The Analysis of Metal Surface Erosion under Irradiation by Pulsed Electron Beams

G.A. Bleikher, V.P.Krivobokov, O.M. Stepanova

Nuclear Physics Institute, pr. Lenina, 2a, Tomsk, Russia, (3822)417954, E-mail: bga@npi.tpu.ru

Abstract – The potentialities of pulsed electron beams with particle energy 10..1000 keV for erosion of the metal surface are presented in the report. The non-equilibrium superficial evaporation is considered as a main mechanism of atom removing from the surface for moderate intensity beams. It takes on the character of hydrodynamic substance spread under the action of high-intensity beams.

The mathematical model of erosion is suggested. The influence of beam parameters on an erosion factor is investigated using the model. The comparison with the case of erosion under the irradiation by pulsed ion beams is carried out. The advantages and disadvantages of pulsed electron irradiation use are revealed.

The knowledge of obtained erosion factor dependences on beam parameters is necessary to develop the technologies of surface modifying and production the materials with new properties.

1. Introduction

At present the technologies of material properties modification by concentrated energy flows based on removing the atoms from the surface are developed actively. The investigations showed that pulsed charged particle beams can be effective instrument for these purposes because they are able to produce very intensive superficial evaporation [1].

The survey of scientific literature shows the pulsed ion beams are considered mainly for these purposes (for example, [2, 3]). But pulsed electron beams can cause the surface erosion as well [1]. Therefore the investigation of erosion regularities under their effect is necessary too.

The erosion factor Y is considered as a main indicator of the process. It is equal to the ratio between quantity of atoms which leave the surface and the number of beam particles which have produced this process.

The constructed mathematical model for calculation of Y is based on description of fundamental regularities of radiation energy dissipation in the substance. The calculated dependences of metal surface erosion factors on the beam parameters enable to find the optimal modes of treatment.

2. Problem formulation

Our research of the metal surface erosion under the action of charged particle beams of submicrosecond duration (pulse duration $\tau \leq 1$ mcs) with particle energy E = 10 ..1000 keV is based on the assumption that the main erosion mechanism is evaporation under the electron irradiation and sum of sputtering and evaporation under the ion one. Under very high beam power density the superficial evaporation turns into hydrodynamic substance spread.

In the case of ion irradiation it's possible to present Y as sum of sputtering factor S and evaporation factor Q. Obviously, on the electron action Y=Q.

Because of ability to provide powerful energy release in a thin near-surface layer during very short time the ion and electron beams in pulse mode cause surface heating up to very high temperature. It can exceed the melting-point sufficiently. As a result very intensive evaporation is developed on the surface. At that the evaporation component can run up to $10^4..10^5$ atoms per particle [1]. This result is 3..4 orders higher than ion sputtering factor.

So, the problem of investigation of the metal surface erosion regularities under the action of submicrosecond charged particle beams is to study the evaporation and hydrodynamic substance spread kinetic.

3. The calculation procedure

At the action of pulsed charged particle beams the evolution of heat processes in the irradiated target is defined by the parameters of an energy release spatial-temporal function rather than by accelerated particle nature. The shape and sizes of the profile of spatial linear energy losses by accelerated particles in the target near-surface layer, the temporal distribution of beam current density and pulse duration are in sight.

Under influence of the concentrated radiation flows on the substance the evaporation mechanisms are defined by beam power density. We consider two ranges of beam power density: the ranges of moderate and high intensity. Since the different mechanisms of evaporation are characteristic for these ranges, the different models for calculation of evaporated matter are required.

On flux of moderate intensity the atoms are taken away the irradiated surface under the action of heat mechanism of evaporation. It has non-equilibrium character. At that the clear boundary between vapour and condensed phases exists. The velocity of evaporation front V_f is not great. Therefore the evaporated atoms scatter quickly on the distance where their interaction is lost.

