ve been estimated. These data are close to corresponding characteristics of streamer tracks. Nonlinear interaction of discharge radiation with semiconductor in waveguide mode results in threadlike form of streamer and decreases (removes) fractures of crystal lattice. Symmetry for crystallographic direction system of streamer discharges in wide-gap semiconductors corresponds to the general principle of symmetry superposition.

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INFLUENCE OF GENERATION MECHANISMS ON PULSE PROFILE OF MECHANICAL STRESS IN METAL TAGET UNDER THE ACTION OF POWER ION BEAMS

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The system model «High power ion beam – metal» is suggested. Regularities of impulse formation of mechanical load in the volume of metal target subjected to the action of ion beams of different component composition in the range of power density $10^7...10^{10}$ W/sm² have been considered. The influence of generation mechanisms on the profile and amplitude-to-time parameters of shock-wave excitation is studied.

Introduction

Modern systems of pulse beam generation of charged particles permit of production of concentrated energy flux in the wide range of intensities $W=10^5...10^{13}$ W/sm^2, at pulse duration $10^{-8}...10^{-6}$ sec. Such a wide range of energy impact defines the excitation within the target volume of different physical phenomena and, consequently, the variety of resultant effects developed both at separate processes and their superposition. These processes could be used for solution of a great number of scientific and theoretical problems.

Intermediate power density range $10^7...10^{10}$ W/sm^2 is characterised by large quantity of excited processes (high-velocity heating, phase transitions, plasma formation, ablation, generation of acoustic and shock waves and others), parallel occurrence of which determines technological possibilities for application of high power ion beams (HPIB). Micro- and nanosecond duration of action and nonlinearity relative to the radiation conditions makes hard-to-reach for investigation of fast phase transformation experimentally. Existing experimental studies [1] give integral picture of «HPIB – metal» system and, consequently, are directed at final result of action. In general, detailed research in dynamics of real physical system is possible only in the course of numerical experiment.

A number of investigations [1–5] are devoted to the questions of shock-wave excitement generation in metals under the HPIB influence [1–5]. In the range of intensities $10^7...10^{10}$ W/sm^2 in «HPIB – metal» system the thermoelastic and shot loading mechanisms occur simultaneously. Separate examination of each mechanism is suitable only for qualitative investigation. Revealing detailed cause-effect connections (between HPIB parameters influencing metal and result of this influence expressed in deformation, dissipation processes, etc) requires the research in dissipation processes of shock-wave excitation and regularities of its transformation into acoustic ones. Development of mechanical stress pulse is in many ways conditioned by the regularities of its amplitude and spatial-time parameter formation at the stage of HPIB interaction with target. Hence, determination of topographical peculiarities in shock-wave excitation and its maximum amplitude parameters by the moment of stopping HPIB action as well as determination of their interconnections with beam parameters is an actual problem.

1. Model of elasto-plastic medium

The problem posed has been solved using authoring hydrodynamic codes presenting a generalized model of elasto-plastic medium under powerful pulse action [6]. The model is based on the Lagrange formalism for description of continuum behaviour. When using the Lagrange coordinates independent on time for description of medium motion, substantial derivatives coincide with partial ones. Partial derivatives are determined for each Lagrange particle, for this purpose it is necessary to know their current Euler coordinates.

Conservation laws, kinematical and physical relations for compressible elasto-plastic medium in the Lagrange form for cylindrical coordinate system r, z, θ can be presented as:

Motion equations

$$a_z = \frac{\partial \upsilon_z}{\partial t} = V\left[\frac{\partial \sigma_{zz}}{\partial z} + \frac{\partial \sigma_{zr}}{\partial r} + \frac{\alpha}{r}\sigma_{zr}\right],$$

$$a_r = \frac{\partial \upsilon_r}{\partial t} = V\left[\frac{\partial \sigma_{rr}}{\partial r} + \frac{\partial \sigma_{zr}}{\partial z} + \frac{\alpha}{r}(\sigma_{rr} - \sigma_{\theta\theta})\right],$$

where ; $\sigma_{zz}=S_{zz}-p$; $\sigma_{rr}=S_{rr}-p$; $\sigma_{\theta\theta}=S_{\theta\theta}-p$ are combined stresses expressed by constituents of hydrostatic pressure tensor and constituents of stress tensor deviator; $\sigma_{zr}=S_{zr}$ is the shearing stress; υ_z, υ_r are the components of velocity vector in axial and radial directions, respectively; $V=\rho_0/\rho$ is the specific volume of Lagrange particle; ρ_0, ρ are the initial and current densities of medium material; p is the hydrostatic pressure; α is the balance factor of the problem (α=0 in flat, α=1 in cylindrical case) [12].

