

# The Model of the Electron-Beam Modification of the Composite

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**Abstract** – The model of the non-equilibrium surface layer formation during the electron-beam modification of the composite is suggested. The features of the transport processes in the matrix and in inclusions, and also the interface character are taken into consideration. The examples of the numerical investigation of the model for the case of the ideal contact between the particles and the matrix are presented. The different character of the diffusion zone formation near by the vicinity of particles, located in the different distance from the outside is shown.

## 1. Introduction

Surface modification of the composite has the features, associating with the difference of the physical processes, flowing in the hard inclusions, in the matrix and on the interface. The experimental investigations [1] indicate that the non-equilibrium structurally phase state develops in the surface layer during the impulse electron-beam treatment of the composite on the base of the TiC with NiCr-binding, supporting the change of the physical-mechanical properties of the surface layer. The largest size particles of the carbide are cracked in the first stage of the beaming, separating into the smaller particles before the metallic bonding heating to its melting temperature. The following beaming is conducted by the melting of the metallic bonding in the thin surface layer; the dissolution of the sharp angles of the carbide particles of the awkward shape; and the decrease of the average size of the particles of carbide phase together with the more shrinkage of sintered composition, accompanied by the decrease of the porosity. The non-equilibrium intermediate layer of the multiple structure is formed in the interface of the "particle-matrix". The kinetic regularities of the structurally non-equilibrium state formation in the surface layer of the metal-ceramic alloy during the beaming are determined by the parameters of the external action, by the properties of the inclusions and matrix, and also by the contact character between them. The role of the various physical processes in the evolution of the surface layer structure and in the change of the physical-chemical characteristics is different.

The detailed experimental investigation of the non-equilibrium processes in the surface layers meets with the technical troubles. Therefore, mathematical simulation takes the important role at the analysis of the non-equilibrium processes.

The object of the present work is consist of the computational investigation of the mathematical model of the surface modification of the composite at the condition of the ideal contact between the particles and matrix.

## 2. Mathematical model

To describe qualitatively the process of the transient layer formation between the particles and matrix, we stop on simplified mathematical [2].

Believe that the particle size is much less then the heating zone of the heterogeneous material, forming at the external heating, and the heat layer, forming in the particle material during some characteristic time  $t_*$  (for example, the influence time):

$$\begin{aligned} r \ll \sqrt{\kappa_{eff} t_*}, \quad \kappa_{eff} &= \frac{\lambda_{eff}}{c_{eff} \rho_{eff}}, \\ r \leq \sqrt{\kappa_p t_*}, \quad \kappa_p &= \frac{\lambda_p}{c_p \rho_p}, \end{aligned} \quad (1)$$

Then, at the condition, when the specimen cross size is less then the effective radius of the cathode beam, the problem takes the simple view

$$c_{eff} \rho_{eff} \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} (\lambda_{eff} \frac{\partial T}{\partial x}) - \alpha (T - T_e), \quad (2)$$

$$x = 0: \quad -\lambda_{eff} \frac{\partial T}{\partial x} = q_0 f(t), \quad (3)$$

$$x \rightarrow \infty: \quad \frac{\partial T}{\partial x} = 0, \quad (4)$$

$$t = 0: \quad T = T_0, \quad (5)$$

where  $T_0$  is the initial temperature of the material;  $q_0$  is the maximum density of the external source (of the electron beam);  $\alpha$  is the effective coefficient of the heat exchange;  $f(t)$  is the function, defining the beaming regime (the function form depends on the quantity and duration of the impulses and pauses)

$$f(t) = \sum_{k=1}^n f_k(t), \quad (6)$$

where  $n$  – impulse quantity,  $k$  – impulse number.

$$f_k(t) = \begin{cases} 1, & (t_i + t_p)(k-1) \leq t < t_i + (t_i + t_p)(k-1) \\ 0, & 0, t_i + (t_i + t_p)(k-1) \leq t < (t_i + t_p)k \end{cases}, \quad (7)$$

$t_i$  – impulse duration,  $t_p$  – pause duration.

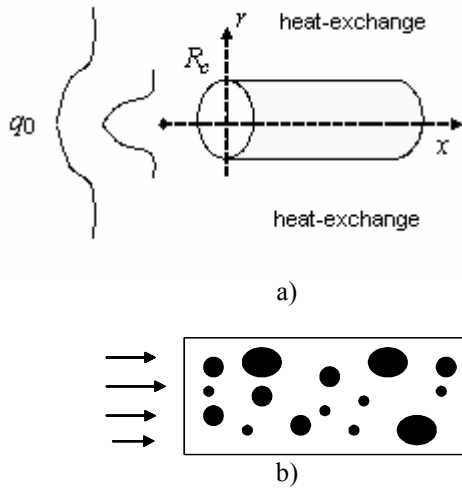


Fig. 1. Illustration to the formulation of heat part of the problem

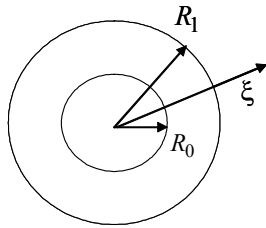


Fig. 2. Illustration to the formulation of the diffusion part of the problem

The radiation dose, accounting on the surface unit, follows from the simple formula

$$I(t) = q_0 \int_0^t f(z) dz = q_0 \sum_{k=1}^n t_{i,k} = q_0 n t_i, \quad \text{J/cm}^2.$$

