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ESTIMATION OF THE EFFECT OF HIGH-CURRENT ELECTRON BEAM IRRADIATION ON THE RADIATIVE HEAT TRANSFER MODES ON THE MOLYBDENUM TARGET

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The article proposes the method for full-scale modeling of the influence of a concentrated energy flux on the reflective properties of an irradiated molybdenum surface. Such research allows us to deepen our understanding of how powerful radiation can affect the processes of radiative heat transfer. The features of structural changes at the macrolevel of the irradiated surface are studied. A quantitative model is proposed to assess the degree of heterogeneity of the distribution of the IR radiation reflectance depending on the angle of irradiation. The applied value lies in the possibility of testing structural materials for their use in fusion units.

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INTRODUCTION

One of the important tasks of practical implementation of energy sources based on thermonuclear fusion is to justify the choice of materials for the first reactor wall, in particular, ensuring its resistance to stationary temperature loads and extreme ones, for example, plasma cord rupture, which is accompanied by a direct exposure on the wall of a concentrated energy flow. To assess the resistance of a material to the action of highly intense radiation flows, various tools are used, for example, plasma accelerators [1, 2], neutron sources, high-current electron accelerators [3]. In our work [3], we partially considered the problem of assessing the resistance of molybdenum as a structural material when conducting research on controlled thermonuclear fusion. It was noted that the exposure on the surface of a high-current relativistic electron beam (HCEB) causes both a change in the structure of the near-surface layer and the formation of a rough surface, which is reflected in the reflectance of IR radiation. Another important component of the assessment of the consequences of the exposure of the HCEB on structural materials is the development of knowledge for the implementation of the inertial fusion method [4]. In the case of extreme loads on the materials of the first wall, the task arises of understanding to what extent the new properties of the material acquired as a result of such exposure are able to maintain their own shape, integrity, strength characteristics, and meet the requirements for hydrogen saturation [5]. It is very important that under the conditions of temperatures at which the plasma of a thermonuclear reactor exists, the prevailing heat exchange mode is radiation heat exchange, therefore differences in the reflectance coefficient of IR radiation can significantly affect the redistribution of temperature fields, the occurrence of thermal stresses in structures, and, if they are cyclical, become an additional destructive factor.

Given the importance of this, infrared thermography has been used in a number of fusion devices [6–8] and has been a key diagnostic tool for monitoring temperature and studying thermal loads on elements facing the plasma, in order to understand the actual values of their thermal load and to study the possibilities of preventing their loss of operational characteristics. Therefore, the task of assessing how irradiation of the surface with its partial inevitable melting will be reflected in the reflectivity (in the IR range) of the surface of the refractory material arises.

Optical methods are one of the tools for assessing the roughness of the microstructure [9] of the surface. These methods consist in the fact that the reflection or scattering coefficients are determined by the microrelief of the surface and, thus, by comparing the basic radiation flux of a certain optical range with the characteristics of the flux reflected from the studied surface, one can draw a conclusion about both its roughness and the role of the initial structure in the formation of the microrelief due to irradiation [9].

In [10], a method for estimating the roughness of metal plate surfaces using the thermographic method in the IR range was described. The authors showed that an increase in surface roughness increases the root mean square deviation of the radiation temperature, which was recorded at an angle of 90 degrees from the surface irradiated by a source of a quasi-uniform IR field at a given angle. These patterns were valid for cases where the radiation source was located starting from a certain distance. At smaller distances, the pattern of an increase in the root mean square deviation of the temperature with increasing roughness was observed up to a certain roughness value, and then its value decreased.

Since the effects of concentrated energy flows on the wall are expected under the operating conditions of a fusion plant, it is of interest to give a quantitative assessment of how this can affect the radiation heat transfer regime.

METHODOLOGY OF EXPERIMENT

A 1 mm thick molybdenum plate was used for the research, which was irradiated with an electron beam with the following parameters: electron energy 350 keV, beam current 2 kA, pulse duration 5 μs, beam diameter 60 mm. The distribution of current density in the beam cross-section was non-uniform, which was due to the shape of the cathode.

Thermographic measurements were made with a Fluke Ti 32 camera. The processing of the results of thermographic measurements was carried out using standard thermographic data processing tools as well as author's software, using a thermographic data matrix.

