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THE SIMULATION OF EMERGENCY ACTION ON CONSTRUCTION MATERIALS BY HIGH CURRENT RELATIVISTIC ELECTRON BEAMS

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Development of many innovative areas in energy, mechanical engineering, aircraft building and other industries is limited by the strength of materials under the action of temperature gradients. In this regard, the problem appears to find and justify technical means to model a complex of operating conditions. High-current relativistic electron beams reasonably belong to such instruments and means. As a result of their impact, pulsed electric and magnetic fields occur in the irradiated targets, temperature gradients are created, and shock waves are generated. The paper investigates the patterns of change in the internal structure of the blades of gas turbine engines and engineering materials, subjected to the action of an electron beam.

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INTRODUCTION

High-current electron beams (HCEB) have a number of global applications, including the development of new methods of accelerating charged particles by wake fields generated in the plasma during the passage of electron beams [1 - 3]. In this regard, strong current beams are one of the tools for generating wake fields together with powerful lasers [4, 5].

A separate direction of application of HCEB can be the testing of materials used under conditions of strong radiation and thermal loads, for example, target converters of reactors on a subcritical assembly controlled by an electron beam [6]. Related to this matter, the studies [7, 8] proposed to use HCEB to form some bimetallic coatings resistant to radiation and heat loads. The perspectives of this approach are in application of the coating under action of a pulsed electron beam, so internal stresses will be on par with the possible critical loads that might occur during operation. The beam method to create coatings may also be enhanced with an additional modifying effect on the coating, which was previously applied by another method [9]. The article [10] describes the methods using the effect of irradiation with a constant electron beam with high spatial accuracy leveraging a complex scanning system.

A separate group of practical applications includes testing the resistance of materials from which cladding is made, to the action of extreme factors in the event of emergency situations. For example, to test the behavior of the surface protective layers of zirconium-based materials [11, 12].

On a way to solve the problems of the energy transition, in particular, the implementation of thermonuclear fusion, high-current electron beams are considered as one of the means of obtaining plasma [13]. Also, HCEB can be used as a tool for modeling residual stresses and sputtering processes that occur in the materials of thermonuclear reactors [14 - 16].

At the same time, an important component of the energy transition is the creation of maneuvering capacities that would compensate for the instability of electricity generation from renewable sources. Gas turbine engines (GTE) are the most agile power generating capacities. They are considered as a link in the disposal of solid household waste by obtaining thermal and electrical energy. Increasing the efficiency of the GTEs consists in increasing the temperature of the gas-plasma flow that interacts with the structural materials of the engine. This, in its turn, poses the task of finding out the limit values of thermal influence at which the operational characteristics of the product are preserved. HCEBs are one of the tools for creating peak radiation-thermal loads. The specifics of their use for these purposes were discussed in [17]. Future investigations are recommended to aim at a more detailed study of the mechanisms of radiation-stimulated segregation of alloying elements and the features of pore formation was required.

METHODOLOGY OF EXPERIMENT

Irradiation of the gas turbine blade samples was carried out using the TEMP-A high-current relativistic electron accelerator (NSC "Kharkov Institute of Physics and Technology" of the National Academy of Sciences of Ukraine). The accelerator is a magnetically insulated diode with an inverted magnetic field.

The relativistic beam is formed in the diode as a result of explosive emission on the surface of the cathode. The power source of the accelerator is a voltage pulse generator according to the Arkadyev-Marx scheme. Electron energy ~ 0.35 MeV, beam current ~ 2 kA, pulse front duration ~ 5 μs. Irradiation of targets is carried out discretely, with single pulses. Beam diameter equal 40 mm. Irradiation is carried out in the vacuum chamber of the accelerator at a pressure of $10^{-4}…10^{-5}$ Torr.

The analysis of the chemical composition of the local microvolumes of the initial alloy samples was carried out using the JEOL JSM-840 scanning electron microscope equipped with an attachment for energy dispersive X-ray microanalysis.

