

# Influence of the Rate Intake of Particles into the Melt on the Structure and Properties of Coating Forming During Electron-Beam Surfacing

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**Abstract – The model of process of electron-beam surfacing taking into account the kinetics of the particle redistribution and dissolution in the melt has been presented. It was shown that the critical values of the technological parameters, dividing the formation of homogeneous and composition coating, exist. The dependence of the mechanical properties of forming coating on technological parameters of the electron-beam surfacing has been obtained theoretically.**

## 1. Introduction

During thermal material treatment and surfacing the choice problem of the technological condition appears, allowing obtaining the materials (and their surfaces) with expected properties. As a rule the modern technologies are multifactor, laboriously and expensively, that restrains in their evolution. Described below results show, that one can found the connection between the properties and composition of the forming coating and technological parameters in the frame of the mathematical model of process of electron-beam surfacing. It may be used in real experimental investigations.

## 2. Mathematical Model

The mathematical model of electron-beam surfacing has been suggested in [1, 2] and consists in following. Let the source moves along the plate surface of the thickness  $h$ . Energy is distributed in the source according to the law

$$q_e = \begin{cases} 0, & |y| > y_0/2; \\ q_0 \exp(-(x-vt)^2/a_t^2), & |y| \leq y_0/2, \end{cases} \quad (1)$$

where  $q_0$  is the maximal density of a power of the heat flux;  $a_t$  is the effective radius of the source; magnitude  $y_0$  is proportional to width of the scanning.

The particles arrive in the arising melt bath at the some interval  $x_a$  from maximum of the energy-release (or at the same place). The properties of the particles differ from ones for base material. The flux density of the particles is distributed according to the Gauss law

$$q_m = q_{m0} \exp\left[-\left((x-x_a-vt)^2 + y^2\right)/a_p^2\right], \quad (2)$$

where  $q_{m0}$  is the maximal density of the particles flux, and the magnitude  $a_p$  is determined by the tube radius, through which the particles are supplied.

Temperature field is obtained from the solution of the two-dimensional heat conduction equation

$$c\rho\left(\frac{\partial T}{\partial t}\right) = \frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right) + Q_s\varphi - \frac{(\varepsilon\sigma T^4 - q_e)}{h}, \quad (3)$$

that are written in the laboratory coordinate system, where  $\varepsilon\sigma T^4$  describes the heat emission from melt bath surface by the Boltzmann law,  $c$  is the heat capacity,  $\rho$  is the density,  $\lambda$  is the thermal conductivity coefficient,  $Q_s$  is the dissolution heat of the particles in the melt. These parameters depend on type of the studied system.

The particles quota satisfies to the equation

$$\frac{\partial \eta_p}{\partial t} = q_m - \varphi(T, \eta_p, \dots). \quad (4)$$

Generally, the function  $\varphi$ , which characterizes the dissolution velocity, depends on the temperature, dispersion, reciprocal solubility of the elements and the local characteristics of the hydrodynamic flow. According to literature data, we take

$$\varphi(T) = \varphi_1(\eta_p)k_0 \exp(-E_a/RT),$$

where  $k_0$ ,  $E_a$  are the formally-kinetic parameters,  $R$  is the absolute gas constant.

The symmetry condition is used at the axis, and the condition of an absence of the heat sources is assumed away from heating region.

Initially we have

$$t = 0 : T = T_0, \quad \eta_l = 0, \quad \eta_p = 0, \quad \eta_s = 1.$$

Generally, thermophysical properties depend on temperature and composition.

1. In the case of the system Ni-Cu with dissolving nickel particles, we have

$$c\rho = (c\rho)_{\text{eff}} + L\rho_{\text{Cu}_s} \frac{\partial \eta_l}{\partial T}, \quad (5)$$

where effective heat capacity is calculated by the formulae

$$(c\rho)_{\text{eff}} = (c\rho)_s(1-\eta_l) + (c\rho)_l\eta_l, \quad (6)$$

$$(c\rho)_s = (c\rho)_{\text{Ni}_s}\eta_p + (c\rho)_{\text{Ni}_s}\xi + (1-\xi)(c\rho)_{\text{Cu}_s},$$

$$(c\rho)_l = (c\rho)_{\text{Ni}_l}\xi + (1-\xi)(c\rho)_{\text{Cu}_l};$$

$$\eta_l + \eta_s + \eta_p = 1,$$

subscript “s” relates to solid state, “l” corresponds to liquid one.

