The Effect of Subnanosecond Electron Pulse on the Solid[1]

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Abstract – The two-temperature mathematical model of the effect of the high-current electron beam with the subnanosecond pulse duration on the solid is described in the paper. The results of numerical investigations of the strains and stresses dynamics in the irradiated matter at varied durations of irradiation are presented. It is shown, that the stress wave in target has a form of the compression pulse, followed by the tensile wave. The value of the tensile strain rates is substantially greater than the value of the compressive strain rates. This value is determined by the beam energy input rate and it can reach the values of 10^7–10^8 s^{-1} for the tensile stresses. The shortening of the energy input time from several tens of nanoseconds to 1ns and less leads to the increase of the mechanical stresses value. The beam energy is more efficiently transformed into the kinetic energy of substance motion and in the potential energy of mechanical stresses in the case of subnanosecond pulse durations.

1. Introduction

The electron gas heating takes place in the solid target firstly during the absorption of the laser irradiation or fast electron beam energy. An ionic component of substance is hearted later due to the electron-phonon collisions [1]. In condensed substance a character time of the equilibrium between electron gas and ionic component is about ≈10^{-14} s. Therefore the accounting of the local deference between the electron temperature and the ion temperature, i.e. the usage of the two-temperature model of continuum mechanics [2, 3], is needed at the theoretical description of interaction between the ultra-short (with the less than 1ns duration) pulses of electron or laser irradiation with the substance.

The realization of two-temperature mathematical model for the problem of the intense subnanosecond fast electron pulse interaction with solid target is described in the present paper.

The features of the ultra-short electron radiation pulses interaction with metals and the mechanisms of the beam energy transformation in the irradiated substance were developed using the numerical simulations.

2. Mathematical model

A two-temperature mathematical model for the elastic-plastic deformations of the substance, irradiated by the intense electron beam, is formulated in this section of the paper. The corresponding equation system in the one-dimensional case with the use of Lagrange coordinates takes the next form:

$$\frac{\dot{V}}{V} = \frac{\partial v}{\partial z}; \qquad (1)$$

$$\dot{v} = \frac{1}{\rho}\frac{\partial \sigma_{zz}}{\partial z},$$

$$\sigma_{zz} = -(p_i(\rho, T_i) + p_e(\rho, T_e)) + S_{zz}; \qquad (2)$$

$$\rho \dot{U}_i = -p_i \frac{\dot{V}}{V} + S_{zz}\frac{\partial v}{\partial z} + \gamma (T_e - T_i); \qquad (3)$$

$$\rho \dot{U}_e = -p_e \frac{\dot{V}}{V} + \frac{\partial}{\partial z}\left(\kappa_e \frac{\partial T_e}{\partial z}\right) - \gamma (T_e - T_i) + D(z,t). \qquad (4)$$

Here (1) – the equation of continuity; (2) – the equation of motion; (3) and (4) – the equations for the electron energy and for the ion energy respectively. There are ρ – the mass density; $V=\rho^{-1}$ – the specific volume; κ_e – the electronic heat conductivity coefficient; U_i, T_i, U_e, T_e – the energy and the temperature of ions and of the electrons respectively; $\gamma=3m\rho C_s^2 Z_i (m_i T_i \tau_{ei})^{-1}$ – the coefficient of relaxation between the electrons and ions [4]; m and m_i – the effective mass of electron and the ion mass; C_s – the ionic sound speed; Z_i – the degree of ionization; τ_{ei} – the relaxation time; σ_{ik} – the stress tensor; S_{ik} – the stress deviator; p_e and p_i – the electron pressure and ion pressure; D – the energy-release function (the dose rate) in the equations (1–4). The expressions for the p_e, p_i can be written in the next form [5]:

$$p_i(\rho, T_i) = p_c(\rho) + \Gamma^{(i)}(\rho, T_i)\rho U_i(\rho, T_i); \qquad (5)$$

$$p_e(\rho, T_e) = \Gamma^{(e)}(\rho, T_e)\rho U_e(\rho, T_e). \qquad (6)$$

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Here $\Gamma^{(i)}$, $\Gamma^{(e)}$ are the Grunaizen coefficients for ions and electrons respectively; $p_c(\rho)$ – the ion pressure at the T_i=0 K. The wide-range equations of state [6] are used here.

