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Surface Manufacturing of Materials by High Energy Fluxes

Stefan Valkov, Maria Ormanova and Peter Petrov

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Abstract

This chapter aims to summarize the topics related to the application of a surface treatment by high energy fluxes (i.e., electron and laser beams) for developing of new multifunctional materials, as well as to modify their surface properties. These technologies have a large number of applications in the field of automotive and aircraft industries for manufacturing of railways, space crafts, different tools, and components. Based on the performed literature review, some examples of the use of laser and electron beams for surface manufacturing (i.e., surface alloying, cladding, and hardening) are presented. The present overview describes the relationship between electron beam and laser beam technologies, microstructure, and the obtained functional properties of the materials. The benefits of the considered techniques are extensively discussed.

Keywords: high energy fluxes, surface manufacturing, alloying, cladding, hardening

1. Introduction

In the era of exhaustion of natural resources as well as of continuous development of the modern industry, the technologies for surface treatment are becoming increasingly important. There exist a number of technologies for surface manufacturing of the materials, including electrochemical processes, electrical discharge processes, additive manufacturing, etc. [1–3].

Considering the electrochemical method, it has been used for synthesizing of nanostructures and manufacturing of advanced materials since the methods are known as cost-effective and resourceful. This technique is based on the removing of metal by electrochemical process, and it is used for treatment of extremely hard materials and materials that cannot be treated by the conventional techniques. However, some drawbacks such as long process time and too high

temperature required can be mentioned. Furthermore, the formation of environmental pollution due to the use of chemicals and the need that the materials must be conductors can also be considered as limitations [1].

The electrical discharge machining process is another method which is used for manufacturing of the materials. This technique is based on the removing of the material using electrical discharge. Series of rapidly recurring current discharge between two electrodes were applied which are responsible for the removal of the material. The method is often used for prototype production and manufacturing of parts, especially for the needs of the automotive and aircraft industries. However, the slow rate of the material removal and the requirement of conductive materials that can be manufactured by the discussed method are of the major drawbacks [2].

Promising techniques for fabrication of new materials with unique properties and for modification of their structure are the additive manufacturing technologies. They are based on layer-by-layer fabrication of components [3]. The additive technologies include several techniques for materials' treatment, such as ultrasonic processes, electron beam processes, laser beam processes, etc. The ultrasonic processing is a revolutionary processing technology widely used for welding and joining. It is based on the scrubbing together with ultrasonic vibrations under controlled pressure or normal load. Nevertheless, this technique is not capable to melt the treated area and operates at a temperature significantly lower than the melting point of the manufactured materials. Thus, although the discussed technique is a revolutionary process for welding and joining, it is not suitable for processes such as surface alloying, cladding, etc. [4].

The methods of a surface treatment by high energy fluxes (HEFs), which are a part of the additive technologies, are intensively used for formation of surface alloys, as well as for modification of the surface structure of different materials. Their main advantage is the precise control of the energy input, which alloys the controlling of the structure and properties of the treated materials. Furthermore, in comparison to traditional manufacturing, some benefits of the additive technologies can be mentioned [5]:

• The use of high energy fluxes alloys manufacturing at comparatively low cost in comparison to the traditional processes.

• Single tools can be fabricated in much shorter time by using high energy flux technologies in comparison to the traditional methods.

• Materials and other products with a complex geometry can be manufactured by additive techniques, while using traditional technologies, many different parts have to be manufactured separately and after that assembled.

• High energy fluxes are useful for a surface modification and hardening and allow design changes of the surfaces. The application of the traditional technologies for these purposes is too expensive and time ineffective for the discussed purposes.

The processes used for surface manufacturing of the materials are treatment by fluxes of photons (laser radiation) or accelerated electrons (electron beam). During this process, the manufactured material is irradiated by electron or laser beam. When the flux of the photons or accelerated electrons interacts with the treated surface, the work-piece is heated and forms thermal distribution from the surface to the bulk [6–9]. After the irradiation, the sample

rapidly cools down. The processes of fast heating and cooling reflect to structural transformations, changes in the chemical composition, melting of the surface, etc. According to the maximum temperature of the heating, several processes can be defined: (i) When, during the heating, the temperature is lower than the melting point of the treated specimen, the material remains in solid-state condition, but some phase and structural transformations may occur. Such technological conditions are widely used for a surface hardening of the materials [10]. (ii) When the maximum temperature is higher than the melting point of the specimen and, in the same time, lower than the boiling point, the material becomes in liquid phase condition. Such techniques are used for alloying and cladding processes [11–13]. (iii) When the temperature is higher than the boiling point of the material, the treated material is partially evaporated. Such technologies are used for a deposition of coatings (electron beam evaporation, laser deposition, etc.), laser ablation, in the field of a laser drilling [13–15].

Currently, the additive manufacturing techniques are considered for different aerospace applications, such as on-orbit constructions of space structures, a manufacturing of small multifunctional systems for astronauts for fabrication of spare parts, etc. Applying these techniques in the space, the typical pressure is up to 10^{-17} mbar. This means that for electron beam processing a vacuum chamber and the equipment are not necessary and the process can be realized directly in the space environment [5]. Also, the discussed techniques are widely used in the field of automotive and aircraft industries for manufacturing of different components and tools, for the needs of the modern medicine, for biomedical applications, and many more [5].