Fractures of irradiated molybdenum samples were studied using a JEOL-840 scanning electron microscope.

RESULTS AND DISCUSSION

A feature of the treatment of metal targets with a high-current relativistic electron beam with the parameters electron energy 350 keV, beam current 2 kA, pulse duration 5 μs is the formation of a complex relief on the surface. As a result of irradiation, a different-scale surface roughness is formed, which is characterized by curvatures, large drops (scale 1 mm), and smaller-scale formations (Fig. 1). It should be noted that different mechanisms are responsible for the formation of these surface fragments. Thus, the different degree of surface erosion is due to the non-uniformity of the beam current density in the cross-section and, accordingly, the different intensity of evaporation of the substance, which is monitored when studying the dynamics of the expansion of a gas-plasma torch [11]. The non-uniformity of the solidified substance after irradiation is responsible for the spatial heterogeneity of internal stresses caused by the thermoelastic effect [12, 13], which leads to the fact that the movement of the crystallization front occurs under the action of an acoustic-thermal pulse. The field of influence of the thermoelastic effect will be determined by the expression [13]

$$\sigma(r,z,t) = \Gamma \cdot D(r,z,t), \qquad (1)$$

where $\Gamma = \dfrac{\alpha}{\kappa \cdot c \cdot \rho}$ – Grüneisen coefficient; κ – tightness; α – specific heat capacity; ρ – density; $D(r,z,t)$ – absorbed radiation energy. Due to the symmetry with respect to the beam axis, we consider cylindrical coordinates, neglecting the azimuthal component. Formula (1) determines the stresses in the solid part of the target, while hydrodynamic disturbances in the molten part will be additionally caused by changes in thermophysical characteristics due to the phase transition from solid to liquid and from liquid to gaseous. Under such conditions, Richtmyer-Meshkov instability will form, which will consist in local penetrations of a denser phase into the neighboring one. Another component of the occurrence of stresses will be the pressure generated during the evaporation of the substance, the value of which is described by the expression [14].

$$\sigma_r = \frac{E}{\left[M / 2k_B T\right]^{1/2} W}, \qquad (2)$$

where E – internal energy of the vaporizing substance; M – mass of a molybdenum atom; k_B – Boltzmann's constant; W – specific energy of evaporation of the liquid phase.

Given that the current density in the beam cross-section is non-uniform, we also obtain a non-uniform distribution of the absorbed radiation energy. The pulse front duration is 5 μs, during which the accelerating voltage and current values also have a pulsed nature, as can be seen from the oscillogram in Fig. 1.

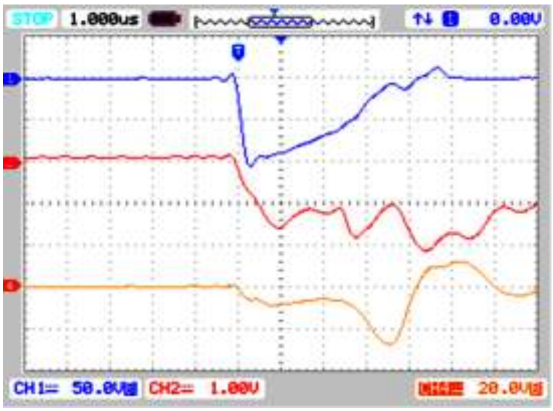

Fig. 1. Oscillogram of the electron beam pulse (upper curve – accelerating voltage, middle curve – beam current value, lower curve – total electric current of the diode)

Thus, we have two sources of non-uniformity due to only electrophysical parameters: one caused by the beam current density, the other by the non-uniformity of the radiation parameters during the pulse action. The irradiation of the molybdenum target was carried out with a single pulse. As a result of the irradiation, a part of the surface melted in places where the absorbed dose was sufficient. Fig. 2 shows the fractograms of the fracture of the near-surface layer of the target. As can be seen, cylindrical pores (contoured by red color rectangular) are formed and the grains are elongated along the direction of internal stress formation pores (contoured by blue color rectangular). High-pressure pulses are also capable of causing a decrease in the lattice period, which was confirmed by us in the work [15].

