THE PARTICULARITIES OF THE HIGH CURRENT RELATIVISTIC ELECTRON BEAMS INFLUENCE ON CONSTRUCTION MATERIALS TARGETS

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Possible approaches to practical application of observed effects at intense relativistic electron beam interaction with solids with particles energy about 0.5 MeV are discusses in the article. Physical actions leading to transformations in irradiated targets are analyzed. The classifications of possible techniques of target irradiation (such as direct irradiation, exposure to an intermediate target to remote welding, irradiation of the target to condense backscattering evaporation products on the substrate) are presented. The results of modification impacts of various materials are submitted.

PACS: 61.80.Fe, 61.82.Bg, 81.40.Wx

INTRODUCTION

Results of the study of interaction processes of high-current electron beams (HCEB) with condensed materials finding increasing application in various practical applications, which can be divided into two groups: the modifying and test impacts.

The modifying impacts involve the receipt of materials with desired properties as a result of irradiation by electron beams (surface remelting, remote welding, obtaining of disperse materials). The test impacts perform the simulation of extreme natural and man-made factors (meteor strike, lightning, earthquake impact) influences on materials.

Activisation of researches in this field is validated by increase of publications which is explained by several factors:

- increasing requirements to operating conditions of construction materials, such as in the manufacture of nuclear radiation converters;
- advent of affordable high-current switches providing high pulse repetition rate and, therefore, the implementation of technological modes of accelerators operation;
- the possibility of a complex reproducing of the physical mechanisms that are the basis for of advanced technologies for new materials synthesis.

Known examples of the successful application of HCEB in various technologies are generally limited to low-energy beams up to 20…30 keV. An example of the frequency mode source of irradiation is described in [1], with beam current of the order of 150 A at energy of 150 keV.

However despite the quite broad list of applied examples of observation of the interaction between HCEB and matter, necessary to dwell on more detailed examination of technological features of the interaction of high-current relativistic electron beams (HCREB) with targets. As well as to investigate the influence of HCREB generated by accelerators of the NSC KIPT on construction material that are used in nuclear technologies and to establish possible areas of technological use of the observed effects.

ANALYSIS OF THE TECHNOLOGICAL FEATURES OF THE INTERACTION OF THE HCREB WITH TARGETS

In order to understand the technological prospects for HCREB in materials science necessary to compare the physical processes inherent in alternative technological approaches with those, that accompany the interaction of intense beams with solid targets.

As an example, consider a list of the basic processes that underlie the explanation of the effect of solid-phase metal compounds and technologies for producing composite materials based on it. These processes include: local heating, dynamic pressure, the activation of the atoms of the surfaces, the formation of juvenile surfaces. And, as a result – obtaining bimetallic compounds with unique properties.

Closer to the physical principles is electron beam remelting refining, allows to achieve the granular structure milling on the surface, removing impurities segregation of alloying elements in the grain boundaries.

It is known that the interaction HCREB with the target is accompanied by the influence of a number of factors: radiation, thermal, mechanical, electromagnetic [2, 3]. Features of afield of action formation for each of these factors, determined by the parameters of the beam: the energy of the particle, current, current density, pulse duration. Obviously that the free path of the particles in a target, and hence the depth of the modified layer is determined by the energy of the beam.

The mean free path of the beam determined from the expression [4]

$$d = 6,67 \cdot 10^{-11} \frac{E^{5/3}}{\rho},$$

where E is the energy of the particles, ρ is the density of the target material.

If the flux density greater than 10^{10} W·cm^2, irradiation leads to a melt of metal surface layer and the emission of the ablation plasma. Moreover, the interaction of the beam with the plasma can lead to a change in the distribution of the absorbed dose in the irradiated object [5]. In addition to changed physicomechanical properties of the observed remelted layer the adjacent to it layer corresponding to the heat affected zone. It should be noted, that the zone of thermal influence is a qualitative characteristic, which defines the upper limit of the temperature range of the melting point and lower as the temperature corresponding to the possible occurrence thermal transformations (phase transformations, recrystallization annealing, etc.). In this respect, the relativistic beams have the peculiarity that the thickness of the modified layer may be about 100 microns - value is sufficient to remote welding technology, hardening of friction pairs, the manufacture of cutting tools.

High current pulsed electron beam irradiation is characterized by the fact that in some cases the region of radiation-induced transformations that consist in the change of the grain structure, changes in the density and orientation of dislocations, etc. exceeds the melting depth of the target and, in some cases, the depth of the temperature action region, which has been called the effect of action at a distance [2]. The physical nature of this effect is explained by the formation of elastic and shock waves in the target volume.