Continuity equation

$$\frac{dV}{dt} = \frac{\partial V}{\partial t} = V\left[\frac{\partial \upsilon_r}{\partial r} + \frac{\partial \upsilon_z}{\partial z} + \frac{\alpha}{r}\upsilon_r\right].$$

Energy equation

$$\frac{dE}{dt} = \frac{\partial E}{\partial t} =$$

$$= -p\frac{\partial V}{\partial t} + V[S_{zz}\dot{\varepsilon}_{zz} + S_{rr}\dot{\varepsilon}_{rr} + S_{\theta\theta}\dot{\varepsilon}_{\theta\theta} + S_{zr}\dot{\varepsilon}_{zr}] + QV,$$

where E is the specific internal energy referred to a unit of initial volume; Q is the function of energy source; $\dot{\varepsilon}_{ij}$ are the constituents of deformation rate tensor:

$$\dot{\varepsilon}_{zz} = \frac{\partial \upsilon_z}{\partial z},$$

$$\dot{\varepsilon}_{rr} = \frac{\partial \upsilon_r}{\partial r},$$

$$\dot{\varepsilon}_{\theta\theta} = \alpha\frac{\upsilon_r}{r} = \left[\frac{\dot{V}}{V} - (\dot{\varepsilon}_{zz} + \dot{\varepsilon}_{rr})\right],$$

$$\dot{\varepsilon}_{zr} = \frac{\partial \upsilon_z}{\partial r} + \frac{\partial \upsilon_r}{\partial z}.$$

Energy source function

$$Q = q_V(z,r) + \mathrm{div}\left(\lambda\left[\frac{\partial T}{\partial z} + \frac{\partial T}{\partial r} + \alpha\frac{T}{r}\right]\right),$$

where q_V is the volume power of energy absorption, λ is the heat-conductivity coefficient.

Components of stress tensor deviator

$$\frac{\partial S_{zz}}{\partial t} = 2G\left(\dot{\varepsilon}_{zz} - \frac{1}{3}\frac{\dot{V}}{V}\right) + \delta_{zz},$$

$$\frac{\partial S_{rr}}{\partial t} = 2G\left(\dot{\varepsilon}_{rr} - \frac{1}{3}\frac{\dot{V}}{V}\right) + \delta_{rr},$$

$$\frac{\partial S_{\theta\theta}}{\partial t} = 2G\left(\dot{\varepsilon}_{\theta\theta} - \frac{1}{3}\frac{\dot{V}}{V}\right),$$

$$\frac{\partial S_{zr}}{\partial t} = G(\dot{\varepsilon}_{zr}) + \delta_{zr},$$

where $G=G(p,T)$ is the shear module, δ_{ij} is the correction including increase in stresses at turn of medium element as a single whole.

$$\delta_{zz} = -\delta_{rr} = S_{zr}\left(\frac{\partial \upsilon_z}{\partial r} - \frac{\partial \upsilon_r}{\partial z}\right),$$

$$\delta_{zr} = \frac{1}{2}(S_{zz} - S_{rr})\left(\frac{\partial \upsilon_r}{\partial z} - \frac{\partial \upsilon_z}{\partial r}\right).$$

Condition of the Von Mises plastic flow

In chosen coordinate system the following equality is true

$$S_1^2 + S_2^2 + S_3^2 = S_{zz}^2 + S_{rr}^2 + S_{\theta\theta}^2 + 2S_{zr}^2,$$

where S_1, S_2, S_3 are the main deviation stresses, consequently, The Mises flow condition has the view:

$$f = S_{zz}^2 + S_{rr}^2 + S_{\theta\theta}^2 + 2S_{zr}^2 \le \frac{2}{3\sigma_T^2},$$

