Thermal phenomena by interaction between 6 MeV electron beams with double samples of C and W

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Study of thermal phenomena in various media under irradiation with relativistic electrons is of major importance for key technological areas like processing of materials used in nuclear fusion installations. C and W behavior under irradiation with relativistic electrons was investigated in recent literature. Here we report on the study of the thermal fields generation in double layered C and W samples when irradiated with 6MeV relativistic electron beams. Two cases are considered when first face submitted to irradiation is either C or W, respectively. Experimental results are analyzed in conjunction with theoretical predictions. The experiments were conducted with the ALID electron accelerator facility at National Institute for Lasers, Plasma and Radiation Physics, Bucharest-Magurele while integral transformation method was applied for theoretical analysis. Special attention is paid to the electrons absorption laws by C and W. Semi-empirical approximations from literature were used in this analysis.

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1. Introduction

A quite large list of models should be mentioned to describe the electron beam interaction with matter. We will here apply a method developed by the Russian School of Theoretical Physics in years 60's, which is based upon integral transformations [1-5]. The method belongs to the family based on Eigen-functions and Eigen-values.

The main advantage of the method is the rapid convergence of the semi-analytical solutions of Fourier equation. An important choice is the absorption laws of electrons in solid targets, in particular C and W [6, 7].

One should also mention the existence of characteristic disadvantages of the method. These manifest e.g. if one cannot take into account the temperature variation of the thermal parameters of the target. That is why our related simulations are strictly valid for medium irradiation powers only.

2. Validity of the Fourier heat equation for the study of relativistic electron-solid interaction

The experimental data which were acquired at the ALID-7 linear accelerator at National Institute for Lasers, Plasma and Radiation Physics (INFLPR) were processed by supposing a top-hat distribution of power in the electron beam cross section.

The electrons with energy in excess of 2.5 MeV are described by the Katz and Penfolds equation [8]:

$$\boldsymbol{d}_{\max}[\boldsymbol{cm}] = (0.530 \cdot \boldsymbol{E}_{\max}[\boldsymbol{MeV}] - 0.106\,[\boldsymbol{cm}]) / \rho[\boldsymbol{g}/\boldsymbol{cm}^3]. \tag{1}$$

Here, d_{max} stands for the maximum penetration depth of electrons in cm, while the target density ρ is expressed in g/cm^3. The energy E_{max} in eq. (1) is in MeV and refers to the maximum energy of the beam. Based upon this equation, one may assume a linear dependence with the distance z of the energy absorbed in the material. The corresponding parameters can be inferred from the two boundary conditions at d_{max}. For the graphite target, ρ=2.23 g/cm^3 and d_{max} results of 1.38 cm, inferior to the sample size. The absorption proceeds in this case according to the law:

$$E_{abs}(z) = \begin{cases} 6 - 4.35 \cdot z, \ for z \le 1.38\ cm \\ 0, \ for z > 1.38\ cm \end{cases}, \tag{2}$$

where E_{abs} is in MeV and z in cm. E_{abs} can serve as a term source in heat equation [9-12]. One obtains from eq. (1) an output energy from C target of 0.78 MeV for z=1.2 cm.

For W target, one has a maximum penetration depth of [13]:

$$d_{\max} = a_1 \left[(1/a_2) \ln\left(1 + a_2 \tau\right) - a_3 \tau / \left(1 + a_4 \tau^{a5}\right) \right] / \rho \quad . \tag{3}$$

Here τ stands for the ratio between the kinetic energy of the electron beam (in MeV) to the electron rest energy.

One has:

$$a_1 = b_1 A / Z^{b2}, \; a_2 = b_3 Z, \; a_3 = b_4 - b_5 Z,$$
$$a_4 = b_6 - b_7 Z, \; a_5 = b_8 / Z^{b9}. \tag{4}$$

The constants b_i are collected in Table 1:

Table 1. The constants b_i from Tabata-Ito-Okabe formula; b_i are unitless

i	b_i
1	0.2335
2	1.209
3	1.78×10^{-4}
4	0.9891
5	3.01×10^{-4}
6	1.468
7	1.180×10^{-2}
8	1.232
9	0.109