Shock-wave impacts arising in the target volume after a single exposure, consists of two components:

$$\sigma_1 = \sigma_t + \sigma_j , \qquad (1)$$

where σ_t - component caused by thermoelastic mechanism, σ_j - amplitude of the stress caused by reactive impact due to the ablative ejection of matter.

The value of the stress caused by thermoelastic mechanism is given by [6]:

$$\sigma_t\left(r,t\right) = \Gamma \cdot \varepsilon\left(r,t\right), \qquad (2)$$

where $\varepsilon\left(r,t\right)$ - density of the absorbed radiation energy in the medium, Γ - Gruneisen parameter of matter

$$\Gamma = \frac{\alpha}{k \cdot \rho \cdot c}, \qquad (3)$$

where α, k, ρ, c - coefficient of the thermal expansion, compressibility, density and specific heat of matter, respectively.

Assess the magnitude of the mechanical impact caused by ablation ejection can be made by the pressure of produced plasma in the energy absorption region of the electron beam [5]

$$\sigma_j = (\gamma_{eff} - 1) \cdot \omega, \qquad (4)$$

where $\gamma_{eff} = 1.2$ - ratio of the specific heats of solid and plasma; ω – volumetric energy density of input radiation to the target, J/cm^3.

According to the paper [2], the condition of formation of shock waves is the fulfillment of ratio

$$I \geq \frac{C_L^4 \rho R_0 \tau}{S}, \qquad (5)$$

where I - intensity of the beam, C_L - longitudinal velocity of sound in the target material, ρ - density, R_0 - path of electrons in the target, S - area of the irradiated surface, τ - pulse duration.

THE EXPERIMENTAL TECHNIQUE

Currently, there is a tendency of development of scientific bases of radiation technologies based on HCREB using the existing accelerator base, created earlier for special applications. The experiments were carried out on pulsed electron accelerators NSC KIPT [6] TEMP-A (2 kA current, electron energy of 0.3 MeV, the pulse duration is 5 ms) shown on Fig. 1, and TEMP-B (5 kA current, electron energy of 0.5 MeV, the pulse duration is 1.5 ms), total energy of the beam ~ 5.3 kJ, shown of Fig. 2.

Fig. 1. Accelerator TEMP-A

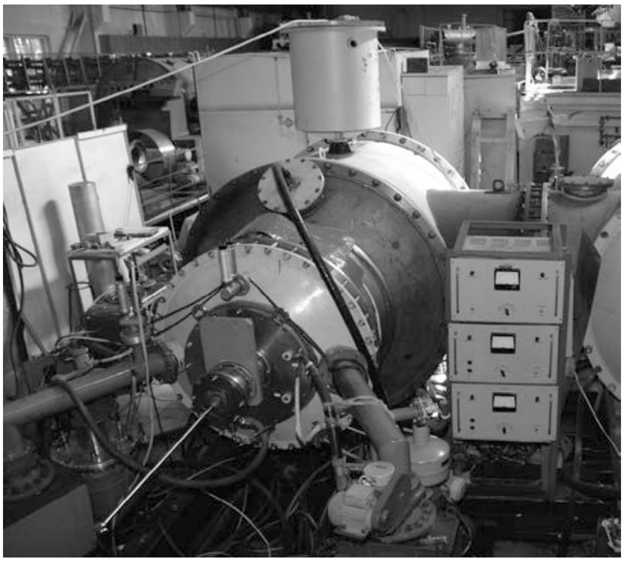


Fig. 2. Accelerator TEMP-B

Tubular relativistic electron beam is formed in the vacuum diode as a result of explosive emission on the edge of a cylindrical stainless steel cathode feeding it a large negative potential. To reduce the length of the cathode stem the driving magnetic field solenoid structurally incorporated within the accelerating column. Moreover, the magnetic flux lines extending from the end of the solenoid, closes the high-voltage electrode of the accelerating column. Such decision has allowed drastically reduce leakage currents from the cathode holder, remove the vacuum electron bombardment of the surface of the accelerating tube and increase the efficiency of energy transfer from the power source into a beam. Electron accelerators are magnetically insulated diodes with "reversed" magnetic field.

In order to increase the density of the energy released at the surface, was formed a tubular beam with a diameter of 60…70 mm and wall thickness of the beam

– 2 mm. Energy density released at the surface of the irradiated target was ~ 1 kJ/cm^2. The intensity of irradiation was about 10^9 W/cm^2. Targets of tungsten, tantalum, copper, aluminum and molybdenum were irradiated.