Here $\sigma_T(p,T)$ is the dynamic limit of target material flow. If $f > \frac{2}{3\sigma_T^2}$, it is necessary to correct the values of deviation component by means of reduction of stresses in flow circle. For this purpose each of them is multiplied by the coefficient

$$S'_{ij}=\sqrt{\frac{2}{3f}}\sigma_T S_{ij}.$$

The S'_{ij} values corrected in such a way are used in integration of initial equation set. Such a stress reduction influences only the plastic part of stress and is equivalent to the use of complete relations for the Prandtl-Reuss theory of plastic flow at $\sigma_i=\sigma_T$ [7].

State equations

$$p=p(\rho,E).$$

Hydrostatic pressure p as well as specific internal energy is divided into elastic and thermal constituents. The first p_s, ε_s are exclusively connected with the forces of interatomic interaction and do not depend on temperature. The second p_T, ε_T are conditioned by thermal atom motion and are functions of T temperature and ρ density:

$$p(\rho,T)=p_s(\rho)+p_T(\rho,T),$$
$$\varepsilon(\rho,T)=\varepsilon_s(\rho)+\varepsilon_T(\rho,T).$$

Such an approach allows us to take into account overcoming the forces of interatomic interaction at substance expansion and phase transitions. Elastic and thermal constituents are determined by the wide-range state equation [8].

Initial and boundary conditions

Under normal conditions continuum is in unperturbed stationary state and the energetic criteria for stable equilibrium state is to be fulfilled – potential energy is minimal. This principle is used as a basis for specification of initial and boundary conditions of our model. At the initial moment of time absorbing substance is in unperturbed state. Lagrange individual particles are at rest, i. e. $\upsilon_z=\upsilon_r=0$. Deformations and stresses are absent, deviator components of stress tensor and deformation tensor are equal to zero ($\varepsilon_{ij}=S_{ij}=0$). The initial thermodynamic state is uniquely defined by the initial temperature. When introduced energy into the system the substance undergoes heat expansion and tends to a new stationary state. Introduced energy is transformed into kinetic one of expanding substance, into thermal and elastic constituents of internal energy. In terms of our model new stationary state corresponds to minimum of complete internal energy, but parameters in the minimum point dictate the boundary conditions («substance – vacuum» boundary). In this case total pressure at the boundary is equal to zero, but density, temperature, internal energy and velocity of boundary motion are defined by the substance adiabatic expansion. Such an approach permits for more correct determination of all state parameters in fictitious cell.

2. Results of numerical simulation and their discussion

In the course of numerical experiments the processes of pulse formation of mechanical excitation generated under the HPIB influence in metal plate at power density $10^7...10^9$ W/sm^2 have been studied. The latter varied with change of ion current density at fixed amplitude values of accelerating voltage U=660 kV and beam duration τ=120 nsec. The forms of accelerating voltage pulses and current density were set according to the real parameters obtained in «VERA» accelerator (Fig. 1) [9]. The beams of different component composition (partial amount of carbon ions and protons) were considered.

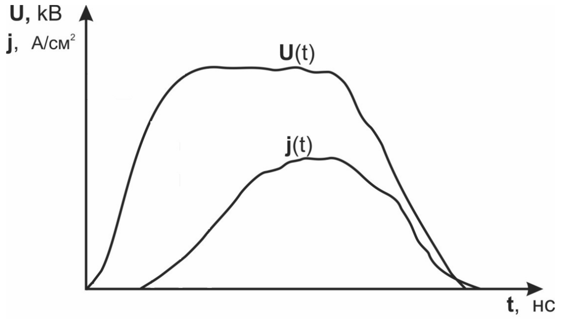

Fig. 1. *Amplitude-time pulse sweep of accelerating voltage and ion current density at output of generation unit*

In Fig. 2 the characteristic pulse of mechanical excitation formed in the aluminium target by proton-carbon beam (60 % of protons, 40 % of carbon ions) of $8{,}43\cdot10^8$ W/sm^2 power density is presented. In elasto-plastic medium pulse of total pressure has complex structure. At amplitudes exceeding the metal flow limits σ_g, stable sequence of elastic and plastic wave is formed [10]. In the region of unloading appearance of elasto-plastic properties, interchange of elastic and plastic unloading waves spreading with different velocities (at pulse amplitude values of total pressure exceeding $2\sigma_g$) is observed [11]. Rise-up portion of elasto-plastic pulse is a shock one. Unloading of substance follows the laws of adiabatic expansion. Besides, in the rise-up portion there is a convex region conditioned by the recoil momentum from hard (carbon) component of beam.

