The Simulation of Microcrater Formation on Pure Metal Targets Irradiated by an Intense Microsecond Electron Beam

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Abstract – The new method for simulation of dynamics of target surface irradiated by electron beams has been developed. There are two irradiation regimes: precritical and supercritical. We have conducted the research of crater formation for different beam parameters: impulse duration, power density, angle of beam incidence on target surface. Also 3D calculations of crater interaction and evolution of craters from initial irregular perturbation are carried out.

1. Introduction

Intensive charged particle beams are applied for material modification of near-surface layers [1–4]. A wide range of beam parameters (current density, pulse duration, particle energy) cause a variety of surface phenomena such as microhardness increase, crystal structure changing, microcrater formation, material droplet detachment, surface structure generation, surface layer mixing.

In case of ion radiation treatment the model of microcrater formation was proposed in Ref. [5]. Irradiated target is considered as three-layer system (plasma – melted phase (liquid) – solid phase) with different mass densities and sharp boundaries between phases. This approach is justified only for ion treatment when there is a sharp boundary of energy release zone. Microcrater is a result of Richtmyer-Meshkov instability on the interface between plasma-liquid (RMI) [6].

Due to the multiple fast electron scattering in substance the dose varies smoothly with target width, plasma spread and thermal expansion result in the smooth dependence of mass density ρ on width, which makes impossible to identify the sharp boundaries between the phases and to use the model [5] for the description of microcrater formation driven by electron irradiation.

The first aim of the given article is the development of the method to simulate the nonlinear dynamics of near-surface target layers irradiated by intense energy stream. The second one is the research of near-surface dynamics depending on beam parameters. We have considered clean target surface with micro-prominences or micro-cavities as initial perturbations.

2. The nonlinear dynamics of near-surface target layers irradiated by intensive beam

In case of irradiation by particle beams with power density more than 10^6 W/cm^2 there are two regimes: precrirical and supercritical. The changeover between them has threshold nature.

In precritical regime the target is in condensed state (solid or liquid). It is subject to thermal expansion. According to estimations and numerical simulation RMI is limited by surface tension in precritical regime. And so microcraters do not form.

In supercritical regime irradiation generates plasma jet which moves with velocity $v_f \geq 10^3$ m/s and acceleration $g_f = \dot{v}_f = 10^9 – 10^{11}$ m/s^2.

Since surface tension is small on plasma surface such velocities and accelerations make necessary conditions for RTI evolution after irradiation.

As inertia force on free surface is maximal the instability dynamics determines material flow in volume. In consequence of plasma evaporation target layers which are crystallized have density close to one of solid state. Therefore after crystallization the surface relief is determined by perturbation on the contact surface between plasma and liquid which is the surface of maximal mass density gradient.

During irradiation it is appropriate to use linear analysis [7] for dynamics of small initial perturbation as inertia forces induced by material acceleration in near-surface layers delay Rayleigh-Taylor instability and produce gravity waves. After irradiation on the contact surface perturbation amplitude grows driven by RMI. Since by this moment plasma jet has low density it does not influence the contact surface dynamics. The further simulation uses the method [8]. Considering potential flow of incompressible liquid we have derived the equations set which determine nonlinear interfacial dynamics (for example RMI) in 2D and 3D geometries.

The RMI evolution goes with temperature reduction due to heat conductivity. Crystallization of melted material delays perturbation growth limiting microcrater depth. We have estimated the time $t_c=\tau+t_{tc}$ as the upper bound of crystallization time, where τ – the beam pulse duration, $t_{tc}=R^2/\chi$, χ – thermal diffusivity, R – the fast electron range in material. The second factor limiting microcrater depth is the depth of the melted layer.

To simulate linear stage [7] it is necessary to know density $\rho(z,t)$ and acceleration $g(z,t)$ fields. For that we have used the program code BETAIN [9]. It is numerical consistent solution of kinetic fast particles equation, one-dimensional continuum mechanics equations for elasto-plastic flows. It takes into account thermal conductivity and wide-range equation of state.

3. Numerical results

To determine parameter space then the crater formation is possible we have conducted calculation series varying power density (or current density) at fixed average electron energy and pulse duration. The calculated curve of threshold power density W dependence on electron energy T_e separates precritical regime from supercritical one (Fig. 1). Calculations (substance is iron, pulse durations are 100 ns, 10 μs, 30 μs) have been carried out using the program code BETAIN [9].