The formation of pores can be caused by the presence of a small amount of low-melting impurities on the surface, which have a lower melting point and form local areas of superheated liquid, the pressure in which is insufficient to violate the integrity of the surface layer. Hollow formations will also be reflected in the thermophysical properties. A decrease in grain size will lead to a deterioration in heat transfer, which was also noted in [16], which studied the effect of laser radiation on the surface of molybdenum. In the case when the internal energy of the locally molten area is sufficient to destroy the outer layer, craters appear, as indicated in [17]. Relaxation of internal stresses caused by a change in the green structure can also form deformation reliefs, as discussed in [18, 19]. The nature of radiation heat transfer will depend on the presence of surface curvatures after irradiation. The formation of the surface relief will occur under conditions of spatial temperature differences. Thus, the dynamics of the temperature field of the molten part of the target will be determined by heat removal into the depth of the target, heat removal to the periphery of the target, and also by the non-uniformity of the beam current density itself. The presence of a temperature difference along the surface can lead to the occurrence of Marangoni instability, which is observed when concentrated energy flows are applied to the surface of metals [20], this instability is another reason for the occurrence of irregularities on the target surface.

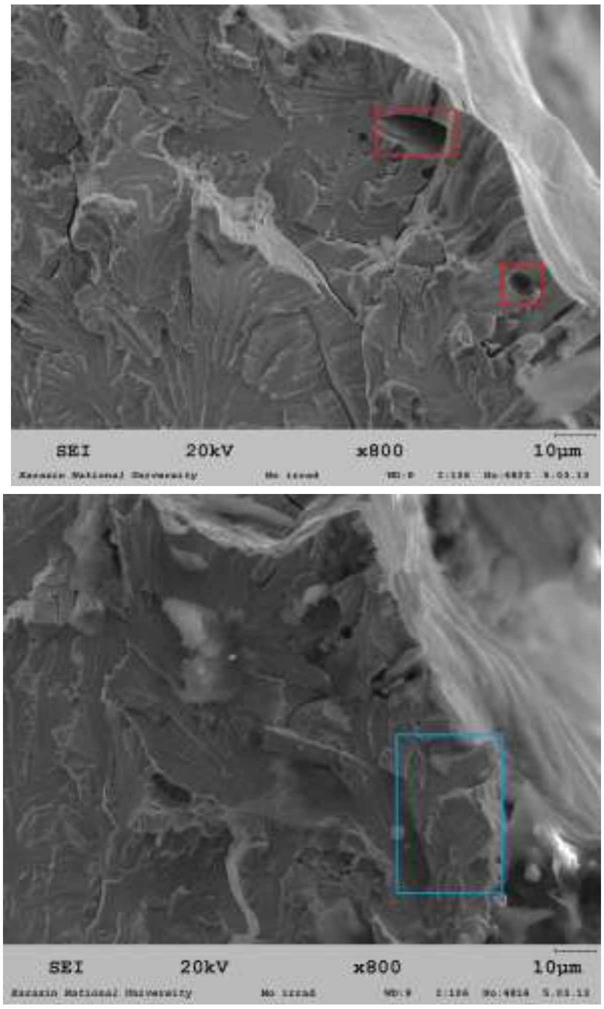

Fig. 2. SEM image of fracture areas of the molybdenum target in the near-surface region

Experimental and numerical studies show that as a result of the action of high-current electron beams on the surface of metals and alloys, a surface with a complex relief is formed [21]. It can be expected that at a curvature scale of 10 μm and more, the angle of incidence of the IR radiation flux will affect the value of the radiation reflection coefficient.

The importance of understanding the influence of the shape features of the formed relief is as follows. In the conditions of a thermonuclear reactor, the predominant part of the heat exchange between the plasma and the reactor walls is carried out in the radiation heat exchange mode. The heterogeneity of thermal loads in the initial state is due to the heterogeneity of the spatial density of the plasma, but in the case of direct plasma exposure on the wall materials, a change in the micro and macrostructure occurs, as a result of which the value of the reflection coefficient in the IR range changes. This, in turn, causes the heterogeneity of the distribution of temperature loads already determined by the state of the surface of the first wall. It is to reproduce the process of damage to the first wall that the molybdenum target was irradiated with a HCEB. Subsequently, the target was placed in a test stand, where an intense stream of IR radiation was directed at the target at different angles, which, after reflection from the target, was recorded by a thermographic camera. Fig. 3 shows a thermogram of a fragment of the surface of the irradiated molybdenum target.