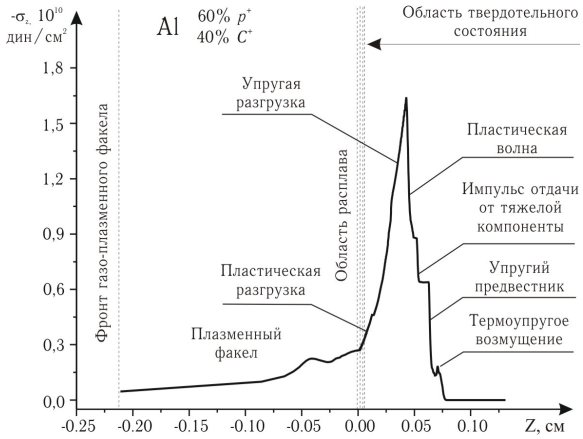

Fig. 2. *Mechanical excitation pulse induced by HPIB of power density $8{,}45\cdot10^8$ W/sm^2 in aluminium target by the moment of current pulse completion*

In study of mechanisms of pulse generation for mechanical stresses (for example [1]) the two items are distinguished as the main ones: thermoelastic determined by intensive heat expansion of energy-release region and ablation (with flash surface evaporation due to intensive heating). In Fig. 2 a clearly defined formation of thermoelastic excitation proceeding elasto-plastic wave is observed. The latter is conditioned by ablation mechanism.

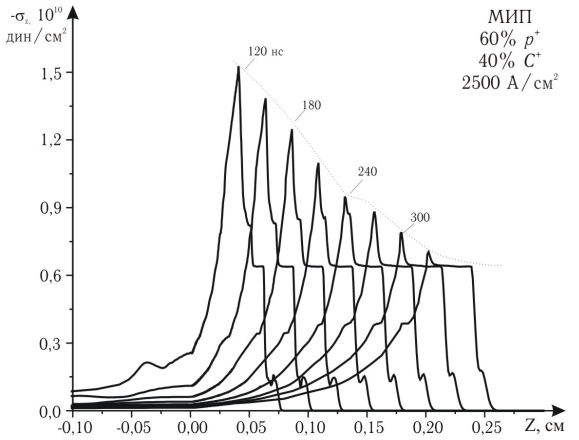

Fig. 3. *Evolution of mechanical excitation pulse (Fig. 2) in aluminium target after of current pulse completion of «VERA» accelerator*

When spreading deep into the target amplitude of mechanical excitation pulse decreases intensively (Fig. 3), which is connected to a great extent with non-hydrodynamic character of attenuation, when elastic dumping wave «overtakes» plastic impact front [12]. In studying the influence of beam power density on regularities of generation mechanisms maximum amplitude values of total pressure in mechanical loading pulse achieved, as a rule, by the moment of current pulse completion have been considered.

2.1. Thermoelastic generation mechanism

In Fig. 4 the dependencies of maximal amplitude in mechanical excitation pulse on ion current density are presented for different component composition of beam. At the values of current densities $1{,}35\cdot10^8$ W/sm^2 for proton and $6{,}75\cdot10^7$ W/sm^2 for proton-carbon beam of «VERA» accelerator «switching on» the ablation mechanism of pulse generation is observed. Consequently, before the power densities mentioned only thermoelastic mechanism is realised.