It follows that the absorption law in C target reads as:
1. In the center of the spot (W target), the electron penetration depth is 0.11cm in case of the system W-C = 2 cm, from which W length = 0.8 cm and C length = 1.2 cm. This means that one cannot obtain electrons penetration of C target and one has:

$$E_{abs}(z) = \begin{cases} 6 - 54.54 \cdot z, \; for z \le 0.11\, cm \\ 0, \; for z > 0.11 cm \end{cases} \tag{5}$$

2. For the same W-C system, penetrated from C target side 1.2 cm and continued with a W target for 0.01 cm, one has again in the center of the spot:

$$E_{abs}(z) = \begin{cases} 6 - 4.35 \cdot z, \; for \; z \le 1.2 cm \\ 0.78 - 78 \cdot z, \; for \; 1.2 cm < z \le 1.21\, cm \\ 0, \; for \; z > 1.21 cm \end{cases} \tag{6}$$

3. Fourier heat equation

The heat equation in case of homogeneous irradiation of the cylindrical sample reads (in standard spatial and temporal notations):

$$\frac{\partial^2 T(r,z,t)}{\partial r^2} + \frac{1}{r}\frac{\partial T(r,z,t)}{\partial r} + \frac{\partial^2 T(r,z,t)}{\partial z^2} - \frac{1}{\gamma}\frac{\partial T(r,z,t)}{\partial t} = -\frac{A(r,z,t)}{k} \tag{7}$$

Where γ and k are the thermal diffusivity and conductivity, and $A(r, z, t)$ the heat rate per volume and time unit. The boundary conditions are:

$$K \left.\frac{\partial T(r,z,t)}{\partial r}\right|_{r=b} + hT(b,z,t) = 0 \tag{8}$$

$$K \left.\frac{\partial T(r,z,t)}{\partial r}\right|_{z=0} + hT(r,0,t) = 0 \tag{9}$$

The temperature, T, is a function of (r, z, t) which coincides in this case with the temperature variation ΔT. One therefore has: $T(r, z, 0) = 0$.

$$T(r,z,t) = \sum_{i=1}^{\infty}\sum_{j=1}^{\infty} \hat{f}(\mu_i,\lambda_j) \cdot g(\mu_i,\lambda_j,t) \times K_r(\mu_i,r) \times K_z(\lambda_j,z) \tag{10}$$

Here,

$$\hat{f}(\mu_i,\lambda_j) = \frac{1}{\pi C_i C_j}\int_0^b\int_0^a E_{abs}(E,z) \times K_z(\lambda_j,z)dz \times K_r(\mu_i,r)dr \tag{11}$$

One has:

$$g(\mu_i,\lambda_j,t) = \frac{1}{(\mu_i^2+\lambda_j^2)\left[1 - e^{-\beta_{ij}^2 t} - \left(1 - e^{-\beta_{ij}^2 (t-t_0)}\right)h(t-t_0)\right]} \tag{12}$$

where $\beta_{ij}^2 = \gamma(\mu_i^2 + \lambda_j^2)$, $h(t-t_0)$ is the Heaviside function and t_0 is the exposure time. The functions $K_r(\mu_{il},r)$, and $K_z(\lambda_j,z)$ are the eigen-functions corresponding to the eigen-values μ_{il}, and λ_j. One therefore gets $K_r(\mu_{il},r) = J(\mu_{il}\, r)$ and $K_z(\lambda_j,z) = cos(\lambda_j z) + (h/k\lambda_j) sin(\lambda_j z)$. J is the Bessel function of order zero. C_i and C_j are the normalizing coefficients.

4. Experimental

New research is now in progress for relativistic electron beams use to thermal processing, local mixing and other new top applications. To this aim, complicated multimaterial structures should be used. One recent, very efficient approach to this complicated question is the laser additive manufacturing (LAM) which allow for the synthesis of structures with different composition, structure and morphology in regular layers or metamaterials [14-17].

Our experiments were conducted with a W-C cylinder of 1.2 cm diameter and 2 cm total length from which 1.2 cm C and 0.8 cm W. The electron beam has a 6 MeV incident energy with a "top-hat" distribution. We measured the temperature at both the interface between W and C and at the exit surface from cylinder. Other experimental details are provided elsewhere [6]. The temperature field by electron beam irradiation of W-C system from either C or W target side, respectively, is given in Figs. 1 and 2. As expected, the temperature at W-C interface is significantly exceeding the one at exit. This is a consequence of electron beam propagation as described by equations (5) and (6) which reaches the interface but is stopped far away from exit face.