Fractographic studies were performed using scanning electron microscope JEOL JSM-840 and SEM-10, metallurgical studies were performed using a microscope MIM-10.Fracture of the first part of samples was carried out in liquid nitrogen, the second part of samples subjected to fracture at room temperature. The testing on the cavitation resistance is mounted on the basis of the ultrasonic generator UZDN-22T, the frequency of 20 kHz, power of 400 W.

TECHNOLOGICAL APPROACHES TO THE USE OF HCREB

As noted above, HCREB can be used for modifying and testing impacts. At the same time modifying impacts may involve the direct irradiation of material surfaces, impacts to an intermediate target to remote welding, irradiation of the target to condense backscattered evaporation products onto the substrate.

In this regard, it was carried out irradiation of materials that can be used in nuclear power plants in the conditions of high-intensity radiation and temperature impacts. Molybdenum targets thickness of 0.3 mm have been irradiated at the accelerator TEMP-B.

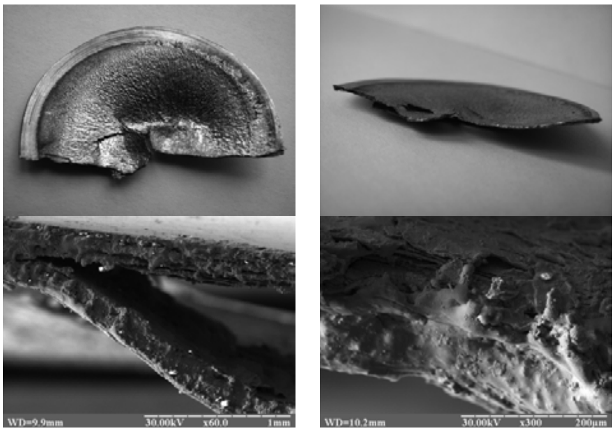


Fig. 3. The target of molybdenum irradiated and HCREB - general view of the target; fractogramm of destruction area

As seen from Fig. 3, the irradiation with such values of intensity targets is destroyed, simultaneously from fractogramm it should be noted that irradiation remelted layer has a continuous structure, whereas the source has a characteristic of molybdenum layered structure. Caused by irradiation mechanical effects have resulted to the bundle of the target. At the same time, for example, when solving the problem of remote welding possible to have data on the recommended thickness of the applied foil.

Welding is one of the ways of modifying the surface properties of metal products, used as a cutting tool operating in conditions of cavitation wear undergoing shock loads and others [1]. Usage for material welding pulsed high-current relativistic electron beams enables to reach a number of positive effects in perspective. This is due to the fact that when electrons beam to the elements pulsed is a sequence of processes: melting of the coating material, the messages melt pulse movement in the direction of the substrate and the activation of the electronic and ionic systems at high pressures and high temperatures. Specified method combines the elements of the process of electron beam welding, explosion welding, plasma and induction welding.

Considering the nature of the pulse impacts such traditionally problematic stages of welding as a preferential evaporation of the fusible elements that causes the occurrence of slag inclusions in the transition region coating-substrate cracking, discontinuities, and others require a separate study.

Ongoing studies of aluminum welding on tungsten substrate are of practical interest for the production in the surface region of the alloy of tungsten and aluminum, characterized by high-temperature strength and oxidation resistance. Due to significantly different values of the melting temperature of both materials, the mechanism of contact consisted in the diffusion penetration of molten aluminum into the surface region of tungsten. Upon placement in cavitation field coating was easily removed from the surface, and low-temperature fracture coating material shows peeling from the substrate, as can be seen in Fig. 4.

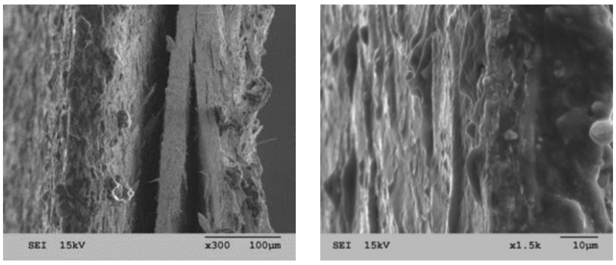


Fig. 4. Fracture surface of the tungsten weld aluminum layer

However, a more detailed examination reveals that the aluminum coating has a uniform fine-grained structure. Fusing is possible to be achieved if duplex treatment consisting in repeated irradiation coating deposited on the surface [5].