This chapter aims to summarize the topics related to the application of a surface treatment by high energy fluxes (i.e., electron beams and laser beams) for developing of new multifunctional materials, as well as to modify their surface properties. We present and discuss the methods and techniques for development and improvement of advanced materials by means of alloying, cladding, and hardening via electron and laser beams.

2. Technological parameters

For both types of techniques (i.e., electron and laser beam), the beam power and power density are of the important process parameters. In the case of laser beam, it can be set directly, while for e-beam it is a product of the accelerating voltage and the beam current. For example, typical values for the accelerating voltage are from 50 to 150 kV. With an increase of the beam power, the kinetic energy of the electrons also increases, which causes an increase in the penetration depth of the beam. The beam power density is an important parameter for the alloying operation since it affects the forces acting in the molten material [16].

The speed of the specimen motion during the process is also a basic parameter. As a result of this movement, the heat is transferred to the volume of the material. It is responsible for the heating and cooling rate as well as for the solidification speed. With an increase of the speed of the specimen motion, the heat input decreases. The beam power and the speed of the specimen motion are responsible for the volume of the manufactured zone, the thickness, and the width [5].
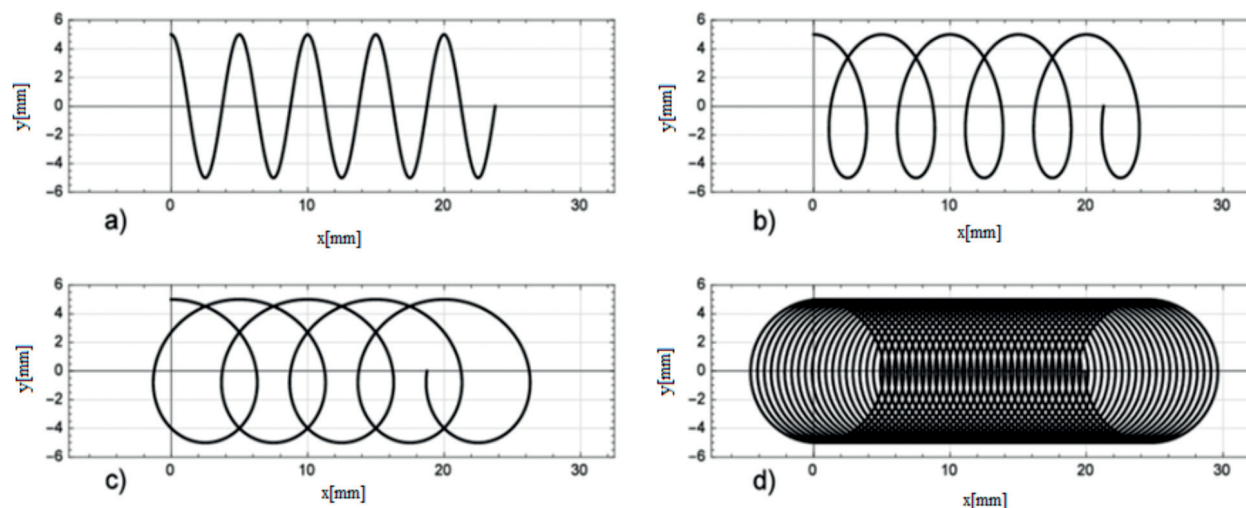
Figure 1. Different types of scanning electron beam: (a) sinusoidal dithering; (b) ellipsoidal rotating; (c) circular rotating with higher specimen movement velocity; and (d) circular rotating with slower specimen movement velocity (the figure is drawn by the authors).

The application of the electron beam for additive manufacturing has a major advantage in comparison to the laser beam, namely beam deflection. Since the electrons are charged particles, they can be deflected from the normal axis by application of electrical and electromagnetic fields. This allows a realization of different scanning approaches which affects the solidification processes and can control further the processes occurring during the abovementioned operations. For example, when applying the e-beam techniques, a scanning can be realized using regime of circular geometry. In this case, the trajectory of the beam is overlapping and maintaining the lifetime of the melt pool further. This is important for the alloying operation since the alloying elements can be distributed significantly more homogeneous [17]. Possible electron beam scanning geometries are shown in **Figure 1**.

Another difference between electron and laser beam processes is the working pressure. When applying electron beam technique, high vacuum state is absolutely required. The presence of some atoms and gas molecules on the way of the beam can result in loss of its power due to absorption and electron scattering. Typically, the pressure should be at least 5×10^{-4} mbar or lower. The laser beam processes are usually realized in atmospheric medium. In order to prevent oxidation of the manufactured area, argon is blown over the surface of the manufactured material [16, 18].