The stress deviator is determined from the Hook's law and the Mizes's condition of the yield [7]:

$$\dot{S}_{ik} = 2\mu\left(v_{ik} - \frac{\dot{V}}{3V}\delta_{ik}\right),$$

$$S_{ik}S_{ki} \le \frac{2}{3}(Y^{(0)})^2, \qquad (7)$$

here v_{ik} – the strains rate tensor; μ – the shear modulus, $Y^{(0)}$ – is the yield stress. The relaxation time τ_{ei} is founded from the expression $\sigma=e^2nZ_i\tau_{ei}m^{-1}$ using the wide-range tables of an electric conductivity [8].

The equation system (1–6) is numerically solved by the method, described in [9].

The energy-release function is calculated over the differential flux density Ψ of the electrons:

$$D(z) = \int_{4\pi} d\Omega \int dT_b B(T_b)\Psi(z, \cos\vartheta, T_b), \qquad (8)$$

here ϑ is the angle between the impulse vector of fast electrons and the OZ axis, $B(T_b)$ – the specific energy losses of the fast electrons having the energy T_b. A kinetic equation $\hat{L}\Psi=S_\Psi$ for the fast electrons is solved with the object of determination of the Ψ. There are S_Ψ – the source function of fast electrons, $\hat{L}$ – the integro-differential translation operator, accounting elastic and inelastic scattering [10]. The solution of electron transfer problem is performed by the method, described in [11].

3. Simulations and discussion

The results of numerical simulation of the intense ultra-short electron irradiations effect on the metal targets are discussed here. This simulation was done in the frames of the two-temperature model described above. An effect of the electron beam with the initial electron energy 300 KeV and the pulse duration varied in the range τ_b=10 ps – 10 ns on the copper target is considered below. The total deposited energy density is maintained invariable and equal to W=8.6 J/cm^2 in simulations. This value corresponds to the energy of electron pulse [12] with parameters: the initial fast electron energy – 300 KeV, the pulse duration τ_b=1 ns, the maximal current density – 50 KA/cm^2.

Let's consider the dependence of the stresses value in irradiated target on the duration of irradiation. The beam energy input time shortening from 10ns to 1ns leads to the substantial increase in the stress value, as it can be seen from Fig. 1. The further shortening (down to less than 1ns) remains the maximal in time stresses value close to the constant value, which is equal to ~24 Kbar in the concerned case. The energy input time is essentially less than a character time of mechanical relaxation $\tau_R=h_0/C\approx30$ ns (here h_0 is the depth of the energy release zone, C – sonic speed) and the substance motion is negligible during the irradiation for such irradiation regimes. A heated layer with thermo-elastic stresses is formed at this stage. The substance unloading begins an important further on the times later the 1ns; the wave of stresses traveling inside the target is formed and the value of stresses decreases down to the level of ~10 Kbar.

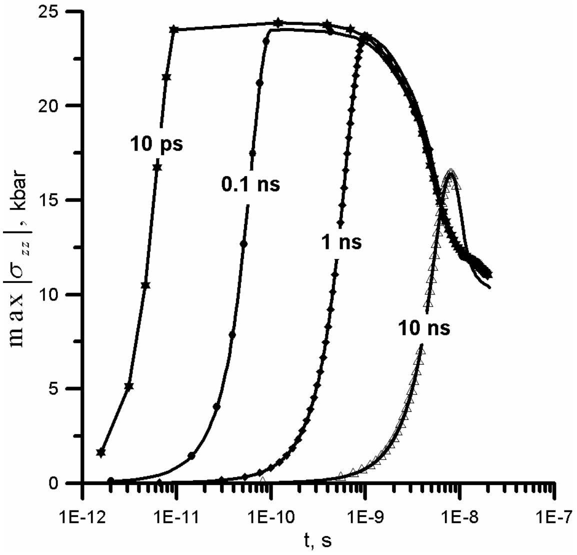

Fig. 1. The time dependences of the maximal in target stress value for the varied pulse durations. The beam parameters are the next: U=300 KeV, W=8.6 J/cm^2