The effective thermophysical properties of the composite depend on the properties of the components (particles and matrix) and also on the inclusion volume fraction of the particles and can be calculated in the first approximation with the help of formulae

$$\begin{aligned} c_{eff} \rho_{eff} &= c_p \rho_p \eta + c_m \rho_m (1-\eta); \\ \lambda_{eff} &= \lambda_p \eta + \lambda_m (1-\eta) \end{aligned} \quad (8)$$

or

$$\begin{aligned} \frac{1}{c_{eff} \rho_{eff}} &= \frac{\eta}{c_p \rho_p} + \frac{(1-\eta)}{c_m \rho_m}; \\ \frac{1}{\lambda_{eff}} &= \frac{\eta}{\lambda_p} + \frac{(1-\eta)}{\lambda_m}, \end{aligned} \quad (9)$$

where  $\eta$  – inclusion volume fraction. Equations (8) and (9) correspond the laminary composite material with the different layer position with respect to the thermal surface.

Further, believe that the particles are inert and have high melting temperature, and the matrix can melt at the enough low temperature. Melting process is described with the change of the effective thermal capacity of the matrix

$$\begin{aligned} c_m \rho_m &= A + Q_{ph} \rho_s \delta(T - T_{ph}); \\ A &= \begin{cases} c_s \rho_s, & T < T_{ph}; \\ c_L \rho_L, & T \geq T_{ph}, \end{cases} \end{aligned} \quad (10)$$

“s” index relates to the solid phase of the matrix; “L” – to the liquid phase of the matrix;  $Q_{ph}$  and  $T_{ph}$  are the melting heat and temperature of the matrix, respectively.

In the each section of the heterogeneous material  $x=x_0=0; x_1; x_2; \dots$ , which is parallel of the worked surface and had the temperature  $T_s=T(0,t)$ ;  $T_1=T(x_1,t)$ ;  $T_2=T(x_2,t); \dots$ , the particles are found in the different conditions, depending on the heating rate, which follows from the heat problem solution.

Using the previous assumption (1), consider the diffusion problem on the formation of the transient zone between the particle and the matrix in the following formulation (the influence of the diffusion zone formation on the heating rate and on the change of the effective properties are neglected in the first approximation)

The concentration distribution of the alloying element (the carbon in the selected model system) follows from the solution of the conjugate diffusion problem, formulated for the spherical coordinate system.

$$\frac{\partial C_p}{\partial t} = \frac{1}{\xi^2} \frac{\partial}{\partial \xi} \xi^2 D_p \frac{\partial C_p}{\partial \xi}, \quad \xi < R_0, \quad (11)$$

$$\frac{\partial C_m}{\partial t} = \frac{1}{\xi^2} \frac{\partial}{\partial \xi} \xi^2 D_m \frac{\partial C_m}{\partial \xi}, \quad \xi > R_0, \quad (12)$$

where  $R_0$  is the effective radius of the particles;  $D_p$ ;  $D_m$  are the diffusion coefficients of the alloying component in the particles and matrix, depending on the temperature

$$\begin{aligned} D_m &= D_{m0} \exp(-E_m / RT); \\ D_p &= D_{p0} \exp(-E_p / RT), \end{aligned}$$

where  $E_p$  and  $E_m$  are the diffusion activation energy of the carbon in the particles and in the matrix;  $D_{p0}$ ,  $D_{m0}$  are the preexponential factors;  $R$  is the universal gas constant;  $T=T_i$  is the temperature corresponding to the chosen section  $i$  and calculated from the heat conduction problem.

The boundary conditions at  $\xi=R_0$  depend on the system type [2] under study.

The particular case of the ideal contact between the particles and matrix leads to the condition

$$\xi = R_0 : D_p \frac{\partial C_p}{\partial \xi} = D_m \frac{\partial C_m}{\partial \xi}; \quad C_p = C_m. \quad (13)$$

The symmetry condition is carried out in the particle center:

$$\xi = 0 : D_p \frac{\partial C_p}{\partial \xi} = 0. \quad (14)$$

On the infinite distance from the particle surface or on the matrix area boundary, related to one particle  $\xi=R_1$ , the mass sources and mass-losses are absent.

The carbon concentration is given in the initial time moment

$$t=0: \begin{cases} \xi \leq R_0 : C_p = C_{p0} > C_{m0}; \\ \xi > R_0 : C_m = 0. \end{cases} \quad (13)$$

The problem is solved numerically because it has nonlinear character.