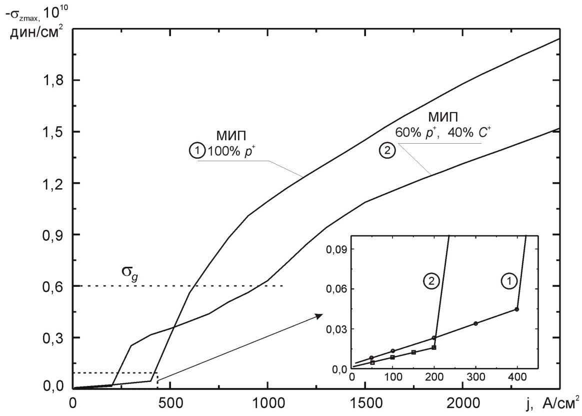

Рис. 4. *Зависимость максимальной амплитуды в импульсе механических возмущений от плотности ионного тока при воздействии МИП различного компонентного состава на алюминиевую мишень*

In realisation of thermoelastic generation mechanism the dependence of excitation amplitude on ion current density is linear [1]. Pulses generated by thermoelastic mechanism do not exceed the limits of metal fluidity in amplitude. In this case the main processes defining modification of metal properties at the depth exceeding energy-release region are those of temperature field relaxation. Presence of carbon component in the beam results in change of amplitude parameters of thermoelastic excitation. Wave mechanical excitation is generated near the irradiated surface mainly due to pressure gradient at the boundary of energy-release region. Presence of carbon component changes the energy-release profile (Fig. 5) and, consequently, gradients of total pressure in the given region. Redistribution of absorbed energy in less deep target surface layers defines earlier (by ion current density) formation of plasma flame and, consequently, earlier «switching on» of ablation mechanism.

In Fig. 6, 7 dynamics of stress field generated in irradiated surface in a time of HPIB action with current density $1\cdot10^8$ W/sm^2 is presented. Beam absorbed energy increases thermal constituent of substance internal energy ε_T, which is indispensably accompanied by local growth of pressure heat component p_T. In the process of thermal target substance expansion specific volume increases, this defines the growth of elastic pressure component negative in sign p_S. In this case thermal internal energy is transformed into kinetic energy of expanding substance and elastic constituent of internal energy. Rate of power supply and that of substance expansion are so that the growth of thermal pressure component p_T is not compensated by the growth of negative elastic component p_S. In one of our papers [6] the mechanism of dumping pulse generation spread deep into the target is theoretically justified. It has been justified by rapid growth (in comparison with thermal pressure constituent) of axial component of stress deviator. In the given case this mechanism is not realized, which is explained by additional account of temperature dependence for elastic properties of metal. Thus, at the boundary of energy-release region compression pulse is generated.

At the pulse exit from interaction zone relaxation of shear stress takes place and «double-humped» compression wave is generated. This is the effect of elastoplastic substance properties and it appears when limit of material fluidity is achieved as a result of substance heating in the zone of energy production, in this case sound speed changes for depression wave step-wise, resulting in repeated stress relaxation and generation of the second compression pulse. In [13] in the course of mathematical modelling in impact on HPIB aluminium plate of rectangular shape (of $(3...4)\cdot10^7$ W/sm^2 power density) probability of formation of such a two-wave shape has been stated. The revealed effect has a stable tendency for appearance and is observed in numerical experiments while varying ion type and energy as well as beam current density. However, at significant deviation from the mentioned density range of summary energy the two-wave structure are not produced. In our numerical experiments the given effect is present even in the case when ablation mechanism becomes the main one. Such a result is obtained in modelling of real beam impact, in pulse sweep of accelerating voltage and current of which there is a long phase of parameter growth. Stress relaxation processes conditioned by metal fluidity occur at the initial stage of interaction, when maximal amplitude parameters have not been achieved yet, but ablation mechanism has not «switched on» yet.