3. Heat processes

As already mentioned, the work-piece is heated on the surface and form thermal distribution. The rapid heating and cooling lead to structural transformations, changes in the chemical composition, melting the surface, etc., and therefore the rate of these processes is of major importance. There exist experimental and numerical approaches to examine the temperature field and, thus, the rates of heating and cooling, which will give us information related to the final microstructure and functional properties of the treated material. The experimental

methods are time- and effort-consuming, and the results are not always reliable. For that reason, the numerical approaches are more appropriate and widely used for evaluating the thermal field and modeling the thermal processes. The heat transfer equation for the case of treatment by high energy fluxes (i.e., electron and laser beams) can be described for homogeneous and isotropic material whose thermophysical properties are temperature-independent from the following field equation of heat conduction [19–22]:

$$\frac{1}{\alpha}\frac{\partial T}{\partial t} - \nabla^2 T = \frac{f(r,t)}{\lambda} \tag{1}$$

Here, $\alpha = \frac{\lambda}{c\rho}$ is the thermal diffusivity; λ is the thermal conductivity, c is the specific heat, and ρ is the density of the specimen.

The solution $T(r,t)$ of Eq. (1) for the case of three-dimensional transient, nonhomogeneous heat conduction problems can be expressed by three-dimensional Green's function:

$$T(r,t) = \frac{k}{\lambda} \int_{\tau=0}^{t} d\tau \int_{R} G(r,t|r',t) f(r',\tau) dv' + \int_{R} G(r,t|r',\tau) \bigg|_{\tau=0} F(r') dv' \tag{2}$$

where $F(r')$ describes the initial temperature distribution. In orthogonal coordinates, the Green's function can be written as follows:

$$G(x,y,z,t|x',y',z',\tau) = G1(x,t|x',\tau) \times G2(y,t|y',\tau) \times G3(z,t|z',\tau) \tag{3}$$

In Eq. (3), each of the Green's functions (i.e., G1, G2, and G3) depends on the boundary conditions and the regions (i.e., finite, semi-infinite, or infinite). For the case of infinite region, the Green's function is the following:

$$G(x,t|x',\tau) = [4\pi\alpha(t-\tau)]^{-1/2} \exp\left(-\frac{(x-x')^2}{4\alpha(t-\tau)}\right), \tag{4}$$

and for semi-infinite, when the boundary is at z′ = 0, the Green's function is:

$$G(z,t|z',t) = [4\pi\alpha(t-\tau)]^{-1/2} \left[\exp\left(-\frac{(z-z')^2}{4\alpha(t-\tau)}\right) + \exp\left(-\frac{(z+z')^2}{4\alpha(t-\tau)}\right)\right] \tag{5}$$

By substituting G1(x,t|x′,τ) and G2(y,t|y′,τ) from Eq.(4) and G3(z,t|z′,τ) from Eq.(5) in Eq.(3), we obtain:

$$G(x,y,z,t|x',y',z'=0,\tau) = 2[4\pi\alpha(t-\tau)]^{-1.5} \times \exp\left(-\frac{(x-x')^2 + (y-y')^2 + z^2}{4\alpha(t-\tau)}\right) \tag{6}$$

By substituting $x' = x - r.\cos\theta$ and $y' = y - r.\sin\theta$ and $G(r,t|r',\tau)$ from Eq.(6) in Eq.(2), the distribution of the temperature is the following:

$$T(x, y, z, t) = T_0 + \frac{2\alpha}{\lambda} \int\limits_{0}^{t} \int\limits_{-\pi}^{\pi} \int\limits_{0}^{\infty} \left[f(x - r\cos\theta, y - r\sin\theta, \tau) \times [4\pi\alpha(t-\tau)]^{-1.5} \times exp\left(-\frac{r^2 + z^2}{4\alpha(t-\tau)}\right) \right] \quad (7)$$

$$\times r\,dr\,d\theta\,d\tau$$

Here, t is the time of temperature calculating, r and θ are the polar coordinates. In Eq. (7), *f(x-r.cosθ,y-r.sinθ)* is the beam intensity distribution. For a beam with Gaussian distribution which moves along a straight line, the beam intensity is:

$$f(x - r\cos\theta, y - r\sin\theta, \tau) = \frac{3Q}{\pi r_0^2} \times exp\left\{-3\left(\frac{(x - -r\cos\theta - v\tau)^2 + (y - r\sin\theta)^2}{r_0^2}\right)\right\} \quad (8)$$

In Eq. (8), r_0 is the beam radius, Q is the power transferred to the irradiated material, and v is the speed of the beam along moving line. For a dithering beam, the intensity distribution is the following:

$$f(x - r\cos\theta, y - r\sin\theta, \tau) = \frac{3Q}{\pi r_0^2} exp\left(-3\frac{(x - \cos\theta - v\tau)^2 + (y - r\sin\theta - l_{max}\cos\left(\frac{2\pi\tau}{\tau^*}\right))^2}{r_0^2}\right) \quad (9)$$

where l_{max} is the amplitude and τ^* is the period for each cycle. In the case of rotating beam, the beam intensity is the following:

$$f(x - r\cos\theta, y - r\sin\theta, \tau)$$
$$= \frac{3Q}{\pi r_0^2} \times exp\left\{-3\left(\frac{(x - r\cos\theta - v\tau - a\sin\left(\frac{2\pi\tau}{\tau^*}\right))^2 + (y - r\sin\theta - l_{max}\cos\left(\frac{2\pi\tau}{\tau^*}\right))^2}{r_0^2}\right)\right\}$$
$$(10)$$

In Eq. (10), *a* is the diameter of the rotation along the moving line.

