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ELECTRON BEAM ADDITIVE MANUFACTURING OF LIGHT METALS

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ABSTRACT

This article aims to summarize the topics related to the application of a surface manufacturing of light metals by means of electron beam additive technologies for developing of new multifunctional materials, as well as to modify their surface properties. These techniques have a large number of applications in the field of automotive and aircraft industries for manufacturing of railways, space crafts, different tools, and components. Some examples of the use of electron beams for surface manufacturing and modification of structure and properties of Ti and Al based materials are presented.

INTRODUCTION

The additive manufacturing technologies are widely used for obtaining new advanced materials, as well as for modification of their structure and properties. They are based on layer-by-layer manufacturing of components where electron beam technologies are known as among the most promising methods for modification of the surface performance of the materials [1]. The electron beam additive manufacturing technologies have a number of advantages in comparison with the conventional methods: (i) these methods are known as low cost in comparison with the traditional processes; (ii) single tools and components can be manufactured in significantly shorter time; (iii) materials with a complex geometry can be easily processed, etc. [2, 3]. In these methods, the kinetic energy of the electrons is transformed into heat and form a thermal distribution. The parameters of the electron beam treatment process can be optimized to melt the processed surface area and form a melt pool where some additives, needed for improvement of the materials' properties are added [4].The distribution of the additives in the melt pool can be explained by high-intensive Marangoni convection which occurs due to the high temperature gradient in the melt pool [5]. The influence of the convection on the melt homogenization can be defined by the surface tension number (S), which is given by (1) [5]:

$$S = \frac{(\partial\sigma/\partial T)qd}{\mu u_0 k}, \qquad (1)$$

where $(\partial\sigma/\partial T)$ is the temperature coefficient of the surface tension; q is the net heat flow; d is the diameter of the electron beam; μ is the viscosity; u_0 is the speed of the specimen motion during electron beam additive manufacturing process; k is the thermal conductivity [5]. Lower values of S lead to negligible convection processes and insufficient mass transport in the melt pool. Higher speed of the specimen motion during the process leads to lower pool temperature which, from thermodynamic point of view, causes low miscibility between the additives and the base material.

The input energy per unit area of the electron beam manufactured surface is another important parameter [6]. It can be defined by eq. (2):

$$E = \frac{UIt}{S}, \qquad (2)$$

where E is the input energy density (J/mm^2); U is the accelerating voltage (V); I is the beam current (A); t is the irradiation time (s) and s is the scanned area (mm^2). Lower values of Ewill not lead to melt the surface and form of a melt pool since the melting point of the material will not be reached. Therefore, the technological conditions (defined by the technological parameters of the electron beam additive technique), namely accelerating voltage, beam current, irradiation time (defined by the speed of the specimen motion and electron beam scanning frequency) and scanned area should be precisely optimized to obtain appropriate technological states of the electron beam additive manufacturing process.

Nowadays, the formation, modification and characterization of light metals and alloys are of great interest for the modern industry due to their light weight, attractive mechanical properties and high temperature performance. The electron beam additive manufacturing of aluminum and titanium based materials are currently under extensive investigations and are a subject of interest of many scientists. Therefore, the following chapters of this article will concern the main results of studies of electron

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beam additive manufacturing aluminum and titanium based materials.

ELECTRON BEAM ADDITIVE MANUFACTURING OF ALUMINUM BASED MATERIALS

As already mentioned, the aluminum and its alloys are widely used in many industrial branches, such as automotive, aircraft, space crafts, rail cars, and other industries due to their light weight and attractive mechanical properties. However, some limitations exist related to the low hardness and poor wear resistance which can be overcome by an appropriate technology for surface manufacturing. In this case, the electron beam additive techniques received a lot of attention and were used by many researchers.

It was known that the incorporation of hard nanoparticles into the molten material leads to a significant grain refinement, mechanical and electrochemical properties improvement. The authors of [7] demonstrated an electron beam additive method for TiCN nanoparticles introduction into Al matrix by means of electron beam surface treatment. The nanopodwer was deposited on the surface of Al substrate then the specimens were electron beam treated. Fig. 1 schematically represents the manufacturing process. The results obtained by the authors of [7] showed a significant increase in the microhardness.

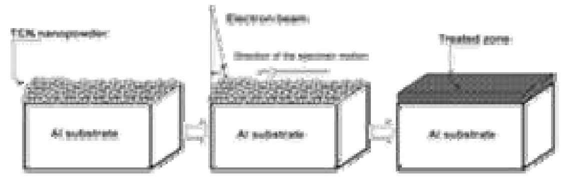

Fig. 1. A scheme of electron beam additive manufacturing technology [8]