RESULTS AND DISCUSSION

For simplicity, we reduce the problem of the interaction of a high-current intense relativistic beam with a metal plate to the problem of a semi-infinite space. This is possible, because the target is firmly and tightly fixed on a thick, massive collector, which makes it possible to neglect the insignificant influence of the opposite surface on the process itself. The model is a complex dynamic thermomechanical problem. The main factor that determines the structural phase state and properties of near-surface layers during irradiation is the distribution of the absorbed dose and, accordingly, the temperature.

The mathematical formulation of the problem looks like this:

$$c \cdot \rho \cdot \frac{\partial T}{\partial t} - k \cdot \Delta T = p(r, z, t), \quad (1)$$

where c – heat capacity; ρ – density; k – thermal conductivity of the material; $p(r,z,t)$ – space-time distribution of absorbed radiation energy, initial condition $T(r,z,0) = T_0$

$$T(r,H,t) = T_0,$$

boundary condition $k \cdot \frac{\partial T}{\partial r}\Big|_{r=R} = 0,$

$$k \cdot \frac{\partial T}{\partial z}\Big|_{z=0} = 0.$$

Considering the axial symmetry of the field (1), it can be rewritten in the following form

$$\begin{gathered} c \cdot \rho \cdot \frac{\partial T}{\partial t} - k \cdot \frac{\partial^2 T}{\partial r^2} - k \cdot \frac{1}{r} \cdot \frac{\partial T}{\partial r} - k \cdot \frac{\partial^2 T}{\partial z^2} = p(r,z,t), \\ c \cdot \rho \cdot \frac{\partial T}{\partial t} - k \cdot \frac{1}{r} \cdot \frac{\partial}{\partial r}\left(r \cdot \frac{\partial T}{\partial r} \right) - k \cdot \frac{\partial^2 T}{\partial z^2} = p(r,z,t). \end{gathered} \quad (2)$$

According to the rule for obtaining a functional from a differential equation, it is possible to write:

$$I(T) = \pi \cdot \int_z \int_r \left[k \cdot r (\nabla T)^2 - 2r \left(p(r,z,t) - c \cdot \rho \cdot \frac{\partial T}{\partial t} \right) \cdot T \right] drdz, \quad (3)$$

The spatial distribution of absorbed energy in a unit of power volume can be determined by the expression

$$p(r,z,t) = P_m \cdot \exp\left[-\left(\frac{r}{r_0} \right)^2 - \left(\frac{z - z_m}{\Delta z_m} \right)^2 \right], \quad (4)$$

where r_0 is a parameter characterizing the transverse size of the beam; r – distance from the center of the beam in the plane of the surface; z_m – position of maximum energy distribution; Δz_m – its half width; P_m – maximum energy value.

Dividing the region of integration into finite elements N of order n, then, given the continuity of temperature, the function of a separate element is also determined by expression (4). The function $T(r,z)$ can be approximated inside the element by a complete polynomial of order n:

$$T(r,z) = \sum_{i=1}^{m} \alpha_i \cdot T_i, \quad (5)$$

where $m = \frac{1}{2}(n+1)(n+2)$, $\alpha_i = f(r,z)$ – interpolating polynomial.

The results of the calculation of the spatial distribution of the temperature field, which occurs after the end of the irradiation pulse, are shown in Fig. 1.

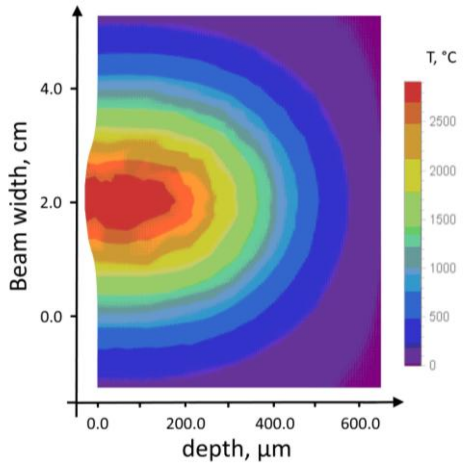

Fig. 1. Spatial distribution of the thermal field at the end of the irradiation pulse

The trace on the surface of the gas turbine blade from beam irradiation is shown in Fig. 2. It is obvious that the surface was partially melted. At the same time, three zones are distinguished: 1 – zone of the epicenter, 2 – intermediate zone and 3 – peripheral zone.