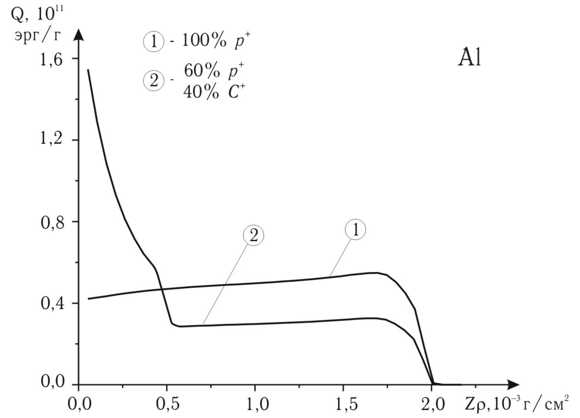

Fig. 5. *Fields of specific absorbed energy per energy pulse duration from 1) proton; 2) proton-carbon beam of «VERA» accelerator*

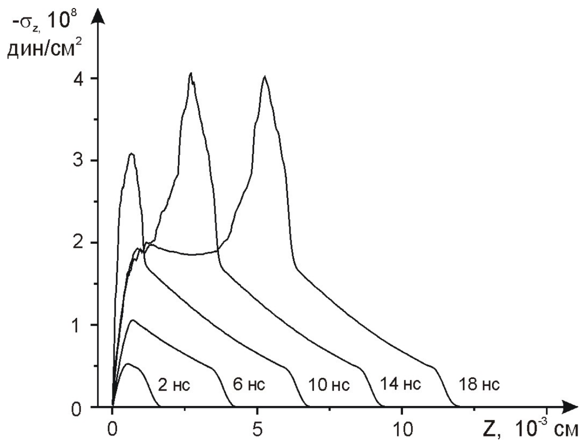

Fig. 6. *Dynamics of axial stress component (with reversed sign) on HPIB axis at the initial interaction stage*

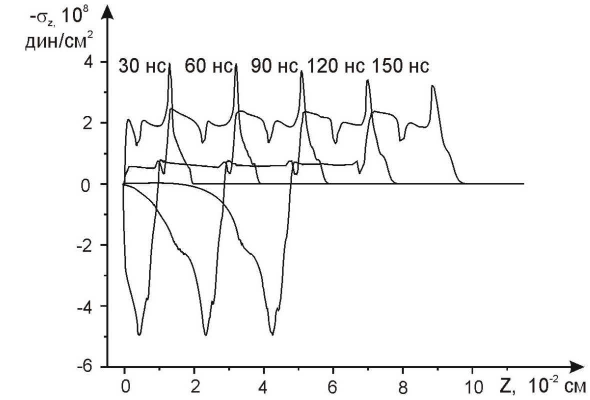

Fig. 7. *Dynamics of axial stress component (with reversed sign) on HPIB axis before the moment of current pulse completion*

By the moment of time nsec from the beginning of interaction at the boundary of local energy-release region the melting point is achieved. Energy consumption for the «solid – melt» phase transition results in decrease of growth rate for thermal pressure constituent outside the pulse generated at the initial stage of interaction. Relaxation of shear stresses in liquid phase as well as increase in absolute value of elastic pressure constituent p_S owing to volume expansion conditions formation of negative phase in mechanical stress pulse. By the moment of current pulse completion the generated pulse is of bipolar structure. Duration of generated bipolar pulse amounts $\tau\approx120$ nsec that corresponds to duration of HPIB action on target. The given fact confirms weak influence of heat conductivity on excitation generation by pulse HPIB [14].

After current pulse completion the generated pulse of mechanical stresses moves deep into the target with longitudinal sound speed. Further processes are characterised by relaxation of temperature field.

2.2. Ablation mechanism of generation

It is seen in Fig. 4 that increase in density of ion current results in discontinuous change in dependence of pulse amplitude of mechanical stresses on ion current