The modified by the nanoparticles surface zone is in the range of 16-22 times harder in comparison with the untreated Al matrix. The same authors [7] have studied the distribution of the nanoparticles in the melt pool during the electron beam additive process. The results obtained showed that the nanoparticles concentration in the depth of the manufactured zone is higher in comparison with the near surface region. As mentioned in the introduction part, the incorporation and distribution of the applied additives is based on the Marangoni convection caused by the high temperature gradient. In this case strong convection flows from the surface from the depth exist which are responsible for the nanoparticles introduction and therefore, significant amount of TiCN is directed to the deeper parts of the melt pool. Work [8] describes the influence of the technological condition of the electron beam process (defined by the technological parameters) on the possibility of incorporation of TiCN nanoparticles by electron beam additive technique and the results showed that the use of a higher electron beam scanning frequency leads to longer lifetime of the melt pool and much better conditions for nanoparticles incorporation. Also, it was shown that the presence of TiCNnanopowder in the manufactured surface region is the main reason for the discussed above increase in the microhardness. In the same work [8] a two-step cycling method of incorporation of TiCN additives was demonstrated where the first one is the described above technique for incorporation of TiCN. The second step represents the same procedure on the already formed by the first cycle specimen using the same technological conditions of the electron beam additive technique. The results showed that the TiCN concentration increases after the second cycle which leads to improvement in the mechanical properties. The hardness was up to 40 times greater in comparison with the pure Al matrix.

Another method for improvement of the discussed drawbacks of Al based materials is the formation of intermetallic compounds with better functional properties in comparison with the base material. Al_3M (M-transition metal) with a body-centered tetragonal lattice, type DO_{22} can be characterized with very high hardness and high melting point. Al_3Ti phase is known as very promising for many industrial branches, where light materials with attractive mechanical properties are needed. However, this compound is characterized as a relatively brittle at room temperature. It is known that the incorporation of Nb in the Al-Ti system is capable in reduction of the brittleness and therefore, to overcome the discussed limitation. The authors of [9] have studied the formation and characterization of Al-Ti-Nb surface alloys on Al substrate by electron beam additive manufacturing. For these purposes, Ti and Nb films with thicknesses of 2 μm were deposited on Al substrate by direct current (DC) magnetron sputtering and then the specimens were additive manufactured with scanning electron beam. It was found that after the additive manufacturing process (Ti, Nb)Al_3 phase was successfully formed. The measured microhardness of the obtained intermetallic compound was about 22 times higher in comparison with the base Al substrate. The same authors [9, 10]have investigated the influence of the speed of the specimen motion on the microstructure and crystallographic structure of the obtained samples. Two velocities were chosen: V_1=1 cm/s V_2=0.5 cm/s. Their results show that the discussed technological parameter significantly influences the microstructure. By using higher velocity of sample motion (i.e. 1 cm/s) the intermetallic phase is mainly in the form of coarse fractions randomly distributed on the surface of the specimen, whileat lower speed, the intermetallic phase is in the form of fine particles homogeneously distributed within the electron beam manufactured area on the surface of the sample (Fig.2.). The obtained results for the crystallographic structure showed that the discussed technological parameter of the e-beam manufacturing does not influence on the formation of preferred crystallographic orientation and changes in the lattice parameters. Also, the microhardness remains unchanged with respect to the speed of the specimen motion [9, 10].

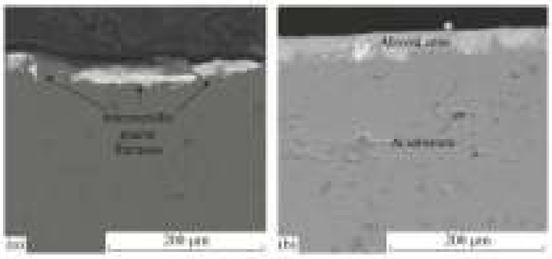

Fig. 2. Cross section SEM image of a sample manufactured by a) V1 and b) V2 [10]

ELECTRON BEAM ADDITIVE MANUFACTURING OF TITANIUM BASED MATERIALS

The titanium and its alloys are another class of materials used in many modern industrial branches due to their light weight and attractive functional properties. However, the microhardness and wear properties need to be improved as the formation of three component intermetallic surface alloys and coatings by means of electron beam additive manufacturing techniques become among the most promising technologies for modification of the surface properties of the Ti based materials.

The authors of [11] have investigated the conditions of formation of Ti-Al-V and Ti-Al-Nb coatings on Ti substrates and the results showed that the formation of an intermetallic compound strongly depends of the input energy density of the electron beam. It was found that the melting point of the materials is of major importance for optimizing the technological conditions. Similar research has been carried out by the authors of [12] where cycling electron beam additive technology for manufacturing of Ti-Al-Nb coatings on Ti substrate was demonstrated. The number of the cycles was 3. The first one represents a deposition of Al-Nb bilayer coating on Ti substrate followed by electron beam manufacturing using the technological conditions optimized in [11]. On the already formed by the first cycle coating, the same bilayer was deposited, followed by electron beam treatment using the selected technological conditions and same procedure was used for the third cycle. The results showed that a Ti_2AlNb based coating has been obtained. Also, the measured microhardness after each cycle is shown in Fig. 3. It was found that for pure Ti it was about 180 HV which increases up to 570 HV after the third cycle. Therefore, this means that it is about four times higher for the formed intermetallic coating in comparison with the base Ti substrate [12].