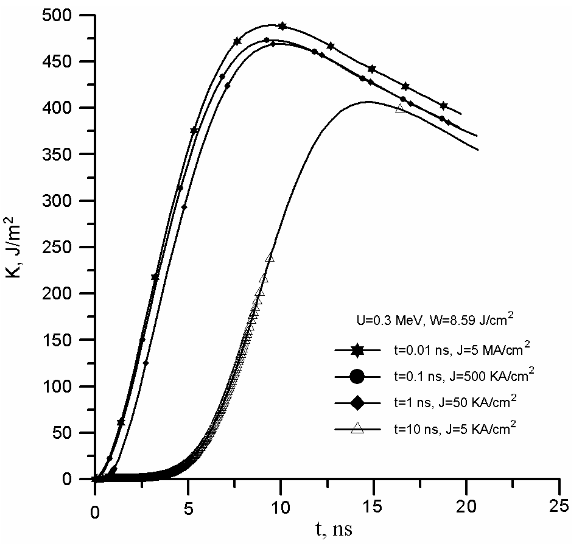

Fig. 2. The time dependences of the kinetic energy of the target substance motion for the varied pulse durations. The beam parameters are the next: U=300 KeV, W=8.6 J/cm^2

The shortening of the beam energy input time leads to the increase of a kinetic energy of the substance as well, as it can be seen from Fig. 2. The kinetic energy is calculated by the next formula:

$$K = \frac{1}{2}\int \rho v^2 dz. \qquad (9)$$

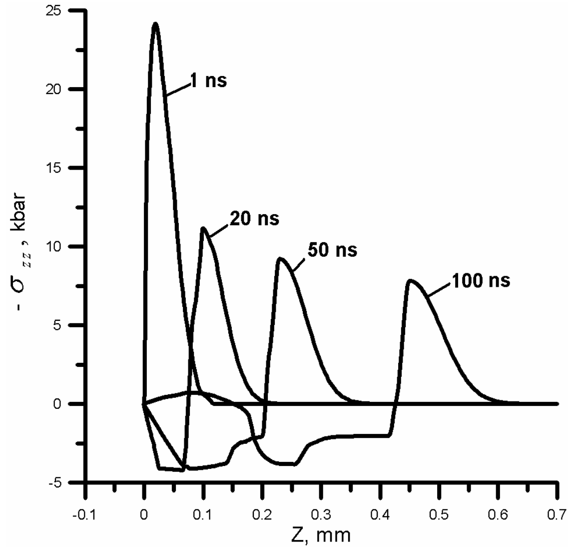

Fig. 3. The stress patterns in the varied time moments. The beam parameters are the next: U=300 KeV, b=1 ns, and the current density – 50 kA/cm^2

It is worth noting that the maximum of the dependence $K(t)$ for the irradiation durations $\tau_b \leq 1$ ns happens at the time moment ~8 ns, corresponding to the formation of the traveling stress wave and to the beginning of the intense substance motion in target.

As a whole, the shortening of the energy input time leads to a more efficient transformation of the beam energy in the kinetic energy of substance motion and in the potential energy of mechanical stresses. But this increase of efficiency does not exceed a few tens of the percents and limited at the ultra-short irradiation durations by the values, corresponding to the instantaneous source.

The stress patterns in target irradiated by electron beam with parameters, corresponding to the paper [12], at varied time moments are presented on Fig. 3. The maximal substance temperature in the copper target does not exceed the value of ≈650 K and the substance of target is in the solid state at this irradiation regime. Therefore, the strong pulse of the expansion with the large tensile (positive) stresses, restricted by the dynamical yield stress, is formed at the irradiated surface. It can be expected, that this region of the target will be subjected to the largest structural transformation.