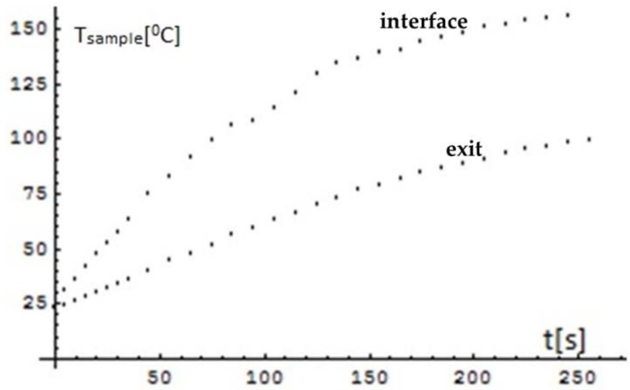

Fig. 1. Temperature field at the interface C-W and at the exit from W target (penetration from C target side)

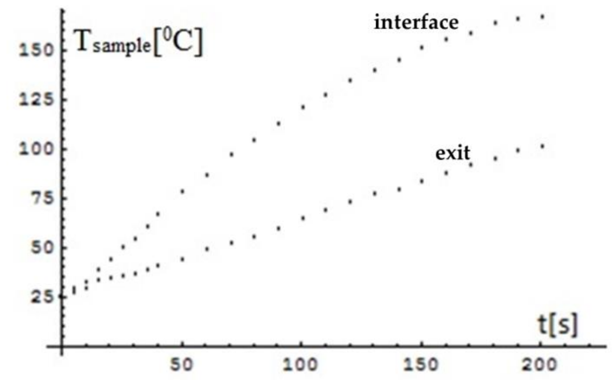

Fig. 2. Temperature field at the interface W-C and at the exit from C target (penetration from W target side)

The thermal field distribution is governed by two important factors: the energy denoted by the term A in Eq. (7) released by the electrons per time and volume unit and the heat transfer constant h, which describes how fast the target loses its heat to the surrounding environment depending on the target material and magnitude of the contact surface between the target and the environment.

5. Experiment and simulations

The geometry of the simulation is a cylinder where the electron beam propagates along the z axis and is incident on a graphite-tungsten sample of 1.2 cm diameter and 2 cm total length. The length of graphite is 1.2 cm while the length of tungsten is 0.8 cm. The results of simulations (plane curves) and corresponding experimental points are given in Figs. 3-6. The relativistic electron beam was of 6 MeV. We used in equation (10) the source terms described by equations (2), (5) and (6).

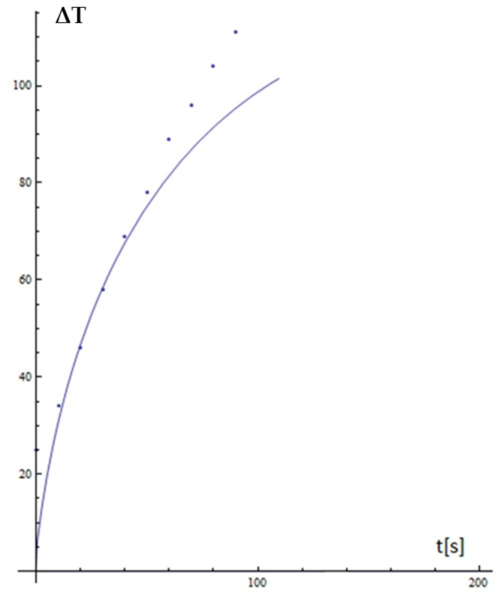

Fig. 3. Temperature variation at C-W interface in case of C - W system irradiation up to 110s (penetration from C target side)

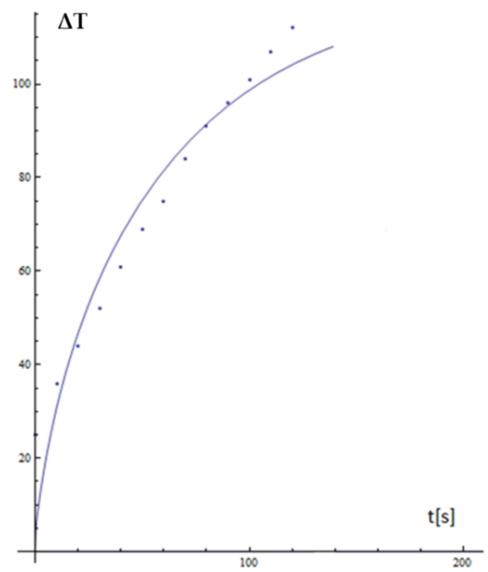

Fig. 4. Temperature variation at W-C interface in case of W - C system irradiation up to 110s (penetration from W target side)