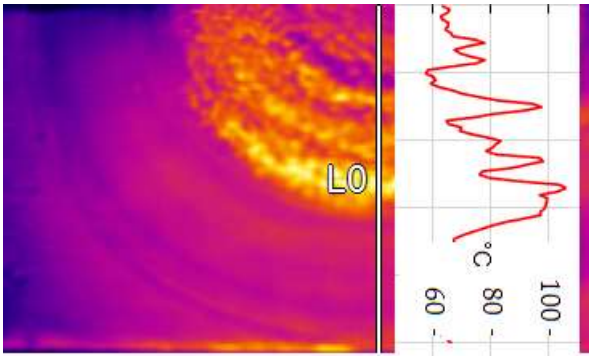

Fig. 3. Thermogram of a fragment of the surface of an irradiated molybdenum target (on the right, the distribution of radiation temperature along the L0 line)

The figure shows that at the same thermodynamic temperature, the value of the radiation temperature is significantly non-uniformly distributed over the surface. The fluctuations in the values of the radiation temperature are an indirect reflection of the non-uniform distribution of the absorbed dose over the surface. Such non-uniformity could not be due solely to the non-uniformity of the beam current density. There is obviously a contribution from various mechanisms of formation of hydrodynamic instabilities. Having obtained a set of thermograms of the irradiated target, the apparatus for quantitative assessment of the non-uniformity of the radiation temperature field was used to establish differences in the spatial distribution of the radiation temperature field due to the change in the reflection coefficient caused by irradiation. The absolute values of the radiation temperature obviously decreased with increasing deviation from the normal of the angle of incidence on the target. At the same time, under the condition of uniform distribution of roughness, the influence of the reflection coefficient from different angles of incidence should be the same. In the case of the formation of a certain surface texture caused by irradiation, we can expect an non-uniform change in the reflection coefficient for different angles. Since the value of the reflection coefficient will be non-uniformly distributed over the surface, it is important for us to assess the dependence of its integral generalizing value on the angle of incidence of the radiation flux. One of the numerous tools for quantifying the background of IR radiation is the use of Shannon entropy, as was done, for example, in [22]. When registering the radiation flux with a thermally sensitive matrix, the Shannon entropy will be determined from the expression:

$$H_k = -\sum_{i=0}^{I} \frac{n_i}{N} \ln \frac{n_i}{N}, \qquad (3)$$

where n – the number of pixels in the selected temperature cluster corresponding to the value of the conditional radiation temperature I ; N – the total number of pixels covered by the studied area on the thermogram. Preliminary clustering of the array into 40, 50, and 60 temperature intervals was carried out, which was done in order to verify the obtained data. The entropy values are shown in Fig. 4 , it is obvious that for a larger number of temperature intervals the entropy will be greater.

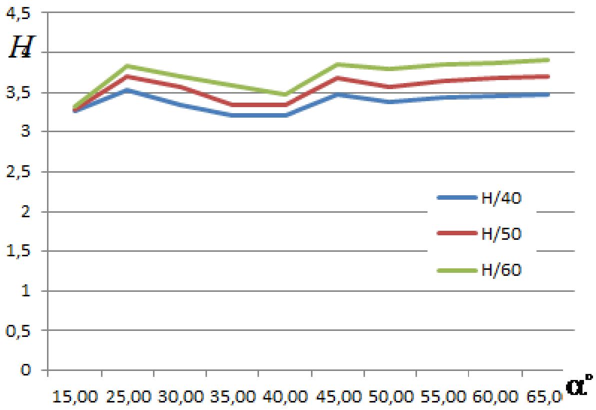

Fig. 4. Dependence of Shannon entropy for the reflection coefficient on the surface of a molybdenum target on the angle of incidence of IR radiation (for previously made clusters at 40, 50, and 60 intervals)

With increasing angle between the normal to the surface and the incident vector of IR rays, the entropy value increases, probably due to mutual scattering on neighboring irregularities and the creation of a pseudo-uniform background. At the same time, at a certain angle of incidence, a decrease in entropy is observed, which may be due to the anisotropy of the relief shape, which arises on a macroscale due to the hydrodynamic instabilities formed in the molten layer of the target.

