HEATING OF MATERIALS WITH A WIDE CLASS OF PULSED ELECTRON BEAMS

Alexey Markov, and Eugene Yakovlev
Tomsk Scientific Center SB RAS,
10/4 Akademichesky Ave., 634055 Tomsk, Russia, a.markov@hq.tsc.ru, e.yakovlev@hq.tsc.ru

In this work, based on the introduced heating type criterion, we analyze the temperature modes induced by pulsed electron beams (PEBs) in a wide range of their parameters. Mainly, we have focused on the investigation of material melting threshold representing both power or/and energy density of PEBs. Computer simulation of the dynamics of temperature fields under irradiation with PEBs has been carried out using the 'HEATPACK-1.0' software package. The U accelerating voltages have been varied in a wide range from 10^3 up to 10^6 V when studying the MMT. It has been established that at low U levels (heating type criterion $\gamma \ll 1$), EMMT increases with rising the τ pulse duration but at high U levels ($\gamma \gg 1$), EMMT decreases with rising the τ pulse duration. Moreover, based on the heating type criterion approach a simple classification of the sources of PEBs can be proposed.

Keywords: pulsed electron beam; material melting threshold; heating type criterion; temperature modes.

Introduction

Recently, sources of pulsed electron beams (PEBs) have been widely used for different purposes in materials science, medicine, and others industries [1-4]. According to the presented data, there are a lot of kinds of PEBs being utilized for materials modification including homogenizing of the surfaces of metallic and non-metallic materials, forming surface alloys, generating microwave or X-ray radiation, sterilizing medical materials, processing plant seeds, etc. The names of some existing PEB source and their key parameters, in particular, U accelerating voltages and τ pulse durations are presented in [5-10].

As follows from the presented data, the U accelerating voltages may vary from 5 up to 1000 kV, i.e. the minimum and maximum values differ by 200 times, while the τ pulse durations evolve from 0.05 up to 300 μs, i.e. by a factor of 6000. Undoubtedly, such sources of PEBs initiate thermal processes in targets that differ in parameters and dynamics. It is interesting to consider benchmarks that would make it possible to understand the nature of processes occurring under irradiation of a particular target and the possibility of using a beam for certain applications. It should depends on the parameters of both the beam and the target.

In processing of metallic materials with PEBs, the initial melting mode is one of the well-known and widely applied for a number of practical purposes, such as surface smoothing or detecting of contaminants on the irradiated surface. The mode of initial melting for a particular material is determined by the parameters of PEBs. However, the power density of PEBs absorbed by the target in the mode of initial melting, called the material melting threshold (MMT), is already a characteristic of the substance. Among other things, the MMT (in some cases, we use energy MMT or EMMT) can be used as a kind of reference point for a comparative analysis of the effects of different PEBs on the same material. Respectively, the research aim has been to analyze the temperature modes induced by PEBs in a wide range of their parameters.

Materials and Methods

Computer simulation of the dynamics of temperature fields under irradiation with PEBs has been carried out using the 'HEATPACK-1.0' software package. In this case, a one-dimensional non-stationary heat equation has been solved numerically with a mixed surface and volume heat sources, considering the energy loss of an electron beam in an irradiated target. The initial temperature of the target was assumed to be room temperature. The target rear side has been sup-posed to be thermally insulated. The melting process has been simulated by the effective specific heat method. However, in this study, the parameters of PEBs have been chosen so that the tar-

get surface temperature reached the melting point by the end of a pulse and does not exceed it.

In computer simulation, rectangular-shaped pulses have been considered, during the pulse duration τ at constant both U(t) accelerating voltage and j(t) current density. The U accelerating voltages have been varied in a wide range from 10^3 up to 10^6 V when studying the MMT.

Numerous materials have been considered as targets, the list of which includes Mg, Be, Al, Ti, BaseM, Cr, Fe, Ni, Cu, Zr, Mo, Ag, and W. The BaseM material is a virtual pseudo-metal that does not exist in nature. Its properties are collective and close to some average values of a wide class of real metals and alloys. Its MMT values have been used as measuring units, against which those of other materials have been calculated to facilitate comparison.

Results and Discussion

Let's introduce the heating type criterion as follows:

$$\gamma = \frac{r}{r_{th}}. \quad (1)$$

The heating type criterion enables to understand the nature of thermal processes occurring in a target of a particular material under irradiation with PEBs.