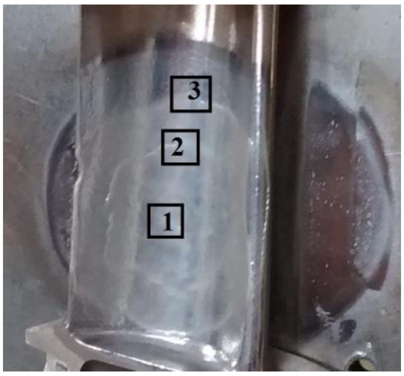

Fig. 2. The irradiated surface of the gas turbine blade

Currently, the main materials to manufacture the working blades are heat-resistant nickel casting alloys, which are complex multi-component heterophase systems. Turbine blades of gas turbine engines are made of heat-resistant corrosion-resistant nickel-based alloys by casting by the method of directional crystallization. The chemical composition of nickel alloys, which are used for the manufacture of blades, is quite complex, since each element performs its function [18]. The content of refractory metals, such as Nb, Mo, Ta, W, Re, for most of these alloys exceeds 10%, and the total content of Al and Ti is in the range from 6 to 8%. The combination of such an elemental composition of alloys due to strengthening by solid-solution and dispersion mechanisms ensures the achievement of a high value of creep resistance, which is especially important for turbine blades. The cobalt (Co) content in such alloys can also be high and range from 8 to 20%. Cobalt contributes to the strengthening of the alloy by the solid-solution mechanism. It should be noted that currently the IN738LC alloy (base Ni, 16.0%Cr, 8.5%Co, 1.75%Mo, 2.6%W, 3.4%Al, 3.4%Ti, 1.75%Ta, 0.9%Nb, 0.11%C, 0.01%B, 0.04%Zr), which well combines the values of creep resistance, oxidation resistance and structural stability [19]. The main mechanical properties, such as heat resistance, plasticity, fatigue resistance, directly depend on the structure of the alloy and its phase composition.

The microstructure of the blades is a matrix with a lattice of the *fcc* type, which contains a coherent intermetallic γ'-phase, γ + γ' eutectic, and M23C6 carbides of equilibrium morphology. The volume fraction of γ'-phase separations can be quite large and reach several tens of percent. The strengthening γ'-phase is characterized by a cubic lattice with particle sizes up to 1 µm, which is optimal for restraining high-temperature creep. In the blades studied in this work, the thickness of the protective coating on the working profile is about 100 µm. The structure of the coating consists of two zones: external single-phase and internal (diffusion) – multiphase. The content of Al in the outer zone of the coating is 18…22%, and 4…4.5% Cr. The diffusion zone contains 12…14% Al and 6…7.5% Cr, as well as an increased content compared to the main material of V, Nb, W, which creates an additional "barrier" of the elements preventing the depletion of the main material of the blades in the process operation. The microhardness of the coating has a value of about 560-630 HV0.010.