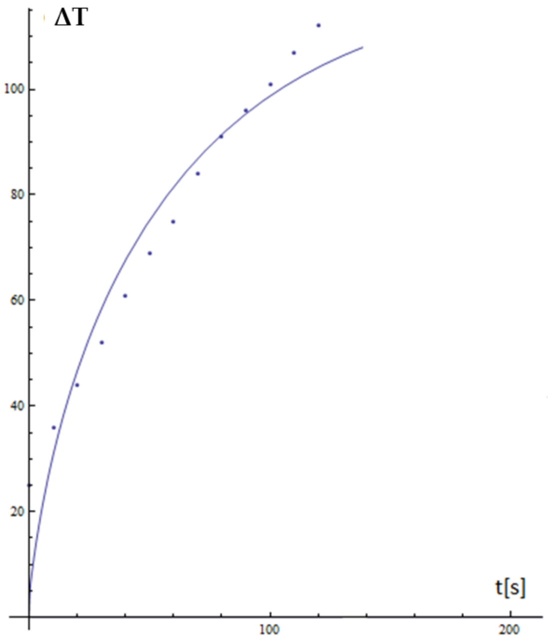

Fig. 5. Temperature variation at the exit of C-W system irradiation up to 110s (penetration from C target side)

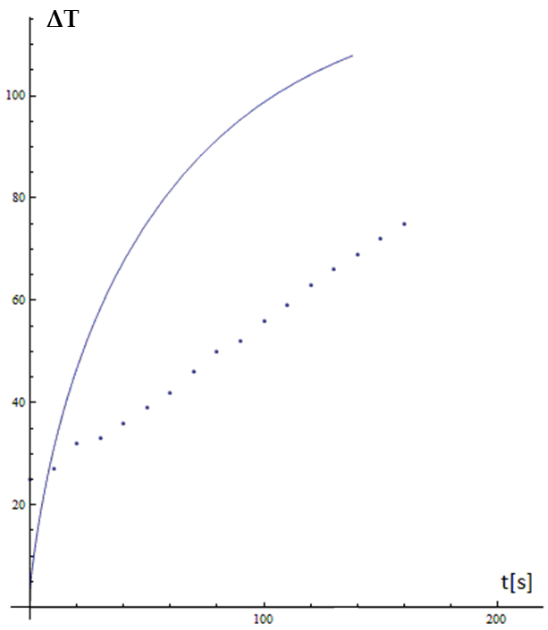

Fig. 6. Temperature variation at the exit of W-C system irradiation up to 110s (penetration from W target side)

One important remark is a general accordance between the results of the experiments described in previews section and the data based upon a rather simple, analytical thermal model of electron beam radiation absorption by the two samples.

As expected, Figs. 3-5 are quite similar, while Fig. 6 shows a significant decrease of temperature inside sample. This is because the irradiation is applied onto W target and the electrons beam is completely absorbed after a penetration depth of 0.11 cm only. The further heat propagation is by conduction first inside W and than C target. One can suppose that this also stands at the origin of the large differences between experimental data and simulations which are to be noticed in this case.

6. Conclusions

We report experimental results of a double sample heating by irradiation with a 6 MeV relativistic electrons beam. The target was a W-C cylinder which was alternatively penetrated from either W or C face.

The temperature at W-C interface and on exit face were measured and found to be in good agreement with the data based upon heat equation solution after integral transformation.

If the irradiation proceeds from C side, the electrons beam penetrates the whole C and a small part of W target. Conversely, if one irradiates from W side, the electrons beam penetrates just a small part of the W target and not the target C at all. This involves that for the most part of W and the entire C target [18], the heat propagates via conduction only. One can thus obtain a fine control of heat/energy release or storage, inside or outside target, which can be monitored and conducted by calculations.

Here, we mention once more that any structure required by a specific application can now be rather easily fabricated by LAM. This opens large prospective to the application of electron beams treatment to quite complicated structures in new advanced technologies.

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