In this case the quantity of evaporated matter can be calculated through the velocity of evaporation front

V_f, which is found from solution of the heat-conductivity equation taking into account the phase transitions. We name this model for calculation of heat processes as bi-phase one. It has following view:

$$\frac{\partial E_T(x,t)}{\partial t} - v_f \frac{\partial E_T(x,t)}{\partial x} = \lambda \frac{\partial^2 T(x,t)}{\partial x^2} + W(x,t); \quad (1)$$

$$\lambda \frac{\partial T(x,t)}{\partial x}\bigg|_{X=0} = \rho v_f \Delta H; \quad (2)$$

$$T(x,0)=T_0; \qquad E_T(x,0)=T_0 c\rho; \quad (3)$$

$$T = \begin{cases} E_T / c\rho, & E_T \le E_m, \\ T_m, & E_m < E_T \le E_m + q_m\rho, \\ T_m + (E_T - (E_m + q_m\rho))/c\rho, & E_T > E_m + q_m\rho. \end{cases} \quad (4)$$

Here T(x,t) is spatial-temporal temperature distribution (the coordinate X is connected with the direction which is perpendicular to the irradiated surface); T_S – surface temperature; E_T – heat component of substance internal energy; W(x,t) – spatial-temporal function of energy release (procedure of its calculation is described in [1]); λ, c, ρ – heat-conductivity coefficient, specific heat and substance density accordingly; T_m and q_m – melting temperature and melting specific heat; $E_m=T_m c\rho$; ΔH – difference of enthalpy in vapour and condensed phases.

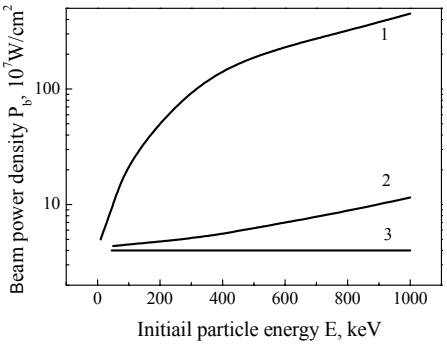

Fig. 1. Dependence of beam power density, at which noticeable copper evaporation begins, on initial particle energy: 1 – electron, 2 – proton, 3 – argon beams (τ = 100 ns in all cases)

V_f depends on surface temperature. The procedure described in [4] was used for calculation of it.

Under the action of high-intensive charged particle beams the superficial layer of the target gets heat energy from bombarding particles which is close to evaporation heat. Flux density of atoms leaving the surface is great. The smooth transition from the normal density to zero is formed near the surface. Evaporation has the character of hydrodynamic substance spread. In this case great part of beam energy spends to increase of cold component of substance internal energy because the powerful waves of pressing and stretching are generated. Change of density and pressure so great that it can influence heat processes sufficiently. To calculate the quantity of evaporated matter it's necessary to solve continuum equations together with wide-range equations of the substance state. We name this modal as hydrodynamic one. It's described in [1].

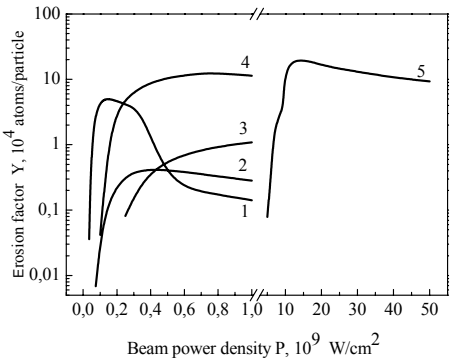

Fig. 2. Dependence of copper erosion factor Y caused by evaporation on power density P under irradiation by various beams: 1 – copper ions, E=1000 keV; 2 – electrons, E=50 keV; 3 – electrons, E=100 keV; 4 – protons, E=1000 keV; 5 – electrons, E=1000 keV; (τ = 100 ns in all cases)

The carried out calculations suggest that development of evaporation according to the hydrodynamic mechanism is typical for irradiation of metal samples by beams of comparatively long-range particles, for example, by protons with E>1 MeV, electrons with E >300 .. 500 keV and at power density P exceeding 10^9 W/cm^2, while evaporation under irradiation of metals by beams of heavy and moderate ions with $P < 5\cdot10^9$ W/cm^2 has superficial character and can be described by bi-phase model.

4. The analysis of result

The calculations show that kinetic of metal evaporation by pulsed electron beams within particle energy range E = 0.01..1 MeV differs somewhat from the case of pulsed ion irradiation within the same range of particle energy [5].