4. Characteristics of the HEFs processes

The processes of surface modification of metals and alloys by using HEFs can be roughly divided into two groups depending on whether the HEFs act on the material in a solid (**Figure 2a**) or a liquid (**Figure 2b**) phase. Both types of techniques have found practical applications. In recent years, and in view of developing novel materials, the alloying with HEFs processing techniques has been widely used [5]. These techniques include additional alloying in the zone treated, which has a significant effect on the physical and mechanical properties of the materials processed [7–9].

4.1. Cladding and alloying

Cladding techniques are used for a coating of a substrate by different materials in order to improve the functional properties of the surface. It can be realized by two different approaches:
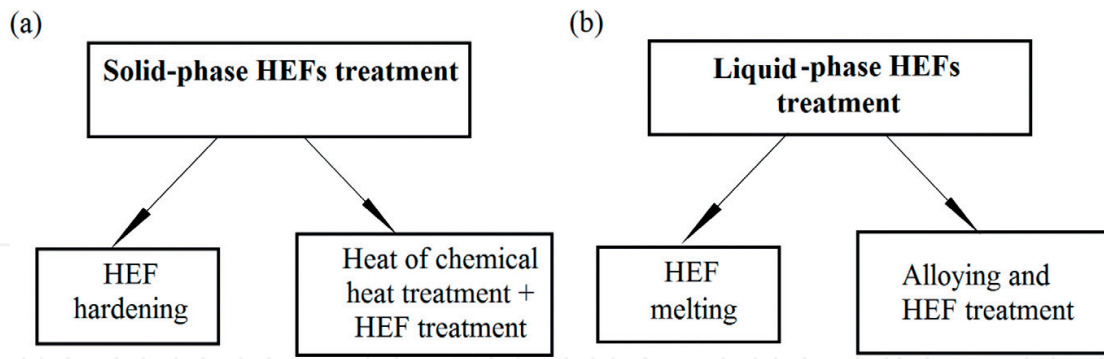
Figure 2. (a) Solid-state HEF processing of metals and alloys; (b) HEF melting and processing of metals and alloys (the figure is drawn by the authors).

by a deposition of a coating material on the substrate and subsequent treatment by laser or electron beam and by direct injection of the coating material into the melt pool. **Figure 3a** shows the cladding technique.

In the case of preliminary deposition of the coating, material is applied on the coated substrate in the form of slurry consisting of powder of the coating material mixed with a binder. The material is melted together with a thin layer of the surface substrate, and after the subsequent solidification, a clad track is formed [23]. However, this approach (a deposition of a coating material on the substrate and subsequent treatment by high energy flux) presents some drawbacks: the application of a slurry powder is taking too much time; it is too difficult to deposit a uniform film on complex surfaces. Also, this approach presents significantly lower productivity and high cost in comparison to direct injection of the coating material into the melt pool [24]. At the direct injection of the coating material, the clad track rises above the surface of the coated substrate. The injected alloying material is usually in the form of powder or wire. According to the authors of [25], at a constant beam power and scanning speed (i.e., scanned distance per second), the main parameter is the powder feed rate. Low powder feed rates correspond to lower input energy needed for melting of the incoming powder. This means that
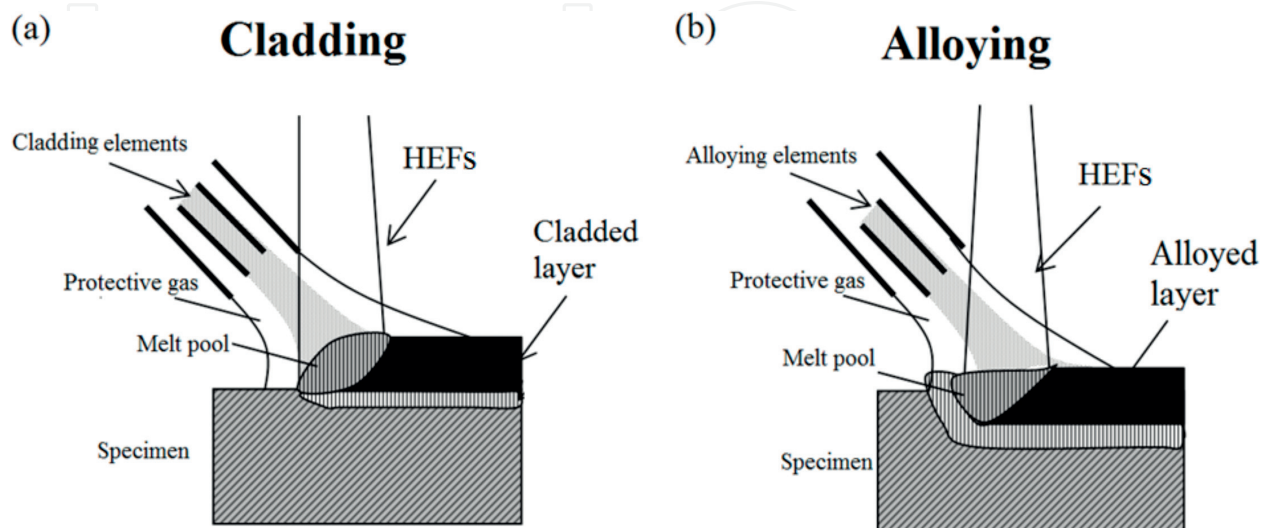
Figure 3. (a) Cladding; (b) alloying by HEFs (the figure is drawn by the authors).

the melt depth of the substrate is too high, which corresponds to low built-up material on the surface and low contact angle between the substrate surface and the tangent to the track surface at the contact edge (α) (**Figure 4**).