The non explicit difference scheme for the heat conduction problem and for the diffusion problem and the double-sweep method are chosen.

The heat losses are not taken into account in the presented below examples.

### 3. Discussion and conclusions

The analysis of the results of the numeral solution of the problem shows that the distribution and the maximal value of the temperature in the treated specimen depend not only on the maximum power density, the impulse quantity and duration, but on the calculation method of the effective thermophysical properties calculation, if the properties of the particle and matrix are different substantially as it is shown. In the case, when the effective properties are calculated from the Eq. (8), the surface temperature not exceed 3000 K, on the curves  $T(t)$  one can see the plateau, connected with the heat losses during the melting process (Fig. 3, a). When the properties are calculated with the help of the equations (9) that corresponds to composite with other structure the temperature is substantially higher then previous one. Due to high thermal conductivity, the plateau on the curves, associated with the melting, is weakly defined (Fig. 3, b). The impulse heating character is shown on the curves, corresponding to the sections, near to free surface, but when the frequency increases at the condition of invariability of all another parameters, the maximal temperature are decreased, but the heating zone grows as it is show on the Fig. 4, a, b for the different frequency value 100 and 1000 hertz at the condition  $t_i = t_p$ .

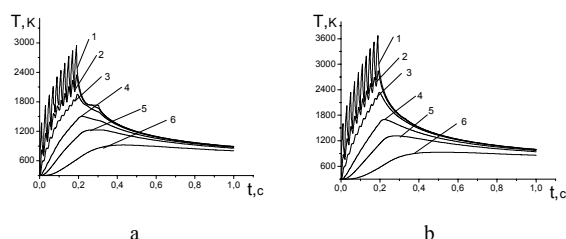


Fig. 3. The temperature versus on time in the different sections.  $n=10$ ;  $t_i=t_p=0.01$  c;  $\Gamma=50$ ;  $I=1.3 \cdot 10^3$  J/cm<sup>2</sup>;  $q_0=1.3 \cdot 10^4$  W/cm<sup>2</sup>;  $\eta=0.4$ ;  $x=$ : 1 – 0; 2 – 0.025; 3 – 0.05; 4 – 0.1; 5 – 0.15; 6 – 0.25 cm

Since diffusion is the more inertial process than thermal conductivity, the particles, located in the

sections closely to free surface, no "feel" the impulse character of the heating: the concentration distribution of the carbon in the particles and in matrix for the different time, including when the temperature decrease to  $T=700-900$  K, lower which the diffusion practically has no place, are identically.

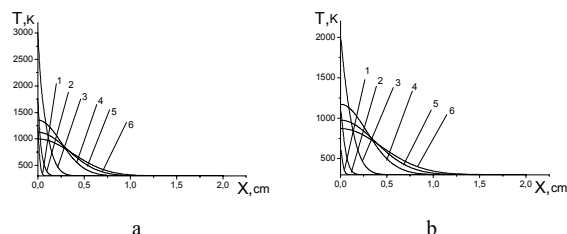


Fig. 4. The temperature distribution along the specimen axis for the different time moments.  $I=1.3 \cdot 10^3$  J/cm<sup>2</sup>;  $q_0=1.3 \cdot 10^4$  W/cm<sup>2</sup>;  $\eta=0.4$ ; a)  $\Gamma=100$  Hz;  $n=20$ ; b)  $\Gamma=1000$  Hz;  $n=200$ ;  $t=$ : 1 – 0.005; 2 – 0.025; 3 – 0.125; 4 – 0.5; 5 – 0.75; 6 – 1.0 cm

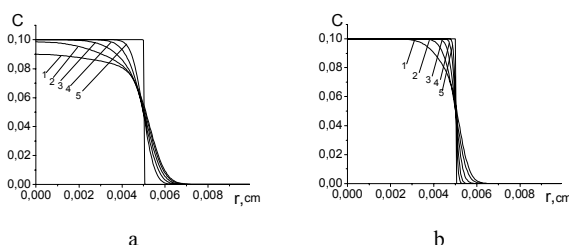


Fig. 5. The concentration distribution of the carbon in the particle and in the matrix in the different sections of specimen  $x=$ : 1 – 0; 2 – 0.025; 3 – 0.05; 4 – 0.1; 5 – 0.15; 6 – 0.25 c to time  $t=1.5$  c (it is the time of the surface cooling to the 900 K)  $\Gamma=100$  Hz; a)  $q_0=1.6 \cdot 10^4$  W/cm<sup>2</sup>; b)  $q_0=1.1 \cdot 10^4$  W/cm<sup>2</sup>

But the power density of the external flux of the heat  $q_0$  effect on the carbon redistribution essentially. It is shown on the Fig. 5, a, b. The concentration distribution does not change in the particles, located in the depth.

Thus, even in the simple approximation (1), it is seen the principal role of the diffusion processes for the non-equilibrium surface layers formation in the composite, when the high-energy sources are used for their modification.

### References

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