Presented results have been obtained on the example of copper irradiation. Though for other metals the numerical values are different slightly but in a qualitative sense the results have the same behaviour.

Let's compare the values of power density P_b on which the noticeable superficial evaporation begins (Fig. 1). Suppose that surface warming up must reach the temperature T_S satisfying the condition: $T_S k_B/L >$ (0.08..0.1). Here k_B – Boltzman constant, L – atom bond energy in a lattice. According to our calculations in this case the layer with thickness $(0.5..1)\cdot10^{-8}$ m is evaporated for a pulse of submicrosecond duration.

Under the electron action P_b increases strongly with growth of E. It's explained by the fact that linear

energy losses of accelerated electrons near the surface diminish distinctly when E increases. When τ = 100 ns metal surface evaporation on electron irradiation becomes noticeable under $P_b = 5 \cdot 10^7 .. 5 \cdot 10^9$ W/cm^2. It's 1..2 orders more than on ion irradiation within the same energy range because of electron linear losses in near-surface layer about 2 orders less than in the case of ion braking with the same values of E.

The indicator of erosion effectiveness – erosion factor Y – is defined by radiation power density P. The dependence Y(P) when τ = 100 ns is presented in the Fig. 2. The greatest values of erosion factors take place under irradiation by long-range particles (protons, electrons). At E ~ 1000 keV they run up to 10^5 atoms/particle and more. At E < 100 keV the values of Y don't exceed $10^3..10^4$ atoms/particle. For electron irradiation with τ = 100 ns the most values of Y (Y ~ $10^4...10^5$ atoms/particle) occur when P > 10^9 W/cm^2. At that it's very important due to what component the required power density is provided: current density j or initial energy of beam particles. When E < 100 keV it's impossible to get Y>10^4 atoms/particle at any current density.

The regularity – the more initial energy the more values of erosion factor it's possible to get – takes place for all kinds of charged particles.

The dependence Y(P) suffers saturation and recession with growth of P for all presented cases. But this behavior of Y(P) is caused by different reasons. Under irradiation by nanosecond ion beams within considered energy range (E = 10…1000 keV) and electron beams with E < 100 keV the power input so high that intensive evaporation occurs during pulse. Evaporation comes to the end almost completely at the close of pulse (Fig. 3). Quickly produced metal vapours shield the target for beam particles. Therefore beam energy remains in vapours and doesn't reach the target surface.

Another picture takes place under irradiation by electrons with E > 100 keV. Due to the fact that the power density of volumetric energy release is some lower in this case, intensive evaporation begins at the pulse end when the surface becomes heated up sufficiently. Then, after irradiation, evaporation takes place fully. In the latter case there is no shielding of the surface by vapours or it shows less. But with growth of P more beam energy is spent to increase the cold component of substance internal energy and so the quantity of produced vapours diminishes.

Sudden change in Y(P) is connected with change of evaporation mechanism in the area of curve jump. Superficial evaporation turns into hydrodynamic substance spread. This phenomenon is characteristic for electron irradiation with E ≥ 300…500 keV and proton irradiation with E ≥ 1000 keV.

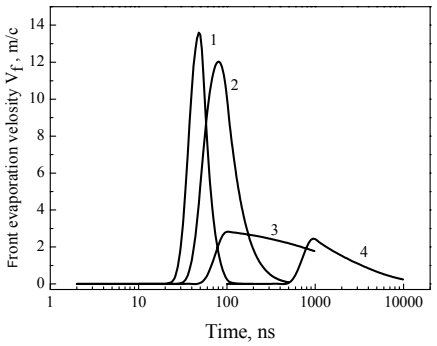

Fig. 3. Evolution of evaporation front velocity on irradiation of copper by: 1 – ions of carbon, E=500 keV, j=600 A/cm^2, τ=100 ns; 2- electrons, E=50 keV, j=15 kA/cm^2, τ=100 ns; 3- electrons, E=300 keV, j=18 kA/cm^2, τ=100 ns; 4- electrons, E=300 keV, j= 1800 A\cm^2, τ=1 mcs

Fig. 2 shows electron beam of submicrosecond duration with particle energy 50..1000 keV is able to provide removing of atoms from the metal surface with the same erosion factors as nanosecond ion beams within the same particle energy range. At that evaporated layer thickness for a pulse is 1..2 orders more (Fig. 4). But current density providing these Y values at τ = 100 ns is about 2 orders more too.