With an increase of the powder feed rate, the input energy needed for melting of the incoming powder also increases and the melt depth of the surface decreases. The clad height and angle α increase as well. After passing a certain value of the powder feed rate and α, the cladded material loses adherence and porosity between the tracks can be formed due to the shadowing of the substrate. The angle α is a good indicator for the quality of the cladded material. The optimal values for α are in the range from 45 to 80° [25]. By overlapping of the clad tracks, a large area can be coated. Important merits of the cladded coatings are the good adhesion between the coating and the substrate, low porosity, and absence of cracking. The typical thicknesses of the coatings formed by cladding technique are in the range from 0.5 mm to 5 mm.

For realizing of alloying mechanism (**Figure 3b**), the manufactured parts are treated by high energy fluxes and built by melting the surface, forming a melt pool. The melt pool is formed due to the energy input of the flux on the manufactured part. During the melting of the surface of the manufactured part, the alloying elements are simultaneously added into the melt pool in the form of powder or wire or are deposited onto the surface as a layer with uniform thickness. Interdiffusion processes between the substrate and the alloying elements occur. The melt pool solidifies rapidly, and after the solidification, the surface alloy is formed [6–9, 12]. The distribution of the alloying elements is based on the Marangoni convection which is caused by the high temperature gradient in the melt pool [26–28]. The influence of the convection on the homogenization process is evaluated by the surface tension number, which is given in Eq. (11):

$$S = \frac{\left(\frac{d\sigma}{dT}\right)qd}{\mu u_0 k} \tag{11}$$

In Eq. (11), S is the surface tension number; $d\sigma/dT$ is the temperature coefficient of the surface tension; q is the net heat flow; d is the diameter of the beam; μ is the viscosity; u_0 is the
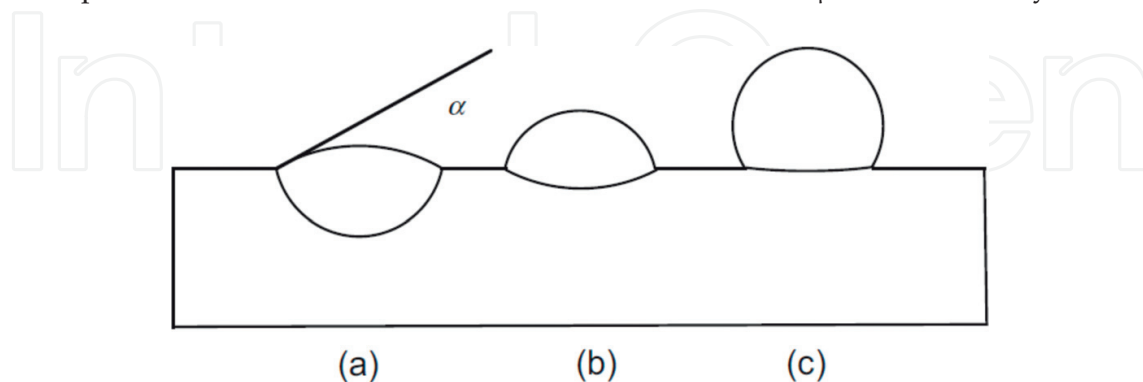

Figure 4. Cross section of cladding tracks: (a) low powder feed rate; (b) optimal powder feed rate; (c) high powder feed rate [24].

scanning speed; and k is the thermal conductivity. When the value of the surface tension number is low (S ≤ 45,000 [27]), the convection is negligible and the melt homogenization will be too slow. For high values of the surface tension number, the convection takes a leading role in the transport mechanism of the melt pool. In this case, the convection speed in high, as this leads to extremely fast homogenization. Therefore, in order to obtain homogeneous surface alloys with attractive functional properties, it is very important to optimize the technological parameters, included in Eq. (1), and the amount of the alloying elements. To achieve the required characteristics of the surface alloys, the dimension and lifetime of the melt pool should be controlled accurately and kept stable during the alloying process.

4.2. Hardening

Beside for alloying and cladding technologies, the high energy fluxes are often used for a surface hardening of the materials (**Figure 5a** and **b**).