Sufficiently good quality of adhesion been observed in surfacing of tantalum on Steel 45. These coatings were investigated in more detail. Inflicted coating characterized by islet nature of contact with the substrate, and the presence of slag inclusions caused by higher volatility fusible element by beam evaporation and their deposition of on the product. In order to determine the specific values of the effective grasping area with a substrate, the applied coating were tested in cavitation. This kind of impact was selected as test by the fact that it provides preferential removal of slag, as well as those fragments of coatings that at condensing had not sufficient energy to create an adhesive bond. As already noted, this welding method has common features with other electron beams and others methods of welding, but as for quantitative estimation is appropriate to address to the geometrical criteria that characterize the stage of the process. Described in [1] on page 366 form factor in this case is

$$\chi = \frac{S_o}{h_i}, \qquad (6)$$

where S_o - area of solid (non-removable during the cavitation process) contact coating to the substrate, h_n - penetration depth into the substrate. These values were determined by comparing the initial weld surfaces (Fig. 5,a) to the surfaces after cavitation treatment (Fig. 5,b). Since the surface of the coating contains a condensed product, volatile elements with low atomic weight, contained as an impurity, and the natural unrepaired pollution for their removal product was exposed of cavitation processing. Surface after cavitation treatment shown in Fig. 5,b.

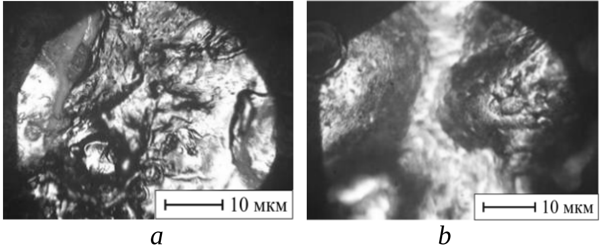


Fig. 5. Steel 45 with the surface of the weld layer of tantalum: a) – original; b) - after cavitation processed

Images of the same surface, subjected to bending, obtained by a scanning electron microscope at different magnification, shown in Fig. 6. As can be seen in the coating is present drip component and surface fracture occurs on the line of separation regions that have adhesion to the substrate.

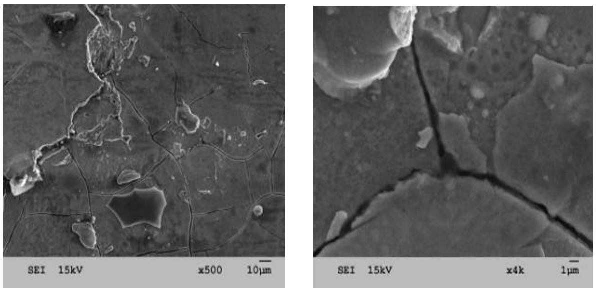


Fig. 6. The surface of the Steel 45 weld with a layer of tantalum

The depth of penetration was determined by manufacturing microsections perpendicular inflicted layer and measuring the penetration depth in the material.

Also introduced such as the estimated value of the coefficient of the effective area of contact:

$$\gamma = \frac{S_0}{S}, \tag{7}$$

where S - total area of the source of the coating. By the results of the observations, it was found that the optimum thickness of the foil, which provides preferential melting of substrate side.

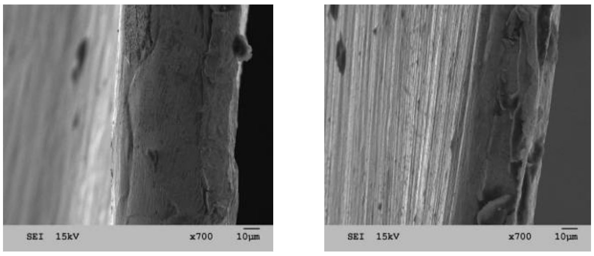
This mode of melting provides the maximum acceleration of the melt particles and hence possibility of sufficiently complete coverage. As another obvious criterion that allows you to perform optimization of surfacing technology using the high-current relativistic electron beams is the utilization factor of the material

$$\alpha = \frac{d_f}{d_s}, \tag{8}$$

defined as the ratio of the thickness d_f of the evaporated layers of foil to the thickness d_s of the coating. This parameter allows evaluating the use efficiency of the coating material, correctness of the choice of foil thickness, the distance from the foil to the substrate.

It should be noted that in the case of thin foils having a thickness comparable to the mean free path of electrons nature of material evaporation significantly depends on the spatial distribution of the absorbed dose. Is obvious that for a more efficient ejection of molten coating material and to achieve its maximum pulse is preferred to melt started on the side facing the target.

Therefore, metallurgical studies of tantalum foil irradiated by high-current pulsed electron beam have been carried out. In particular, the low-temperature fracture was examined of the foil thinned due to exposure to the of initial thickness 50 microns to 30 microns in order to establish the zone of maximum energy release on structural changes along the path of the electrons (Fig. 7). As can be seen, after irradiation structure becomes more uniform, and although in both cases the fracture occurs by a viscous mechanism to the original sample a large fragility, is inherent which resulted in fracture to appearance of pit fracture fragments having a long shape.



a b

Fig. 7. The fracture in the tantalum foil: irradiated sample (a); non-irradiated sample (b)

Tantalum foil placed at different distances from the substrate d. The results of these studies are summarized in Table.