CONCLUSIONS

Irradiation of the molybdenum surface to remelting with high-current electron beams leads to the formation of a spatially disordered surface relief of various scales. The nature of the irregularities is influenced by the non-uniformity of the electron beam current density, the non-uniformity of the heat flux absorption field by the target volume and the mechanisms of hydrodynamic instability that arise in the liquefied part of the target material.

The influence of the newly formed relief on the non-uniformity of the reflectance coefficient in the IR range at different directions of irradiation can be assessed by registering the reflected flux to determine the value of Shannon entropy in the matrix array of the radiation temperature field.

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REFERENCES

1. A.A. Shoshin, A.V. Arzhannikov, A.V. Burdakov, et al. Plasma-surface interaction during iter type i ELMs: Comparison of Simulation with QSPA Kh-50 and the GOL-3 Facilities // *Fusion Science and Technology*. 2011, v. 59(1), p. 57-60; DOI.org/10.13182/FST11-A11574

2. I.E. Garkusha, V.V. Chebotarev, S.S. Herash-chenko, et al. Novel test-bed facility for PSI issues in fusion reactor conditions on the base of next generation QSPA plasma accelerator // *Nuclear Fusion*. 2017, v. 57(11), p. 16011; DOI 10.1088/1741-4326/aa7924

3. S.E. Donets, Yu.F. Lonin, A.G. Ponomarev, et al. Behavior of molybdenum target in condition of irradiation by the high current relativistic electron beam // *Problems of Atomic Science and Technology*. 2018, N 6(118), p. 229-232.

4. G. Yonas. Fusion Power with Particle Beams // *Sci. American*. 1978, v. 239 (5), p. 40-51.

5. Chase N. Taylor. Hydrogen and its detection in fusion and fission nuclear materials – a review // *Journal of Nuclear Materials*. 2022, v. 558, p. 153396; DOI.org/10.1016/j.jnucmat.2021.153396

6. Y. Gao, M. Jakubowski, P. Drewelow, et al. Approaches for quantitative study of divertor heat loads on W7-X *// 14th Quantitative InfraRed Thermography Conference*, 25-29 June 2018, Berlin, Germany, p. 81-82; DOI 10.21611/qirt.2018.p23

7. X. Courtois, M.H. Aumeunier, Ph. Moreau, C. Balorin, et al. Full coverage infrared thermography diagnostic for WEST machine protection *// Fusion Engineering and Design*. 2019, v. 146, p. 2015-2020; DOI.org/10.1016/j.fusengdes.2019.03.090

8. A. Saifi, A.E. Amiri1, A. Elhassnaoui, A. Obbadi, Y. Errami, S. Sahnoun. Use of the active thermography for the detection of cracks in metal structures of nuclear power plants *// Proceedings of Engineering and Technology (PET) Copyright IPCO*, 2016, p. 121-125.

9. A.A. Savchenko, A.I. Belyaeva, A.A. Galuza, I.V. Kolenov. The role of surface energy anisotropy in the formation of a stepped relief of polycrystalline W under sputtering with Ar ions // *Journal of Applied Physics*. 2019, v. 125(6), p. 06530.

10. M. Kaluza, R. Olbrycht. Thermographic method for metallic surface roughness evaluation // *16th Quantitative InfraRed Thermography Conference*, 4–8 July 2022, Paris, France, p. 1-2.

11. V.F. Klepikov, V.V. Lytvynenko, Yu.F. Lonin, A.G. Ponomarev, O.G. Tolstolutskiy, V.V. Uvarov, V.T. Uvarov. The dynamics of the gas – plasma torch induced by the high current REB on solid state targets // *Problems of Atomic Science and Technology*. 2009, N 1(59), p. 119-121.

