Sci.: Phys.*, 2015, vol. 79, pp. 1169–1172. https://doi.org/10.3103/S1062873815090087

30. Kim, J.S., Lee, W.J., and Park, H.W., The state of the art in the electron beam manufacturing processes, *Int. J. Precis. Eng. Manuf.*, 2016, vol. 17, no. 11, pp. 1575–1585. https://doi.org/10.1007/s12541-016-0184-8
31. Ivanov, Yu.F., Itin, V.I., Lykov, S.V., Markov, A.B., Rotshtein, V.P., Tukhfatullin, A.A., and Dikii, N.P., Structural analysis of heat-affected zone of steel 45 treated by low-energy high-current electron beam, *Fiz. Met. Metalloved.*, 1993, vol. 75, no. 5, pp. 103–112.
32. Markov, A.B. and Rotshtein, V.P., Calculation and experimental determination of size of hardening and tempering zones in hardened U7A steel irradiated with a pulsed electron beam, *Poverkhnost*, 1998, vol. 4, pp. 83–89.
33. *Structure and Properties of Metals at Different Energy Effects and Treatment Technologies*, Klimenov, V.A. and Starenchenko, V.A., Eds., Trans. Tech. Publ., 2014, p. 324.
34. Ivanov, Yu.F., Zagulyaev, D.V., Nevskii, S.A., Gromov, V., Sarychev, V.D., and Semin, A.P., Microstructure and properties of hypoeutectic silumin treated by high-current pulsed electron beams, *Progr. Phys. Met.*, 2019, vol. 20, no. 3, pp. 451–490. https://doi.org/10.15407/ufm.20.03.447

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