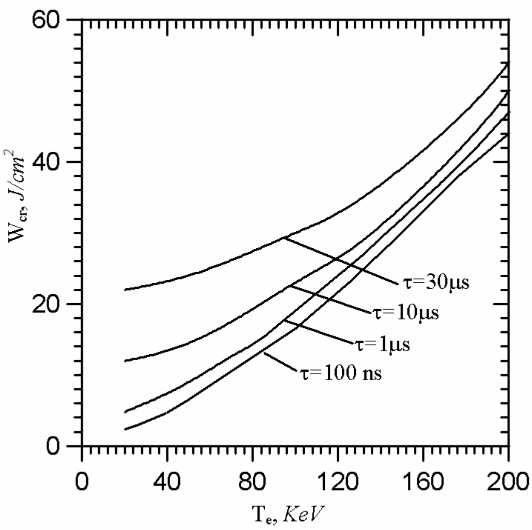

Fig. 1. The threshold power density dependence on electron energy at varied pulse durations

The threshold power density becomes higher with electron energy increase. The higher energy electrons have the larger distance they move therefore the more target volume heats and for surface layer vaporation it is necessary to transmit more energy to target.

Heat conduction becomes more essential for longer irradiation. And so if electron energy is equal then for longer pulse it is necessary more heat to form plasma jet.

Computed dependences of growth rate on wavenumber (Fig. 2) have an extremum at k_0 that is firstly determined by distance between the free surface and the contact surface. As perturbation growth on the contact surface is induced by free surface the reduction of growth rate $\dot{a}_c$ at large wavenumbers is connected with strong short-wave damping with width. Long-wave perturbations develop longer than short-wave ones [6] therefore $\dot{a}_c$ decrease at small wavenumbers.

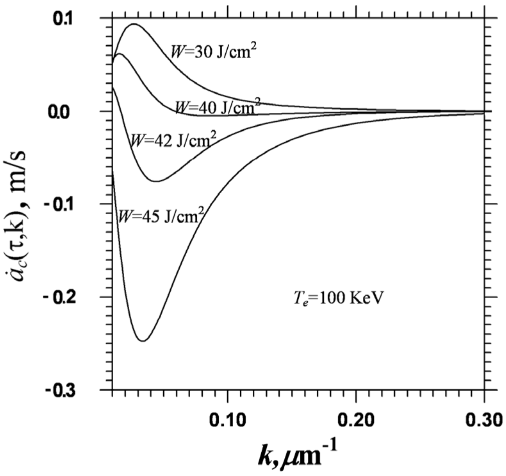

Fig. 2. The dependence of the perturbation grow rate on the wave number

The microcrater formation has threshold nature as a consequence of the existence of two irradiation regimes: precritical and supercritical.

Having defined initial perturbations on the free target surface we have computed the contact surface relief and velocity field at $t=\tau$ using linear analysis. They are initial conditions for simulation of nonlinear dynamics of the contact surface between plasma-liquid at $t\geq\tau$ computed by the method [8].

Let note the main evolution regularities of initial perturbation – a tubular cavity with depth h_0 ($1\leq h_0(\mu m)\leq 4$) and diameter D_0 ($10\leq D_0(\mu m)\leq 200$) for experiments with electron irradiation [4]. In initial spectrum the fastest modes have wavenumbers k close to k_0 which determines perturbation dynamics. As a result microcrater tends to have a diameter $D^*=\pi/k_0$. At $D_0<D^*$ there is strongly increase of diameter and depth $h(t_c)$ (Fig. 3, 4), at $D_0>D^*$ diameter and depth change slowly. The microcrater diameter $D(t_c)$ does not depend on h_0 and is defined only by D_0.

The increase of h_0 results in increase of $h(t_c)$ but the value of $h(t_c)$ is limited so that at large h_0 depth $h(t_c)$ becomes stationary value which corresponds to melted layer width 20–27μm.

It may come to a conclusion in these irradiations regime cases the largest amount of experimental microcrates should have diameters about D^*=100–120 μm and crater depths 15–25 μm which is adjusted with results [4].

To research crater interaction we have conducted 3D simulation of two crater dynamics for equal and different initial diameters and depths. All results reveal the common tendency: when intercrater distance is less than D^* they merge into elongated one with size close to D^*. If intercrater distance is about D^* material ejected from one crater delay another crater growth (depth reduces by 10–15 %). If the intercrater distance is larger than D^* craters grow independently.