Obviously, the following three options are possible: $\gamma \gg 1$, which means that we have the volume heating; $\gamma \sim 1$ which means that we have the mixed heating; and $\gamma \ll 1$ which means that we have the surface heating.

Let us find an expression for the heating type criterion in a case of target irradiation with PEBs. Firstly, an r_{th} thickness should be assessed for the layer heated via thermal conduction during a pulse duration. It can be written based on the $\Delta T(0,\tau) \gg \Delta T r_{th},\tau)$ condition and taking into account the temperature field expression for the case of surface heating

$$r_{th} = 2\sqrt{a\tau}. \quad (2)$$

Then, substituting formulas (2) and the well-known expression for the depth of penetration of electron in target into expression (1), the dependence of the γ heating type criterion can be obtained. It follows from expression obtained the that γ values are positive in all cases. If the target material is irradiated with different types of PEBs, the γ values are the same if the U^3/τ=const condition is met. Thus, a pulse duration has to be increased by 8 times when a U accelerating voltage is doubled.

Since MMT depends on the *U* accelerating voltage as the $U^{\frac{3}{2}}$ power function for the $\gamma \gg 1$ case, it has been interesting to follow the change in both EMMT and MMT over the entire *U* range of the studied sources of PEBs. Fig. 1 shows the calculated EMMT curves obtained using the 'HEATPACK-1.0' software package for the BaseM material at three different τ pulse durations. Also, dashed lines indicate curves calculated using analytical expressions for the $\gamma \gg 1$ and $\gamma \ll 1$ cases, respectively. In addition, arrows indicate the points on the curves corresponding to certain γ values. It can be concluded that the agreement between the calculated and analytical curves is satisfactory.

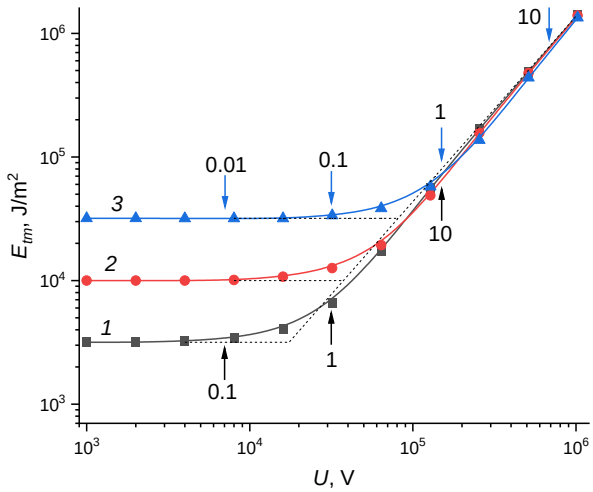

Fig. 1. The EMMT versus *U* accelerating voltage dependences. Curves (*1*)–(*3*) for τ=0.1, 1 and 10 μs, respectively

It follows from Fig. 1 that EMMT changes by an order of magnitude as the τ pulse duration increases, from 3.2×10^3 J/cm^2 at τ=0.1 μs up to 3.2×10^4 J/cm^2 at τ=10 μs, at low U values. However, the difference between the EMMT levels decreases with increasing the U accelerating voltage, and they cease to depend on the pulse duration starting from a certain U

value.

Moreover, we can conclude that Fig. 1 presents a good algorithm for satisfactorily estimating EMMT for both any materials and any PEBs. It suffices, using analytical formulas to draw two straight lines, which, as we can see, describe EMMT well in all ranges, except for the $\gamma \in [0.1;1]$ interval. As for this interval, EMMT can be predicted by any known interpolation method.

As for the calculated MMT curves for the same pulse durations as shown in Fig. 1. It can be concluded from the obtained data that the MMT behavior is completely different: the variations between its levels do not decrease, but increases with rising the U accelerating voltage. In contrast to EMMT, MMT reduces with rising the pulse duration.

Conclusions

1. Both MMT and EMMT have been calculated over the wide ranges of U accelerating voltages and τ pulse durations. At low U levels ($\gamma \ll 1$), EMMT increases with rising the τ pulse duration. The longer the τ pulse duration, the more energy is transmitted into a target bulk and the more it needs to be input to the surface layer. At high U levels ($\gamma \gg 1$), heat removal into the target bulk does not occur. Therefore, only the fact of accumulation of a given amount of energy becomes important, regardless of the τ pulse duration.

2. It was established that to calculate MMT and EMMT for any both materials and PEBs, it is sufficient to use analytical formulas and interpolate the data within the $\gamma \in [0.1;1]$ interval.

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