The dependence of the characteristics of the tantalum welded layer on the substrate of Steel 45 of the distance (foil-substrate)

d, mm	α	γ	χ, mm
5	0.9	0.7	7
10	0.85	0.8	9
15	0.6	0.5	11

As can be seen from the table, better value for the most important specifications - coefficient effective contact area is achieved when the distance from the foil to the substrate of 10 mm.

The next direction of technological use of HCREB is irradiation and subsequent condensation products formed by the target ablation. At the accelerator TEMP -A copper target was irradiated using the near target equipment, allowing condensation to position the substrate ablation products (Fig. 8).

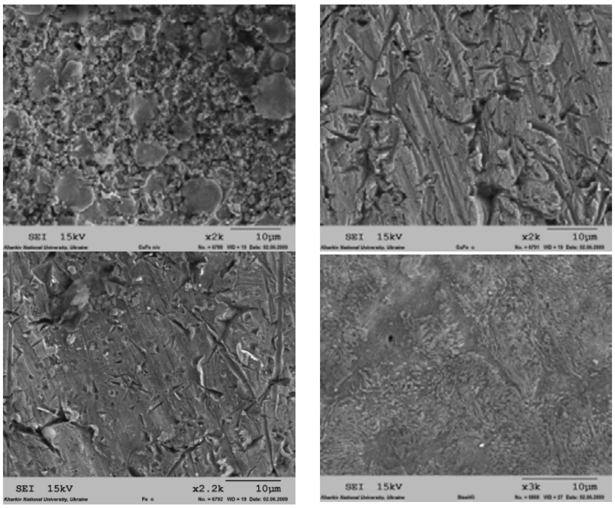


Fig. 8. Products of copper condensation

CONCLUSIONS

The direction of the possible use of high-current accelerators for material applications is determined. Irradiation of metals and alloys by high-current relativistic electron beams with energies of particle 0.3…0.8 MeV can reproduce the set of effects: obtaining the fine-grained structure as a result of remelting of the surface, generation of the shock waves causing creation of softening layers deep inside the target as well as the destruction of the target. This opens up new prospects for the development of radiation technologies:

- aimed achievement of the gradient operational characteristics in the volume of solid irradiated target;
- testing of the operating characteristics stability of the nuclear installations materials by modeling the radiation, temperature and shock-wave influences;
- remote welding of protective coatings and coating by condensation of backscattered ablation products on the surface of construction materials.

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Article received 02.10.2013

ОСОБЕННОСТИ ВОЗДЕЙСТВИЯ СИЛЬНОТОЧНЫХ РЕЛЯТИВИСТСКИХ ЭЛЕКТРОННЫХ ПУЧКОВ НА МИШЕНИ ИЗ КОНСТРУКЦИОННЫХ МАТЕРИАЛОВ

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Рассматриваются возможные подходы к практическому использованию эффектов, наблюдаемых при воздействии сильноточного электронного пучка с энергией частиц порядка 0,5 МэВ на твердые тела. Проанализированы физические механизмы, приводящие к превращениям в облучаемых мишенях. Приведена классификация возможных способов технологического облучения поверхностей материалов: непосредственного облучения, воздействия на промежуточную мишень с целью дистанционной наплавки, облучения мишени с целью конденсации обратнорассеяных продуктов испарения на подложку. Представлены результаты исследований модифицирующих воздействий на различные материалы.

ОСОБЛИВОСТІ ВПЛИВУ ПОТУЖНОСТРУМОВИХ РЕЛЯТИВІСТСЬКИХ ЕЛЕКТРОННИХ ПУЧКІВ НА МІШЕНІ З КОНСТРУКЦІЙНИХ МАТЕРІАЛІВ

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Вивчаються вірогідні підходи щодо практичного використання ефектів, які спостерігаються при взаємодії потужнострумового електронного пучка з енергією частинок порядку 0,5 МеВ з твердими тілами. Проаналізовано фізичні механізми, які призводять до перетворень в опромінених мішенях. Наведено класифікацію ймовірних методів технологічного опромінення поверхонь матеріалів: безпосереднього опромінення, впливу на проміжну мішень з метою дистанційного наплавлення матеріалу, опромінення для конденсації зворотньорозсіяних продуктів випаровування на підкладку. Наведено результати досліджень для різних матеріалів.