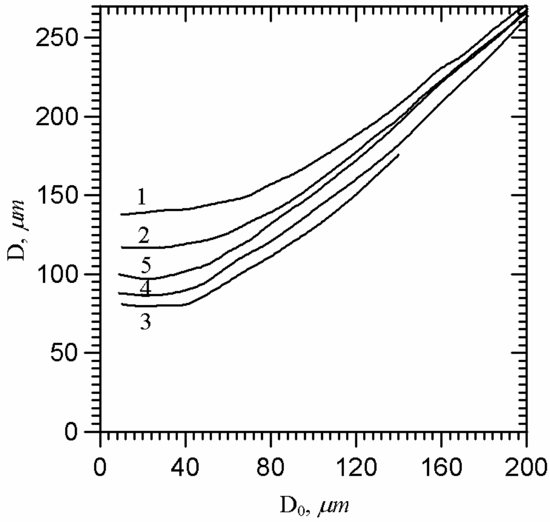

Fig. 3. The dependence of the resulting crater diameter on the initial perturbation diameter.
1 – 32 J/cm², 2 – 40 J/cm², 3 – 45 J/cm², 4 – 50 J/cm², 5 – 55 J/cm²

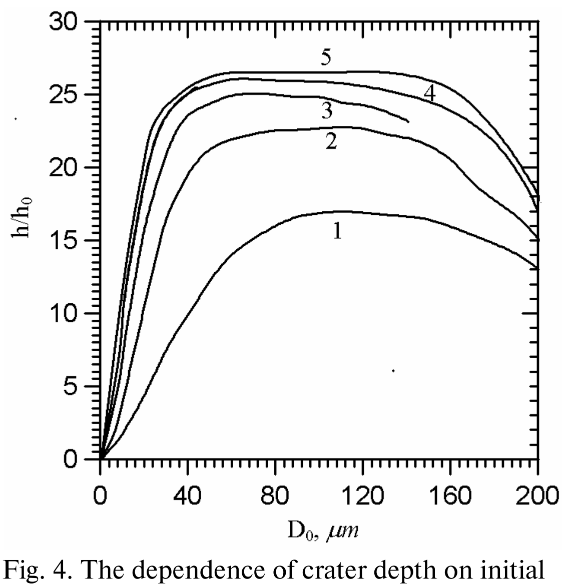

Fig. 4. The dependence of crater depth on initial perturbation diameter
1 – 32 J/cm², 2 – 40 J/cm², 3 – 45 J/cm², 4 – 50 J/cm², 5 – 55 J/cm²

The scale D^* appears also in crater development for irregular shape perturbation (as rule such craters have round shape). If initial size exceeds D^* an initial crater divides into several ones with diameters close to D^* (Fig. 5). In the experiments [4] with the scratch on the target surface as initial perturbation formed craters have close diameter.

We have carried out numerical research oblique electron incidence on iron target. Angle of incidence varies in the range of 0–70°. The beam parameters are T_e=100 KeV, τ=10 μm, W=60 J/cm². The dominant mode and melted layer thickness are approximately equal for incidence in the range of 30–60°. As a result crater forms and depths are close too.

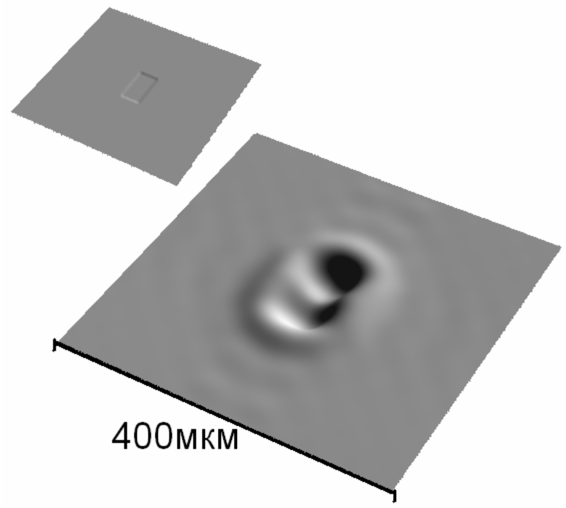

Fig. 5. Crater break-up

In nanosecond beam case for mentioned angle range (T_e=100 KeV, τ=100 nm, W=60 J/cm²) heat conductivity has less impact on crater formation. If angle of beam incidence on target increases plasma thickness decreases. Therefore, perturbations from free surface decay less. On the other hand increase of the angle results in decrease of absorbed power density and surface acceleration. Combined effect of these factors causes complex crater depth dependence on angle of beam incidence.

The calculations with the varied form of the current density first front (with parameters T_e=115 KeV, τ=30 μm, W=35 J/cm²) reveal crater depth is maximal at increasing current as in this case momentum effectively transmits to melted layer.

Conclusion

We have developed the method for simulation of near-surface target layer dynamics in case of intensive energy stream irradiation. After irradiation target material may be in condensed state (precritical irradiation regime) or plasma jet forms and fastly widens (which corresponds to supercritical regime). The changeover between precritical irradiation regime and supercritical one has threshold nature. In precritical regime case perturbation growth is limited by surface tension. In supercritical irradiation case Taylor instability is essential and causes growth of surface perturbations, crater formation, mixing of near-surface layers.

The research of crater formation regularities for normal and oblique electron beam incidence have been conducted. We have revealed the dominant scale which is important in crater dynamics.

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