On Evaporation Smoothing Mechanism of Metal Surface under the Irradiation by Submicrosecond Ion Beams

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Abstract – Lately it has been revealed that pulsed charged particle beams are able to diminish the micropeaks on the irradiated surface and in that way to decrease its roughness. But it isn't clear now what mechanisms produce this effect. Most likely the superposition of various mechanisms takes place, at that the contribution of each one is different in dependence on the beam parameters and the target properties.

It's been supposed that the preferred evaporation of peaks is able to be one of the dominating mechanisms when submicrosecond ion beams with the ion energy of 100…1000 keV and the power density of $10^7…10^9$ W/cm^2 are used. The calculations have been carried out confirmed this supposition. The analysis of micropeak reduction effectiveness depending on beam parameters has been realized.

1. Introduction

Nowadays it is known that many practical significant effects of the high-power pulsed charged particle beams (HPCPB) on a material concern with intensive heating with following melting and evaporating thin surface layers. Owing to this fact HPCPB are attractive for being used in material treatment technologies based on modifying structural-phase properties of surface, deposition of thin films, creating microrelief of a surface and so on.

The intensive fluxes of charged particles have recently been discovered to be able to smooth a surface microrelief and as a result of it reduce the surface roughness [1, 2]. Reducing a micropeak height is experimentally detected under the irradiation of samples by the electron beams.

The thin surface layers are discovered to warm up to the melting temperature.

The mechanisms which explain the surface smoothing have been proposed. For instance, in [3] the smoothing mechanism concerning with the elastic-plastic deformation of a substance until melting, the surface tension, the viscosity and the inertia forces at the formation of the melted layer on an irradiated surface.

Since HPCPB can heat the surface up to the evaporation temperature the smoothing surface relief seems to be able to result from not only processes of the elastic-plastic stress, the surface tension, the viscosity and the inertia effected a melted substance but the evaporation too. Due to the fact that the heat transfer on peaks is different from the heat transfer on valleys, it is evident that the peak evaporation is difficult in comparison to the valley evaporation, the evaporation of peaks seems to occur stronger and result in reduction of its height and hence surface relief smoothing. Therefore, a problem of estimation the possibility of appearance of this mechanism and revealing the conditions under that its contribution is the most noticeable emerges.

2. Mathematical model of micropeak smoothing

To reveal a role of the evaporation in reduction of a micropeak and a surface microrelief smoothing the mathematical model of thermal processes in solid structure with cone has been developed. It describes warming up and heat spread in a sample due to the irradiation by HPCPB. The energy consumption for melting and evaporation is taken into account in the model. The spatial design area represents the surface microstructure.

The investigated beam parameters correspond to the range of moderate intensity [4], therefore the problem of warming up and heat spread are based on solving the heat conductivity equation taking into account phase change and volume source of energy release. The design area is represented with a cone peak on a cylindrical basis (Fig. 1).

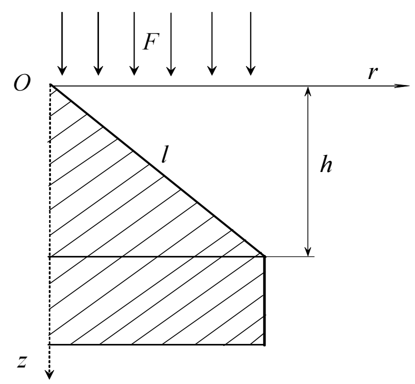

Fig. 1. The design area of the problem

The reasonable assumption of an axial symmetry allows writing down the equation in cylindrical coordinates, temperature field being also symmetrical on an azimuth angle.

Taking into account all the mentioned above requirements and assumptions the mathematical model is described as following:

$$\frac{\partial E(z,r,t)}{\partial t} - v_f(r,t) = \\ = \lambda\left[\frac{1}{r}\frac{\partial T(z,r,t)}{\partial r} + \frac{\partial^2 T(z,r,t)}{\partial r^2} + \frac{\partial^2 T(z,r,t)}{\partial z^2}\right] + \\ + W(z,r,t). \quad (1)$$

Here E is the thermal component of the internal energy of the target material; T is the temperature; λ is the thermal conductivity coefficient; v_f is the evaporation front velocity; $W(x,t)$ is the function of the volume energy release source:

$$T = \begin{cases} E/c\rho, & E \le E_m, \\ T_m, & E_m < E \le E_m + q_m\rho, \\ T_m + (E - (E_m + q_m\rho))/c\rho, & E > E_m + q_m\rho. \end{cases} \quad (2)$$

Here c and ρ are the specific thermal capacity and target material density, respectively; T_m and q_m are the temperature and specific melting heat of the target material, $E_m = T_m c\rho$.

The boundary condition corresponded to surface evaporation in approaching existence of Knudsen's layer on a side of cone designing micropeak is written down as

$$\lambda \left.\frac{\partial T(z,r,t)}{\partial n}\right|_{Z=sur} = \rho v_f \Delta H, \quad (3)$$

where n is the normal to the lateral surface of a cone; ΔH is the difference between the specific enthalpies of the solid and gaseous phases.