The purpose of such techniques is to increase the hardness and wear resistance of the materials as a result of the processes occurring during the heating and cooling. The hardening is a technological process, in which the metals and alloys are heated to a certain temperature, followed by a rapid cooling which results in formation of metastable structures as well as finer microstructure, leading to an increase in the hardness and wear resistance [29–34]. The high cooling rate required for the structural transformations occurring during the self-quenching process strongly depends on the thermophysical properties of the hardened material. This hardening technique has received attention only in the metallurgical industry since it offers the advantages of low hardening distortion and low energy consumption. The application of a hardening by means of high energy fluxes provides the metallurgist an additional option to conventional hardening techniques [29].
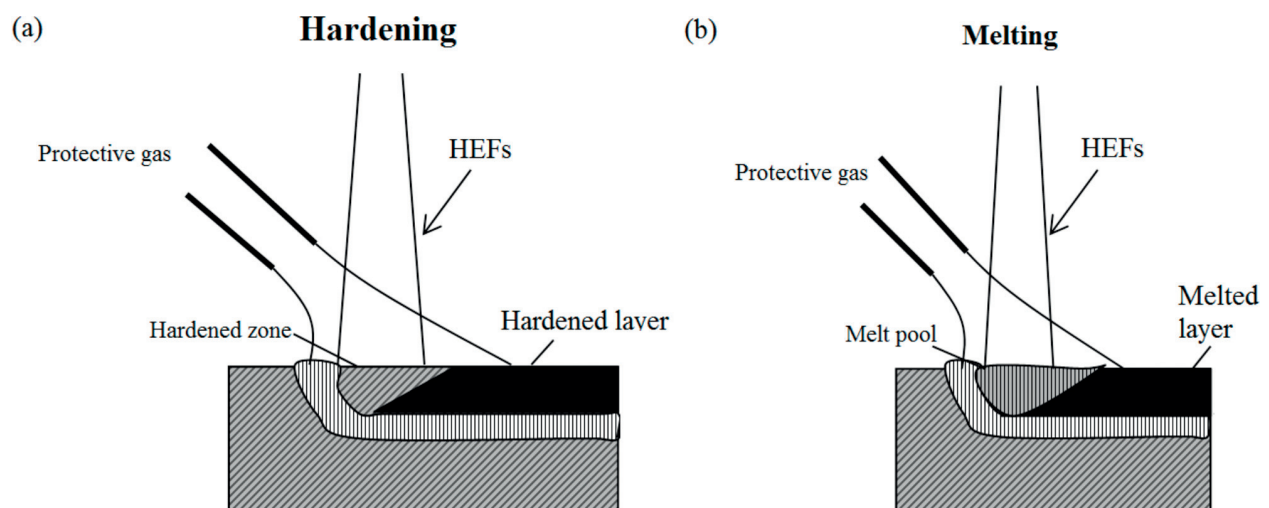
Figure 5. Surface hardening is (a) solid and (b) liquid HEFs treatment.

5. Overview of the processes

5.1. Alloying

As already mentioned, the alloying processes are based on the melting of the surface of the alloyed material and applying alloying elements into the melt pool which are dissolved into the matrix of the based material and forming surface alloys. The alloying material can be applied previously in the form of coatings by means of other techniques (e.g., magnetron sputtering, plasma spraying, etc.) or can be incorporated into the melt pool directly in the form of a powder stream or wire.

The high energy fluxes alloying techniques are widely used for fabrication of materials for the needs of the automotive and aerospace industries, for manufacturing of railway cars, space crafts, light ships, etc. Such materials are aluminum alloys due to their attractive mechanical properties and light weight. Alloying of pure aluminum with different transition metals by means of high energy fluxes is among the most promising methods for fabrication of surface alloys and for improvement of the surface properties of the materials. For that reason, many researchers are working on the formation and characterization of surface alloys by high energy fluxes.

The alloying of titanium and titanium alloys is a subject of investigations for many scientists due to the application of these materials in the field of the contemporary aviation and automotive industries, for different biomedical applications and many more.

The authors of [35] have studied a laser alloying of Ti-Si compound coating on Ti6Al4V in order to improve the bioactivity. They have reported that the microhardness increases dramatically after the alloying process. Also, the corrosion resistance of laser-alloyed Si coating is 27% improved in comparison to the base Ti6Al4V alloy. The evolution of the cell growth is the same for the case of Si alloyed layer and base Ti6Al4V materials on the first day, but in the progress, the cell growth starts to be faster on the laser-alloyed Si layer in comparison to the Ti6Al4V alloy.

Similarly, the authors of [36] have studied a laser alloying of titanium with boron and carbon. Their results show that the microstructure of the alloyed zone consists of a hard ceramic phases, namely, $TiB + TiB_2$, $TiB + TiB_2 + TiC$, or TiC. A significant increase in the hardness and wear resistance of all surface alloys has been observed in comparison to the commercially pure titanium.

As already mentioned, in addition to the laser alloying, the electron beams are also widely used for alloying processes. The authors of [37] have studied a cycling mixing of predeposited Al films onto Ti substrate by means of pulsed electron beam. The phase composition of the alloyed zone consists of $TiAl$ and $TiAl_2$ phases. The measured nanohardness of the near-surface region is significantly greater in comparison to the base Ti substrate—11 GPa.

Similarly, Valkov et al. [38] have studied an electron beam surface alloying of pure Ti with Al films, and their results show that the alloyed zone consists of biphasic structure of Ti_3Al and $TiAl$, which is transformed in single phase structure of $TiAl$ in depth. This transformation is accompanied by a decrease in the hardness from the surface to the depth. Also, Valkov and

coauthors [39] have studied the conditions of alloying of pure Ti with Al and Nb and with Al and V. The results showed that the formation of an intermetallic surface alloy by means of electron beam alloying strongly depends on the input energy of the e-beam. The same authors [39] have claimed that the melting point of the materials plays a major role in the optimization of the technological parameters of a selective electron beam technology.