Almost all metals reduce their volume during crystallization. During solidification, a jump-like change in volume occurs. The solidified metal has a greater density than the liquid one. A decrease in volume during crystallization is called shrinkage. A decrease in the volume of the metal occurs when the metal is cooled and during the transition from the liquid phase to the solid phase. The amount of shrinkage depends on the nature of the metal. The casting begins to crystallize from the edge to the center. Since the volume of the metal decreases during solidification, the cooling of the casting must be accompanied by the appearance of empty space. This space is pores or shrinking shells. They can be filled with gases dissolved in liquid metal and released during crystallization. Pores can be located in different parts of the casting, but more often in the upper part or in the center. Shoulder blades are no exception. One of the common defects in the initial blanks of cast blades, which are characterized by a very complex geometry, is the presence of internal shrinkage defects. An example of such defects is the presence of pores in the structure of the surface layer of the blade. To eliminate the pores, hot isostatic pressing can be used, the essence of which is the simultaneous effect on casting of high temperatures and comprehensive compression in the environment of special liquids or gases. However, porosity may be present in the shoulder blades. Under the influence of electron radiation, porosity develops significantly depending on the received dose, causing the formation of cracks. In Fig. 3 the depicted surface of the blade is irradiated by the peripheral part of the beam. At the same time, we observe minimal cracks that formed due to the release of pores.

In fact, the ordered dendritic microstructure of the material is preserved in the peripheral part of the electron beam, although the formation of microcracks is observed. From Fig. 4 shows the results of microdisperse analysis of an intact part of the material (zone 3), see Fig. 2. Its basis consists of intermetallics of refractory metals formed with nickel.

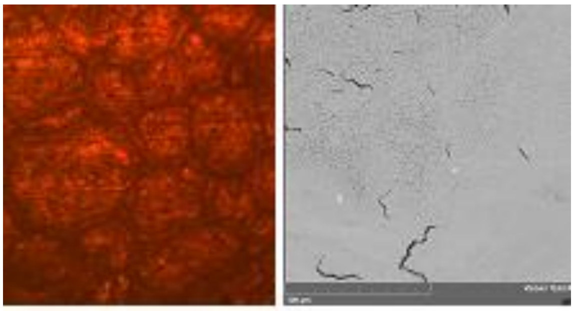

Fig. 3. Optical microscopy image (left) and SEM image (right) of the blades surface in zone 3 – the peripheral area affected by the electron beam

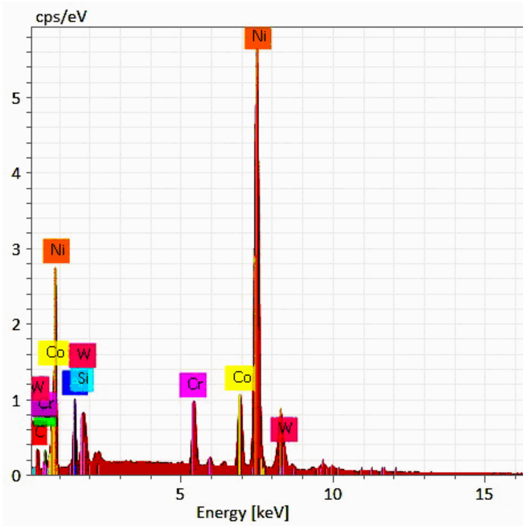

Fig. 4. Energy dispersive analysis of the blade surface in zone 3

An increase in the current density of the beam causes disorientation of grains, melting of their boundaries, and fusion. The SEM image (Fig. 5) shows that the number of cracks increased and traces of surface displacement are visible. Even in the case when the energy of the beam is not sufficient for the complete melting of the surface, an irreversible change in operational characteristics should also be expected, due to the fact that upon reaching the pre-melting temperature values, partial melting may occur along the grain boundaries, since low-melting eutectics are usually formed there [20].