Through the rest of boundaries of the design area the heat flow is absent.

The setting techniques of spatial-time energy release function allows taking into account a real current density oscillogram for impulse radiation and also spatial distribution of linear energy losses of accelerated particles during its stopping in the matter.

To estimate surface relief smoothing as a result of evaporation smoothing coefficient D is introduced:

$$D = \frac{y_p - y_v}{h}, \quad (4)$$

where h is the initial peak height relatively valley's coordinate; y_p and y_v are the thicknesses of evaporated layer on a peak and a valley, accordingly.

The purpose of calculations is to reveal the beam parameters under that represented smoothing mechanism makes a noticeable contribution in reduction of a micropeak height.

3. The calculation results and discussion

The mechanism of primary evaporation of micropeaks occurs when the deference between intensities of evaporation of a peak and a valley arises. It is evident that heat transfer on a peak is more difficult than on a valley (basis). Owing to this fact, substance on a peak heats up stronger and evaporates more intensively. The calculation results show that this effect takes place for micropeaks in case a size of the stopping area is less than a peak height.

The released heat cannot spread to a great depth during heating and equalize the temperature distribution throughout a target depth. Earlier carried out investigations allow concluding that the ion beam of the nanosecond duration with the particle energy of 100…1000 keV and the power density of $10^7…10^9$ W/cm^2 can produce this effect. The data obtained according to the described model approve of this supposition.

In Fig. 2 the dependence of the smoothing coefficient D calculated by (4) on the beam current density J at the different peak height h and the different ion initial energy E is presented.

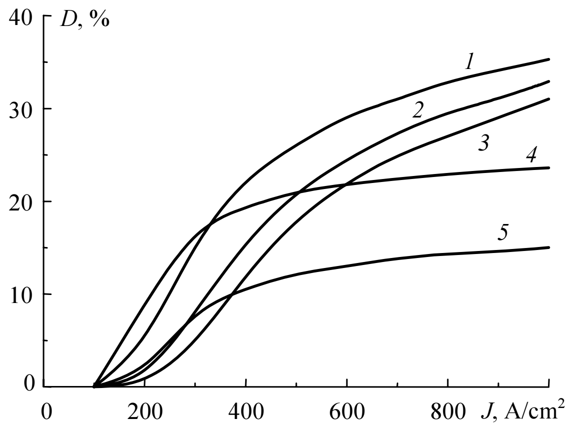

Fig. 2. The dependence of the smoothing coefficient D on the beam current density J at the various peak height h and ion initial energy E: *1* – $C^+ \to$ Cu, $h = 1$ μm, $E = 500$ keV; *2* – $C^+ \to$ W, $h = 1$ μm, $E = 500$ keV; *3* – $C^+ \to$ Cu, $h = 1$ μm, $E = 300$ keV; *4* – $C^+ \to$ Cu, $h = 5$ μm, $E = 500$ keV; *5* – $C^+ \to$ Cu, $h = 5$ μm, $E = 300$ keV (pulse duration is 100 ns)

The calculations have been carried out for irradiation of copper and tungsten by carbon ion beam with duration of 100 ns. During one impulse, a peak height can reduce on some tens of percents due to primary evaporation.

The value D depends not only on the irradiation intensity but also on the ion energy, in other words the ratio of the area of the ion energy release R_p to a peak height h. The dependence of D on R_p/h for the ion beams with the duration of 100 ns and the power density 10^8 W/cm^2. The calculation results show that a maximum in the reduction of a peak height appears when a size of the energy release area is 10…30% of a peak height. If the initial ion energy lies in the range of 100…1000 keV the evaporation mechanism of smoothing is quite correct for peaks with the height around 1…10 μm.

The smoothing coefficient depends on the duration of irradiation τ. The dependence $D(\tau)$ obtained for the irradiation of copper by carbon ions with the initial energy E = 300 keV at the same energy density of 7.5 J/cm^2 is shown in Fig. 4.

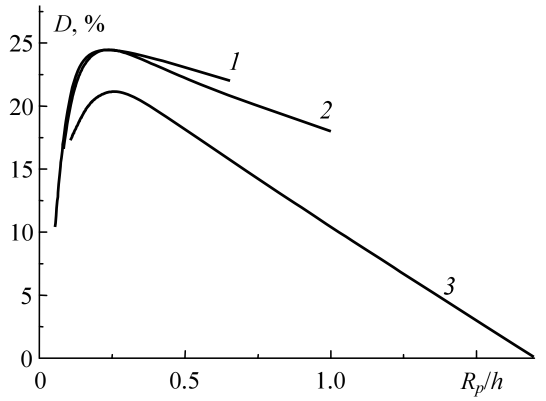

Fig. 3. The dependence of the smoothing coefficient D on the ratio R_p/h for irradiation of the copper target by the carbon beams with the power density of 10^8 W/cm^2, the pulse duration of 10^{-7} ns and the various ion initial energy: *1* – 300; *2* – 500; *3* – 1000 keV