From the performed literature review, it is obvious that the modification of titanium with different transition metals by means of high intensity energy fluxes tends to a significant improvement in the functional properties of the discussed materials. As already mentioned, the modification of aluminum for improving of its operational characteristics is also a subject of investigations in the field of the modern materials science.

Lazarova et al. [40] have demonstrated a modification of the mechanical properties of pure Al by incorporation of TiCN nanopowder by means of electron beam alloying. Their results show that the alloyed zone has a thickness in the range of 14–33 μm and microhardness from 562 to 798 HV or the alloyed zone is 16–22 times harder than the base Al substrate.

The authors of [41] have studied the improvement in the surface properties of Al-Si cast alloy by means of laser beam surface alloying with Fe. Their results present an increase in the microhardness. Similarly, Almeida et al. [42] have studied laser beam surface alloying of Al with Cr using two-step process (alloying and remelting). The results show that an increase of the remelting speed points to an increase in the volume fraction of the intermetallic compound and the hardness, respectively. Almeida et al. [43–46] have studied an alloying of pure Al with Nb by means of laser alloying technique. The results obtained by the authors show that the distribution of the alloying element is not homogeneous and undissolved Nb particles surrounded by dendrites of Al_3Nb exist. However, the characteristics of the alloyed layers were greatly improved after a laser remelting. Most of the structural defects were eliminated, and undissolved Nb particles have not been observed. The manufactured laser beam surface alloys have been successfully formed with an Al_3Nb dendritic microstructure. The same authors [46] claimed that the microhardness increases with an increase of the scanning speed during the laser alloying technology. The reported microhardness changes from 480 to 650 HV with varying of the scanning speed from 5 to 40 mm/sec. Valkov et al. [47] have studied an alloying of pure aluminum with as-deposited Ti-Nb coatings by means of a scanning electron beam, and their results show that undissolved particles have not been observed after the alloying process, contrary to the case of laser beam alloying. The alloyed zone consists of $(Ti,Nb)Al_3$ intermetallic fractions randomly distributed in the biphasic structure of fine $(Ti,Nb)Al_3$ particles dispersed in the Al matrix. The increase of the speed of the specimen motion tends to more homogeneity distribution of the intermetallic phase in the soft Al matrix and much finer microstructure. Also, the measured microhardness reaches values of 775 HV and it does not depend on the speed of the specimen motion during the electron beam alloying process. Therefore, a significant difference between the properties and structure of the fabricated surface alloys by electron and laser beam exists. The authors of [48] have made a comparative study of electron and laser beam surface alloying of pure Al with Nb. The results reported in [48] have shown that the observed differences in the microstructure of the surface alloys formed by both techniques are explained by the different way of controlling the lifetime of

the melt pool. The electron beam alloying technique can be realized in different geometries of scanning (circular, linear, etc.) since the electrons can be deflected and guided due to their nature of charged particles. When using circular scanning mode, the trajectory of the e-beam overlaps which points to longer lifetime of the melt pool. Using laser beam alloying technique, such technological conditions cannot be realized and the lifetime of the melt pool is significantly shorter [48]. The authors of [49, 50] have performed detailed investigations of the microstructure and the crystallographic structure of surface alloys fabricated by electron and laser beam alloying and explain the difference in the hardening mechanism of both kind of alloys. Vilar et al. [49] have studied the crystallographic structure of laser beam–manufactured surface alloys, and their results show that the increase of the scanning speed during the alloying process reflects to formation of a preferred crystallographic orientation while such effect of electron beam–fabricated surface alloys has not been observed [50]. According to the authors of [51, 52] the formation of a preferred crystallographic orientation can significantly affect the mechanical properties which, as mentioned in [50] can be a possible reason for the observed differences in the hardening mechanism of electron- and laser-processed surface alloys.

5.2. Cladding

The cladding technique is widely used for manufacturing of coatings for protective purposes, against adhesive wear (when two bodies with similar mechanical properties slide against each other) and abrasive wear (when hard particles or hard body slide against softer one). Such materials which can overcome these drawbacks are alloys in the system of Co-Cr-W-C due to their high strength and resistance to corrosion and wear at high temperatures [53]. These alloys are also known as stellites.

Such coatings have been applied by [54] using laser cladding of preplaced powder on stainless steel substrates, as the authors have studied the influence of the energy density of the laser beam on the degree of dilution. Their results show that an energy density of 6.4 kJ/cm^2 is needed to melt the powder and wet the substrate in order to form a good quality continuous track with less than 6% dilution. An increase in the energy density leads to significantly higher and inappropriate dilution of up to 27%. Lower energy density is capable to melt the powder without wetting the substrate. The authors of [55–57] have studied the formation of stellite coating on austenitic steel substrate as a function of the scanning speed which was in the range 1.67–167 mm/s. They have reported that coatings free of crack and pores with excellent adherence have been formed. The same authors have claimed that the microstructure of the coatings does not depend on the technological conditions of the cladding and becomes similar in the range of the scanning speed. However, the same authors [57] have mentioned that stellites can be applied without preheating of the substrate, but carbon-rich coatings have higher brittleness and are capable to crack. Therefore, the substrate must be preheated in order to avoid such defects.