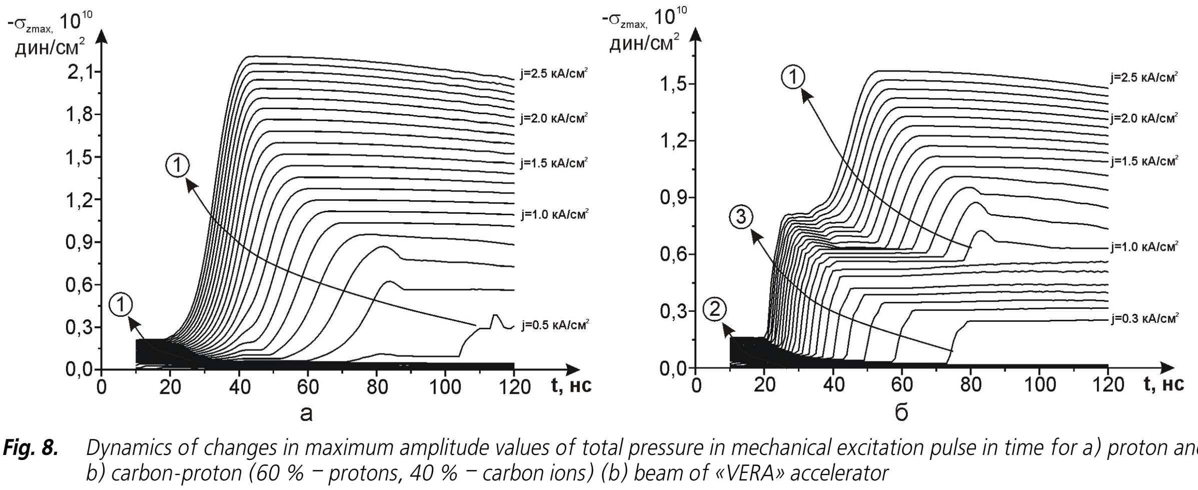

Fig. 8. *Dynamics of changes in maximum amplitude values of total pressure in mechanical excitation pulse in time for a) proton and b) carbon-proton (60 % – protons, 40 % – carbon ions) (b) beam of «VERA» accelerator*

density. In case of large densities of absorbed energy, when the evaporation processes in target substance occur, the processes responsible for pulse disturbance excitation change too. In increasing current density saturation of amplitude values for mechanical stress pulse is observed. The given fact is explained by influence of beam particle screening by plasma flame [15]. Intensive plasma yield leads to the case when part of energy delivered by beam is absorbed by gas-plasma flame.

In Fig. 8 changes in maximal values of total pressure in mechanical excitation pulse in time are presented for proton and proton-carbon beam of «VERA» accelerator. It follows from the analysis of the results obtained that realisation of thermoelastic mechanism (region 1 in Fig. 8) always proceeds ablation one independently of ion current density (in the considered range of power densities), the generation mechanisms being divided in time. Ablation mechanism «is switched on» by jump at appearance of plasma flame on the target surface, which is characterised by sharp growth of amplitude valued for pressure pulse.

As a result of numerical experiments it is stated that two serial recoil momentums are formed in presence of carbon component in the beam. Plasma yield starts when sublimation energy on the surface in thermalization region of carbon component is achieved. Formation of gas-plasma phase in the region of PIB proton component thermalization causes generation of the second, more in amplitude recoil momentum. Such a processes sequence of plasma yield in irradiated volume results in appearance of two fronts in plastic compression pulse (Fig. 2). Difference of recoil momentum amplitude parameters from various components is explained by the fact that formation of plasma crown on the surface prevents from plasma spreading in deep layers of target.

The process of plasma yield leads to screening of deep target layers moving to the beam in the form of gas-plasma cloud. The main part of beam energy is absorbed by the flame, which conditions saturation of recoil momentum. Thus, amplitude of generated recoil momentum is limited by screening processes. For example, at ion current density, A/sm^2, the maximum amplitude of mechanical stress pulse is achieved in 40 nsec after the beginning of impact. The rest of beam energy is spent for «heating» gas-plasma flame.

In Fig. 9 the dependence of pulse duration of mechanical stress on ion current density is presented. «Switching on» of loading ablation mechanism defines the growth of pulse duration. Region of plasma yield undergoes expansion throughout the volume. At the «plasma-melt» boundary the conditions of pressure equality is met. Slow relaxation of pressure out of the front of generated compression pulse at the «plasma-melt» boundary results in increase of pulse duration. At thermoelastic mechanism pulse duration is equal to that of beam. Realisation of generation ablation mechanism causes sufficient (by the order) increase in pulse duration and transition into microsecond range. In this case the dependence of pulse duration for mechanical stress on impact power density is of asymptotic character and tends to saturation. In the flame front at the «plasma-vacuum» boundary the pressure tents to zero, therefore, generated compression pulse is of unipolar structure.