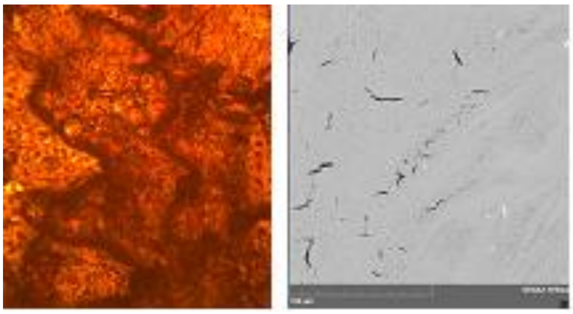

Fig. 5. Optical microscopy image (left) and SEM image (right) of the blades surface in zone 2 – the intermediate area affected by the electron beam

Analyzing the (Fig. 6) elemental composition on the surface area in zone (2), it should be noted that the mechanisms of changing the elemental composition, especially of low-melting elements such as Al, may also be caused by the presence of residual oxygen in the processing chamber. Its content at high temperatures is sufficient for the oxidation of those alloying elements that stand out on the surface, for example, Al, as we have shown in [21].

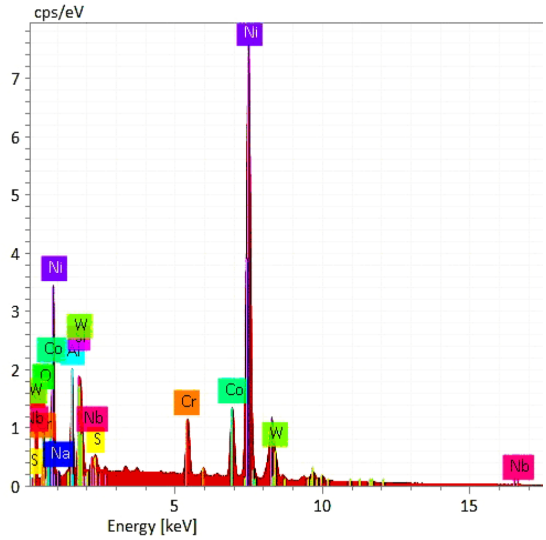

Fig. 6. Energy dispersive analysis of the blade surface in zone 2

For the zone of the most intensive exposure to radiation (zone 1), the formation of a melt, which is accompanied by the emission of a molten substance, is typical. The melt is kept in the subsurface layer for a certain time during irradiation, followed by the formation of a gas-plasma torch [22]. As a result of irradiation, a wave-like relief was formed on the surface in the area of intensive action of the beam Fig. 7, which is consistent with the results of the calculation of the field of mechanical displacements [17] and the field of temperature distribution (see Fig. 2) and shows that the molten substance shifted tangentially to the surface.

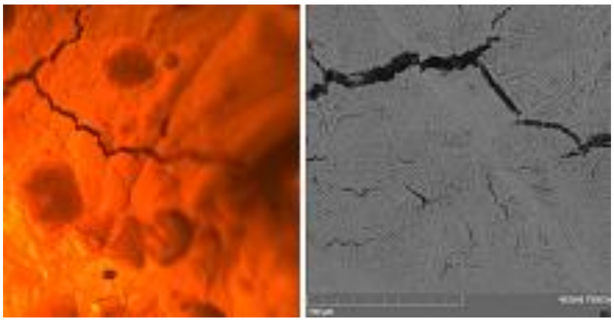

Fig. 7. Optical microscopy image (left) and SEM image (right) of the blades surface in zone 1 – the epicenter area affected by the electron beam

In the zone of intense irradiation, melting and merging of grain boundaries was observed. Among the main components of the elemental composition, there was also a redistribution (Fig. 8), in particular, the specific proportion of tungsten increased, which probably formed more refractory compounds, while other elements evaporated or moved to the neighboring area as a result of the ablation emission of the gas-plasma torch.

According to the data of [23], irradiation of the HCEB surface can also cause a change in electrophysical characteristics, as evidenced by a change in the values of ellipsometric angles in the irradiated aluminum alloy. The mechanism of such a change may consist in a change in the geometry and composition of the grain boundaries, where intermetallic phases are isolated. Structural transformations are caused by the impact of the beam. In particular, generation of high temperature gradients, internal stresses and microdisplacements, is an additional stimulating factor for the transformation of the phase composition, which is accompanied by the removal of low-melting alloying additives [24].