The authors of [58] have studied an electron beam cladding of Cr_3C_2/Ni-Cr powder on steel substrates. The conditions for obtaining an increased thickness and modified area of still good surface layer have been investigated. The results show that the thickness and cladded area can

be increased simply by increasing the number of formation passes and the beam oscillation amplitude. The measured hardness was 791 HV.

Similarly, Abe et al. [59] have studied WC12% Co- and Ni-base self-fluxing alloy powder with a mild steel substrate. Their results show good quality coatings with superior functional properties, including wear and corrosion resistance. The microhardness of the formed cladding layer reaches values of 1400 HV.

5.3. Hardening

As already mentioned, the hardening process by means of high energy fluxes is based on the irradiation of the hardened surface and formation of metastable structures as well as on the changes in the microstructure.

Such approach for improving of the functional properties of the materials has been used by the authors of [60]. They have analyzed the influence of the laser treatment of carbon steel on the changes of the microstructure and microhardness in depth. The results are compared with those obtained by conventional hardness, and it has been concluded that the laser treatment technique leads to 80% harder structure in comparison to the conventional processes. Similarly, Sarnet and coauthors [61] have conducted a surface treatment of alloyed steels by an excimer laser. As a result of the treatment, the microhardness increases with about 200%.

In study [62] the results of investigation of the electron beam surface modification of 5CrMoMn steel are shown. The beam current in the study has been varied from 6 to 8 mA with a step of 0.5 mA. The results show that surface properties of the modified specimens are greatest at a beam current of 7 mA. The microhardness reaches from 355 HV for the base material up to 656 HV and decreases with further increasing of the current above 7 mA due to the reduction of martensite and carbon content.

The authors of [63] have performed similar investigation. They have studied an electron beam surface hardening of 30CrMnSiA steel as the subject of discussion is the influence of the density of the input energy of the e-beam on the possibility of formation of hardened layers. The results show that the hardness increases dramatically, from 320 to 520 HV when the input energy density reaches a value of 1.857 kJ/cm^2. By further increasing the input energy, the hardness decreases because of the convective mixing of the melted zone, which effect becomes predominant after the discussed density of the input energy of the electron beam.

Also, electron beam surface hardening can be combined with other methods, such as physical vapor deposition [64], plasma nitriding [34, 65], etc. Grumbt et al. [64] have studied a duplex treatment $Ti_{1-x}Al_xN$ coatings with subsequent electron beam treatment of steel substrates. The results of study [64] show that the coating significantly enhanced the absorption properties, resulting to an increase in the hardened depth for the same parameters of the electron beam hardening process of coated and uncoated steel. Moreover, the hardened depth increases with an increase of Al content or the thickness of the coating. Also, it was demonstrated that the electron beam hardening of previously coated steel substrates is capable to form significantly harder surfaces in comparison to uncoated materials.

The authors of [34, 65] have studied an electron beam surface hardening of previously nitrogen-alloyed steel. Their results show a significant increase in the microhardness as well as double improvement of the wear resistance. The authors of the discussed studies [34, 65] claimed that the reasons of these improvements of the functional properties are the refined microstructure consisting of α-solid solution (nitrous martensite) and γ-solid solution (nitrous austenite) and dispersed fine nitride precipitates. Ormanova et al. [22] have presented a combined method for surface modification of tool steels, consisting of electron beam hardening followed by plasma nitriding and subsequent electron beam hardening, and the results demonstrate a hardness of 760 HV after the electron beam treatment and plasma hardening. The application of additional electron beam treatment process tends to a slight decrease in the hardness due to structural transformation and reduction of the amount of N atoms.

6. Summary

The current state of the surface manufacturing of the materials by means of high energy fluxes (electron and laser beams), including surface alloying, cladding, and hardening, has been discussed in the present book chapter. The presented data are based on our own experience as well as on the available studies in the literature. The various applications of the high energy fluxes in the field of the surface manufacturing were demonstrated with a focus on the relationship between the technological processes and the properties. It was shown that the electron and laser beams have a number of benefits as a small comparison between both techniques is provided at the discussions of each surface manufacturing process.

The area of future developments of the surface manufacturing by means of high energy fluxes will be concentrated on the optimization of the techniques, processes as well as modeling and simulations. Considering the fact that the number of the machines for high energy fluxes manufacturing, installed in the industry, extensively grows, these technologies should be rapidly incorporated in the wide range of the industry, such as aerospace, automotive, railway, biomedicine, etc.

Up to now, the materials which are extensively treated and manufactured by high energy fluxes are the steels as well as small amount of other high-performance materials, such as titanium aluminides. It can be concluded that the state of research on the applications of high energy fluxes in the field of the surface manufacturing processes is well developed and extensively introduced for different industrial applications.

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Conflict of interest

The authors have no conflict of interest to declare.

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