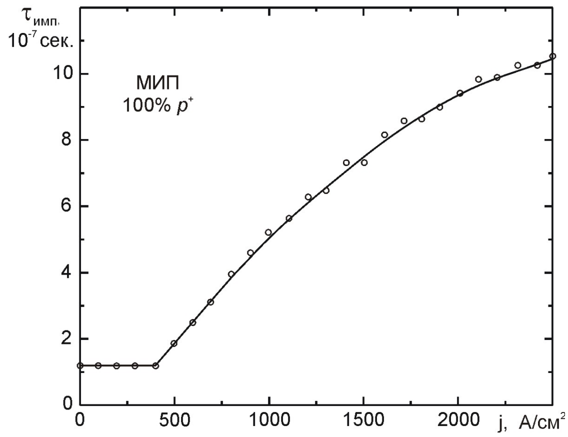

Fig. 9. *Dependence of pulse duration of mechanical excitation on ion current density*

Conclusions

1. Under the influence of powerful ion beam on metallic target the linear growth of amplitude at mechanical excitation pulse (thermoelastic mechanism) is limited by «switching on» the ablation generation mechanism. Such pulses do not exceed the limits of metal flow in amplitude. Consequently, in this range of power density the main processes defining modification of metal properties at the depth exceeding the region of energy release are those of temperature field relaxation.
2. Presence of hard component (carbon ions) in the beam results in decrease of amplitude parameters of mechanical excitation pulse as well as defines earlier (by ion current density) «switching on» of generation ablation mechanism.
3. In compression pulse division of perturbation fronts formed by different mechanisms is observed. When moving the pulse deep into target the front of elastic precursor of ablation shock wave overtakes slowly the front of thermoelastic excitation.
4. Under the action of proton-carbon beam two regions of plasma yield are formed in the target. This leads to spatial heterogeneity of formed plasma flame as well as to generation of two serial recoil momentums in time with formation of characteristic profile in plastic pulse.
5. At thermoelastic mechanism the pulse duration equals to that of beam. Realisation of ablation mechanism causes sufficient growth of pulse duration which transfers from submicrosecond to microsecond range. Dependence of mechanical excitation pulse duration on power density is of asymptomatic character and tends to saturate.

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THE PROBLEMS OF UTILIZING GRAPHITE OF STOPPED GRAPHITE-URANIUM REACTORS

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A list of radioactive nuclides, the activity of which forms the main part of total activity of graphite stack and graphite elements of the construction of stopped industrial graphite-uranium reactors has been defined. The analysis of activity part contributed by these nuclides at different moments of time after stopping reactor was carried out. A set of construction graphite elements, in which there is a possibility of self-sustaining release of the energy stored (Wigner's energy) was determined. It was stated that the most value of the Wigner's energy is achieved in graphite constructions operated in low-temperature region or at high values of flux densities of damaging neutrons and concurrent gamma radiation.

Introduction

The question on removing nuclear plants with commercial carbon-uranium reactor (CCUR) from the service constitutes a complex of problems connected with the choice of optimal ways and methods of handling with stored radioactive waste (RAW). Among the whole mass of stored RAW spent graphite of CCUR occupies a special place. After long irradiation graphite has not taken on any properties for useful application. Therefore, irradiated graphite falls in the category of unused RAW and requires individual approach to the choice of methods in its treatment. It is explained by many factors:

1. Reactor graphite has a unique crystal structure and is characterised by porosity, which defines its properties and behaviour at irradiation.
2. Graphite stack is a basic element of CCUR core not to be replaced during the operation life and it has the most accumulated neutron fluence among the RAW.
3. Graphite of CCUR stack blocks and bushes has a number of features in size, isotope composition of radioactive pollution and character of radioactive nuclides distribution both in stack volume and in separate graphite details. Radioactive contamination of graphite details is, first of all, determined by induced activity (mainly ^{60}Co, ^{3}H, ^{14}C) due to impurity activation contained in original material. In this case ^{14}C, forming 95 % of graphite activityб is involved into biological chains. In addition to activation products, graphite activity is defined by radioactive nuclides (^{137}Cs, ^{90}Sr, ^{154}Eu etc.), formed in the stack