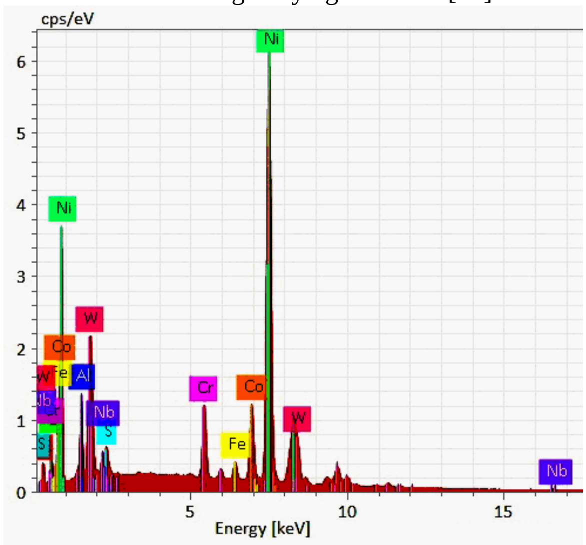

Fig. 8. Energy dispersive analysis of the blade surface in zone 1

As we can see on the example of the blade sample, as a result of beam melting, alloys with a highly ordered grain structure become amorphous, while for structural alloys with an imperfect grain structure, which needs to be improved by technological processing, beam remelting contributes to the grinding of grains and their partial ordering. This contributes to the improvement of their plastic characteristics, allows to obtain products of complex shape, avoiding the occurrence of internal stresses [25].

One of the obstacles for live monitoring of processes occurring during HCEB irradiation of targets is powerful electromagnetic pulses and bremsstrahlung streams that cause destructive effects on electronics. To prevent this, it is advisable to use protective composite metal-polymer materials [26 - 29].

The complexity of the course of processes on the target in the area of intense influence is due to the fact that a gas-plasma torch is formed along the axis, which contains an unstable ionic component with a significantly non-uniform density distribution, caused by a current jump and a disturbance of the focus of the magnetic field around the collector. This, in turn, significantly affects the processes of reverse condensation of evaporated elements [30].

CONCLUSIONS

The conducted studies show that high-current relativistic electron beams are a promising tool to study the stability of thermally loaded elements of power equipment. Among the difficulties of their introduction into production, it should be noted that accelerators of this type are single products that were manufactured for special tasks. At the same time, the mode of test trials allows the use of machines available in scientific institutions. It should be noted that the use of such beams is associated with the generation of bremsstrahlung and electromagnetic radiation flows that affect diagnostic tools. When working on them, compliance with radiation protection standards is achieved by using composite materials.

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МОДЕЛЮВАННЯ АВАРІЙНОГО ВПЛИВУ НА КОНСТРУКЦІЙНІ МАТЕРІАЛИ ІЗ ЗАСТОСУВАННЯМ СИЛЬНОСТРУМОВИХ РЕЛЯТИВІСТСЬКИХ ЕЛЕКТРОННИХ ПУЧКІВ

С.Є. Донець, В.В. Брюховецький, В.В. Литвиненко, Ю.О. Касаткін, О.А. Старцев, Ю.Ф. Лонін, А.Г. Пономарьов, В.Т. Уваров

Розвиток багатьох інноваційних напрямків в енергетиці, машинобудуванні, авіабудуванні та інших галузях обмежений міцністю матеріалів під дією температурних градієнтів. У зв'язку з цим постає проблема пошуку та обґрунтування технічних засобів, які б моделювали комплекс факторів впливу, характерних для умов експлуатації. До таких засобів обґрунтовано відносять сильнострумові релятивістські електронні пучки. В результаті їх впливу в опромінюваних мішенях виникають імпульсні електричні та магнітні поля, створюються температурні градієнти, генеруються ударні хвилі. У роботі досліджено закономірності зміни внутрішньої структури лопаток газотурбінних двигунів конструкційних матеріалів під дією сильнострумового електронного пучка.