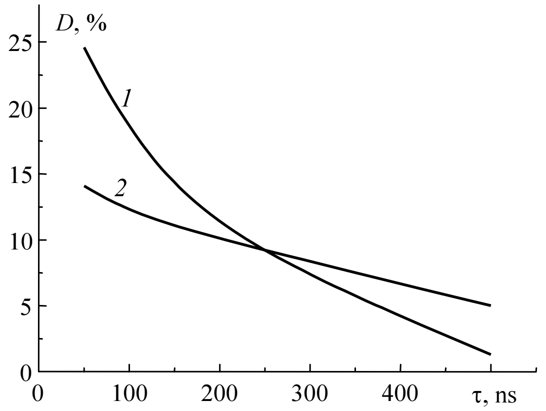

Fig. 4. The dependence of the smoothing coefficient D on the pulse duration τ at irradiation of the copper target with the various peak height h (*1* – h = 1; *2* – 5 μm) by the copper beam with the ion initial energy of 300 keV and the total beam energy density of 7.5 J/cm^2

The lesser the impulse duration, the more significant contribution of evaporation mechanism in reduction of peak height. The shorter impulse at the equal energy density, the more high-power irradiation and the more intensive evaporation. Moreover, at shorter duration of irradiation the temperature field equalizes by heat conductivity slightly.

Being estimating the role of the mechanism of the primary substance evaporation of a peak it is necessary to take into account that under the ion irradiation with the duration of 50…200 ns the evaporation process begins at 20...30 ns of the duration and ends almost completely by the end of the duration [5]. In this interval of time, as mentioned above, a peak height can be reduced by 10…30%. A liquid phase keeps on during some hundreds of nanoseconds after that. The melt movement effects are quite likely to contribute to relief smoothing. However, the evaporation mechanism is rather noticeable.

The pulsed electron beams which is used in surface polishing technology [2] possess the following parameters: the initial energy E is equal to 10…100 keV, the beam energy density is around 10 J/cm^2, the impulse duration lies in the microsecond range. The carried out calculations suggest that for them the mechanism of the primary evaporation of peaks is of little importance or does not appear at all. A peak is reduced by tenth portions of a percent at the beam energy density 2.4…14 J/cm^2 due to this smoothing mechanism, as seen in Fig. 5.

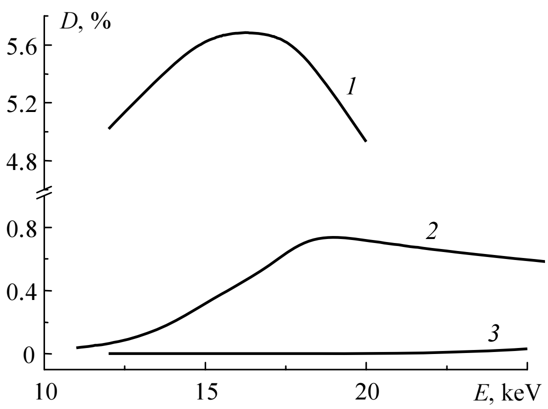

Fig. 5. The dependence of the smoothing coefficient D on the initial particle energy E at irradiation of the various targets (*1*, *2* – titanium; *3* – copper) by pulsed electron beam with the pulse duration of 2 μs and the various current density (*1*, *3* – 500; *2* – 200 A/cm^2)

This takes place for rather easily melted metals like, for instance, titanium. While copper does not evaporate at all at the same power.

4. Conclusions

The submicrosecond pulsed ion beams with the initial ion energy of 100…1000 keV and the power density of 10^7…10^9 W/cm^2 are able to smooth a metal surface with a peak height up to 10 μm noticeably, with the mechanism of primary evaporation of peaks in comparison to valleys being greatly significant. The smoothing efficiency depends on both the power density and the initial particle energy optimal values of that are determined with a peak height.

Under the pulsed electron beams, the given smoothing mechanism appears much weaker, with not acting almost for the microsecond beams with the energy density around units J/cm^2.

References

[1] P. Raharjo, K. Uemura, A. Okada, and Y. Uno, *in Proc. of the 7th Conf. on Modification of Materials with Particle Beams and Plasma Flow*s, 2004, pp. 263–266.

[2] Y. Uno, A. Okada, K. Uemura, P. Raharjo, S. Sano, Z. Yu, and S. Mishima, J. of. Material Proc. Technol. **187–188**, 77–80 (2007).

[3] V.S. Krasnikov, A.Ya. Leivi, A.E. Mayer, and A.P. Yalovez, Zh. Teor. Fiz. **77**/4, 77–80 (2007).

[4] G.A. Bleicher, V.P. Krivobokov, and O.V. Paschenko, *Thermal mass transfer in solids under high-power charge particle beam*s, Novosibirsk, Nauka, 1999, p. 176.

[5] G.A. Bleicher, V.P. Krivobokov, and O.M. Stepanova, Izv. Vyssh. Ucheb. Zav. Fiz. **5**, 31–36 (2007).