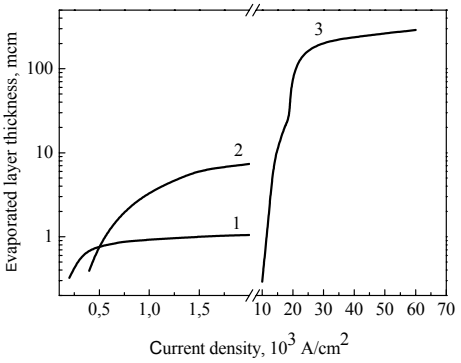

Fig. 4. The dependence of copper evaporated layer thickness on beam current density of 1 – carbon ions, 2 – protons, 3 – electrons (E=1000 keV, τ=100 ns in all cases)

Let's consider influence of pulse duration on Y. It was obtained on ion irradiation [5] with E = 100 .. 1000 keV that this influence very sufficient for submicrosecond mode. The greatest values of Y take place at τ < (100 .. 200) ns. It's caused by heat conductivity. But under electron action with E > 100 keV it influences the results much less. One can see from Fig. 5 that at the equal values of total irradiation doze for the pulse (F) with E > 100 keV the erosion factor decreases sufficiently at τ > 10 mcs only. It's turn out that increase of pulse duration from 100 ns up to 1..10 mcs

allows to diminish beam current density the same times, keeping Y.

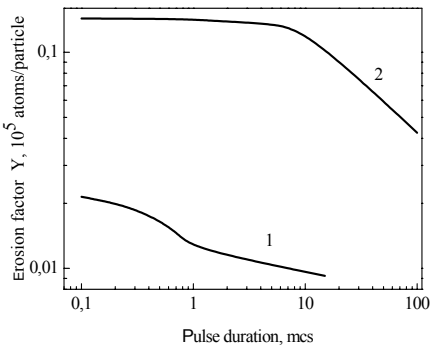

Fig. 5. Pulse duration influence on erosion factor on irradiation of copper by electron beam with the parameters: 1 – E=50 keV, F = 37,5 J/cm^2; 2 – E=300 keV, F=270 J/cm^2

5. Conclusion

Submicrosecond electron beams can be the instrument for modification of material and article properties based on atom removing from the surface, just as ion beams. At that the erosion factor is connected with non-equilibrium superficial evaporation under the action of moderate intensity beams (up to $5\cdot10^9..10^{10}$ W/cm^2) and with hydrodynamic substance spread under higher power density.

For energy range 10..1000 keV the beams with E>100 keV are more effective in the view of getting the greatest erosion factor. In this case Y is within the range 10^4 ..10^5 atoms/particle. These values agree with figures in the case of nanosecond ion irradiation with the same E. Under electron irradiation removed layer thickness for a pulse is 1..2 orders more than under ion irradiation with the same values of E.

On electron irradiation pulse duration 1..10 mcs is more advantages. At these values of τ the erosion factors are about the same high as at $\tau \sim 100$ ns, but current density can be 1..2 orders less.

References

[1] G.A. Bleikher, V.P. Krivobokov, O.V. Paschenko, *Heat and Mass Transfer in Solids under the Action of Powerful Beams of Charged Particles,* Novosibirsk, Nauka, 1999, 176 p.

[2] G.E. Remnev, A.N. Zakutaev, Yu. Ph. Ivanov et al, Letters to ZhTF **22**, 8, (1996).

[3] V.K. Struts, V.M. Matvienko, A.V. Petrov et al, *in Proc. 7th Int. Conf. on Modification of Materials with Particle Beams and Plasma Flows,* 2004, pp. 465–468.

[4] S.I. Anisimov, Ya.A. Imas, G.S. Romanov, Yu.V. Hodyko, *Influence of High Power Irradiation on Metals,* M., Nauka, 1970, 272 p.

[5] G.A. Bleikher, V.P. Krivobokov, O.V. Paschenko, *in Proc. 7th Int. Conf. on Modification of Materials with Particle Beams and Plasma Flows,* 2004, pp. 281–284.