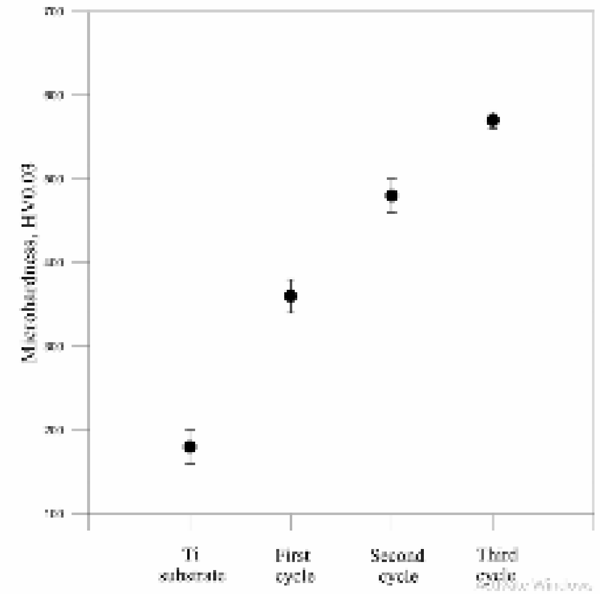

Fig. 3.The microhardness of the obtained Ti-Al-Nb coatings after each cycle [12]

The wear performance was also evaluated and it was demonstrated that the wear loss of the intermetallic coating formed after the third cycle is about two times lower in comparison with the pure Ti material.

CONCLUSION

In this paper we present the possibilities for formation and modification of advanced materials based on light metals by means of electron beam additive manufacturing technologies. It was demonstrated that the functional properties of aluminum and titanium based materials were greatly improved by incorporation of TiCN additives as well as by formation of intermetallic coatings on the surface of the substrates. It was demonstrated that the hardness of pure Al substrates can be increased to about 40 times by adding TiCN nanoparticles into the base material and more than 20 times by formation of three component intermetallic Al-Ti-Nb coating. The hardness of pure Ti can be increased to about 4 times combined with 2 times decrease in the wear loss by formation of intermetallic Ti-Al-Nb coating.

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REFERENCE

[1] Frazier W.E., Metal additive manufacturing: a review, J. Mater. Eng. Perform. 23(2014) 1917–1928.

[2] Weglowski M., Electron beam rapid prototyping using wires and modification of the surface, In: T. Srivatsan, T. Sudarshan, K. Manigandan, editors. Manufacturing Techniquesfor Materials: Engineering and Engineered. 1st ed. Boca Ration, FL, USA: Taylor andFrancis Group,(2018) 133-160.

[3] Valkov S., M. Ormanova, P. Petrov, Surface manufacturing of the materials by high energy fluxes, In: Mohammad Asaduzzaman Chowdhury, editor. Advanced Surface Engineering Research. 1st edition, InTechOpen, UK, (2018) 69-87.

[4] Draper C.W., J.M. Poate, Laser surface alloying, Int. Met. Rev. 30 (2) (1985)85–108.

[5] Chan C., J. Mazumder, M. Chen, A two-dimensional transient model for convectionin laser melted pool, Metall.Trans. A 15 (1984) 2175–2184.

[6] Fu Y., J. Hu, X. Shen, Y. Wang, Wansheng Zhao,Surface hardening of 30CrMnSiA steel using continuous electron beam,Nucl. Instrum. Meth. Phys. Res. B410 (2017) 207–214.

[7] Lazarova R., R. Dimitrova, Y. Murdjieva, S. Valkov, P. Petrov, Layers obtained on aluminum by nanopowder deposition and subsequentelectron beam scanning Materials and Manufacturing Processes 33,1128-1132 (2018).

[8] Valkov S., R. Bezdushnyi, R. Lazarova, R. Dimitrova, P. Petrov, Surface Modification of Al Substrate with TiCNNanopowder by Electron-beam Treatment, AIP Conference Proceedings 2075 (2019) 160017.

[9] Valkov S., P. Petrov, R. Lazarova, R. Bezdushnyi, D. Dechev, Formation and Characterization of Al – Ti – Nb Alloys by ElectronBeam Surface Alloying, Appl. Surf. Sci. 389(2016) 768–774.

[10] Valkov S., D. Neov, R. Bezdushnyi, A.Beskrovnyi, D. Kozlenko, P. Petrov, Study of themicrostructure, crystallographic structure and thermal stability of Al–Ti–Nb alloys producedby selective electron beam alloying, Journal of Surface Investigation: X-Ray, Synchrotronand Neutron Techniques 12 (2018) 436-441.

[11] Valkov S., R. Bezdushnyi, P. Petrov, Study of the influence of vanadium and niobium on thestructure of Ti-Al-V and Ti-Al-Nb alloys formed by selective electron beam alloying, Journal of Physics: Conference Series 992(2018) 012053.

[12] Valkov S., R. Bezdushnyi, P. Petrov,Synthesis, structure and mechanical properties of Ti-Al-Nb coatings formedby electron beam additive technique, Vacuum 156 (2018) 140-145.