12. Y. Qin, J. Zou, C. Dong, et al. Temperature–stress fields and related phenomena induced by a high current pulsed electron beam // *Nuclear Instruments and*

Methods in Physics Research B. 2004, v. 225(4), p. 544-554; DOI.org/10.1016/j.nimb.2004.06.008

13. I.I. Zalubovskiy, A.I. Kalinichenko, V.N. Lazurik. Vvedenie v radiacionnuyu akustiku. Kharkov: "Vyscha shkola", 1986, 167 s. (in Russian).

14. G.Z. Ganeev, S.B. Kislitsin. Evaporation and thermal stresses in molybdenum irradiated by electrons // *Eurasian Journal of Physics and Functional Materials*. 2018, v. (2), p. 159-164; DOI: 10.29317/ejpfm.2018020208

15. V.V. Bryukhovetsky, V.F. KLepikov, V.V. Lytvynenko, et al. The features of the structural state and phase composition of the surface layer of aluminum alloy Al-Mg-Cu-Zn-Zr irradiated by the high current electron beam *// Nuclear Inst. and Methods in Physics Research B.* 2021, v. 499, p. 25-31; DOI.org/10.1016/j.nimb.2021.02.011

16. R Montanari, E. Pakhomova, R. Rossi, et al. Surface Morphological Features of Molybdenum Irradiated by a Single Laser Pulse // *Coatings.* 2020, v. 10, p. 67; DOI:10.3390/coatings10010067

17. V.V. Bryukhovetsky, V.V. Lytvynenko, O.A. Startsev, et al. Formation mechanism of craters on the surface of AA6111 aluminum alloy irradiated by quasi-relativistic high-current electron beam // *Vacuum.* 2023, v. 215, p. 112263; DOI .org/10.1016/j.vacuum.2023.112263

18. V.V. Bryukhovetsky, V.V. Lytvynenko, O.A. Startsev, et al. Mechanisms of deformation induced by high-current pulsed electron beam irradiation // *Materials Letters*. 2024, v. 367, p. 136642; DOI.org/10.1016/j.matlet.2024.136642

19. V.V. Bryukhovetsky, V.F. Klepikov, V.V. Lytvynenko, et al. The structural phase state and strength properties of the surface layer of AA6111-T4 aluminum alloy irradiated by the high-current electron beam *// Nuclear Inst. and Methods in Physics Research B*. 2022, v. 519, p. 1-8; DOI.org/10.1016/j.nimb.2022.03.008

20. P.D. Lee1, P.N. Quested, M. McLean. Modelling of Marangoni effects in electron beam melting // *Phil. Trans. R. Soc. Lond. A.* 1998, v. 356, p. 1027-1043.

21. A.L. Huspek, V. Mataloni, A. Mohtashamifar, L. Paterlini, M. Bestetti. Thermal Modelling of Metals and Alloys Irradiated by Pulsed Electron Beam: Focus on Rough, Heterogeneous and Multilayered Materials // *J. Manuf. Mater. Process.* 2025, v. 9, p. 130; DOI.org/10.3390/jmmp9040130

22. J.C. Mello Román, J.L. Vázquez Noguera, H. Legal-Ayala, et al. Entropy and Contrast Enhancement of Infrared Thermal Images Using the Multiscale Top-Hat Transform // *Entropy.* 2019, v. 21, p. 244; DOI:10.3390/e21030244

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ОЦІНКА ВПЛИВУ ОПРОМІНЕННЯ СИЛЬНОСТРУМОВИМ ЕЛЕКТРОННИМ ПУЧКОМ НА РЕЖИМИ РАДІАЦІЙНОГО ТЕПЛООБМІНУ МОЛІБДЕНОВОЇ МІШЕНІ

С.Є. Донець, В.В. Литвиненко, О.Л. Рак, В.В. Шатов, А.Р. Шимановський

Запропоновано спосіб імітаційного моделювання впливу концентрованого потоку енергії на відбивні властивості опроміненої поверхні молібдену. Таке дослідження дозволяє поглибити розуміння того, як може впливати високопотужне випромінювання на процеси радіаційного теплообміну. Досліджено особливості зміни будови на макрорівні опроміненої поверхні. Запропоновано кількісну модель оцінки ступеню нерівномірності розподілу коефіцієнта відбиття ІЧ-випромінювання залежно від кута опромінення. Прикладне значення полягає в можливості тестування конструкційних матеріалів для їх використання в термоядерних установках.