The dependences of maximal in target strain rate $\dot{\varepsilon}=\partial v/\partial z$ on the time at varied irradiation durations presented on Fig. 4. One can see that the strain rates increase with the shortening of the energy input time and reach the values of 10^8 s^{-1} for the beam with 10ps duration. It is worth noting that for the beam durations less than 0.1 ns the strain rate amplitude tends to the certain maximal limit with further shortening of the energy input time; this limit corresponds to the source with duration $\tau_b << \tau_R$.

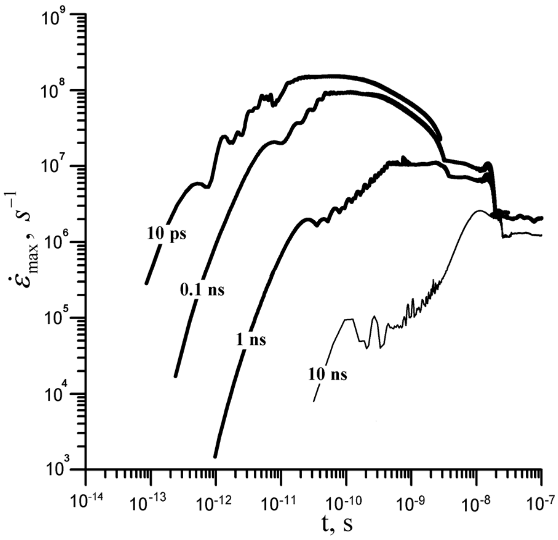

Fig. 4. The time dependences of the strain rate value maximal in target for the varied pulse durations. The beam parameters are the next: U=300 KeV, W=8.6 J/cm^2

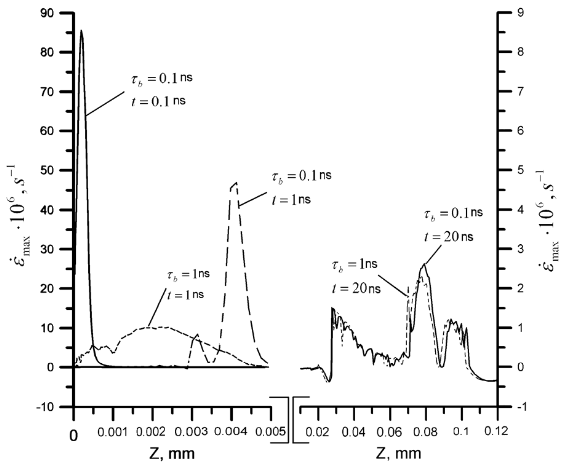

Fig. 5. The strain rate patterns in target for the varied pulse durations and for the varied time moments

The strain rate patterns in target irradiated by electron beam with parameters, corresponding to the paper [12], at varied time moments are presented on Fig. 5. The maximal strain rates arise near the irradiated surface and have a form of localized intense strains zone. The thickness of this zone just after irradiation is determined by the target substance unloading and is about $C\tau_b$. In future the intense strains zone travels deep into target with sonic speed. The maximal strains value substantially decreases in time to the level of the running stress wave (it is also seen from Fig. 4 for the times more than 10 ns). One can see that the rate of the tensile strains ($\dot{\varepsilon}>0$) substantially exceeds the rate of the compressive strains.

At the pulse durations less than 1 ns the forms and amplitudes of the formed stress wave and of the corresponding strains pattern are not depended on the pulse duration as it seen from Fig. 1 and Fig. 5.

Thus, the shortening of the beam energy input time leads to the substantial (in several times) increase of the tensile strain rates. The greater strain rate values at the subnanosecond durations of irradiation can cause the more intensive generation of the lattice defects and to the more intensive modification of material in comparison with the case of the more traditional nanosecond durations of irradiation.

4. Conclusions

The numerical simulations result in the next conclusions:

1) The subnanosecond and the picosecond fast electron beams are the perspective tools of stresses generation in the condensed substance. They provide a more efficient beam energy transformation in the energy of substance motion and in the energy of stresses in comparison with the beams of nanoseconds duration.
2) A remarkable feature of the intense ultra-short electron beam effect is the large values of strain rates in irradiated substance.

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