Following notations are assumed in (5), (6).  $(1-\eta_l) = (\eta_s + \eta_p)$  is the volume part of the whole solid phase;  $\eta_p$  is the volume part of the insoluble particles;  $(1-\eta_p)$  is the volume fraction of the solution (a liquid or a solid);  $\eta_l$  is the volume fraction of the liquid phase (without particles or with particles, i.e. suspensions), defining according to conception of the two-phase zone theory from the relation

$$\eta_l = 1 - \left( \frac{T_{\text{liq}} - T}{T_{\text{liq}} - T_{\text{sol}}} \right)^n; \quad (7)$$

the parameter  $n$  is varied for different alloys in the two-phase zone theory;  $L$  is a latent melting heat of copper,  $\eta_s = 1 - \eta_p - \eta_l$  is the volume fraction of the solid solution;  $T_{\text{liq}}$  is the liquidus temperature;  $T_{\text{sol}}$  is the solidus temperature on the state diagram Ni–Cu (we have  $\eta_l = 1 - \eta_p$ , at  $T \geq T_{\text{liq}}$  and  $\eta_l = 0$  at  $T \leq T_{\text{sol}}$ );  $(1-\xi)$  is the volume fraction of the copper in the solution;  $\xi$  is the volume fraction of nickel in the solution, which satisfies to the equation

$$\frac{\partial \xi}{\partial t} + v \frac{\partial \xi}{\partial x} = \varphi(T, \eta_p, \dots).$$

Using the state diagram of the system Ni+Cu, the liquidus  $T_{\text{liq}}$  and the solidus temperatures  $T_{\text{sol}}$  are approximated by linear dependences

$$\begin{aligned} T_{\text{sol}} &= a_s + b_s \cdot C_m + c_s \cdot C_m^2; \\ T_{\text{liq}} &= a_l + b_l \cdot C_m + c_l \cdot C_m^2, \end{aligned} \quad (8)$$

where  $C_m$  is the mass part of nickel in the solution, calculated from the relationship

$$C_m = \frac{\xi M_{\text{Ni}}}{\xi M_{\text{Ni}} + (1-\xi)M_{\text{Cu}}} \quad (9)$$

$$a_s = 1358.18; b_s = 323.11; c_s = 43.71;$$

$$a_l = 1373.64; b_l = 637; c_l = -286.13.$$

2. In the case of the melting (crystallization) of the pure copper (without particles), the heat capacity variation is described by the formula

$$c\rho = A + (1-\eta_p)L\rho_{\text{Cu},s}\delta(T-\theta), \quad (10)$$

near by the vicinity of the melting temperature, where  $A = (c\rho)_{\text{Cu}_l}$  for  $T \geq \theta$  or  $A = (c\rho)_{\text{Cu}_s}$ ,  $T < \theta$ ;  $\theta$  is the melting temperature of the pure copper;  $\delta$  is the delta function, that is replaced  $\delta$  – like function in the real calculation

3. When the particles of any type are insoluble and non-melting, we have the formula (8), where

$$A = \begin{cases} (c\rho)_{\text{Cu}_s}(1-\eta_p) + c_p\rho_p\eta_p, & T < \theta; \\ (c\rho)_{\text{Cu}_l}(1-\eta_p) + c_p\rho_p\eta_p, & T \geq \theta, \end{cases}$$

$c_p$ ,  $\rho_p$  are the heat capacity and density of the particles (in particular, tungsten, chromium and others).

Generally, the heat conductivity depends also on the temperature and composition

$$\lambda_{\text{eff}} = \lambda_{\text{Cu}}(1-\xi-\eta_p) + \lambda_p(\xi + \eta_p),$$

where  $\lambda_{\text{Cu}}$  is the heat conductivity of copper;  $\lambda_p$  is the heat conductivity of the base material, depending on temperature (these dependences can be presented in the form of the cube polynomials).

Dependences of substances properties on temperature are taken from literature data for solid and liquid phases.

Purpose of this work consists in the investigation of an influence of the parameters characterizing the surfacing on the melting bath formation, the heat-affected zone formation, and the phase structure of the forming coating.

The problem is solved numerically with the help of implicit linearized difference schema, coordinate splitting and double-sweep method.

### 3. Analysis of the Results

The analysis of the results of numerical investigation has shown that quasi stationary regime establishes when source moves along the treated surface. That takes a place for insoluble and for soluble particles W and Ni and means following (Fig. 1).

The maximal temperature  $T_{\text{max}}$  along the axis of the source motion, the size of heat-affected zone  $y_T$ ,  $x_T$  and molten pool  $y_m$ ,  $x_m$ ; the part of the particles on the boundary of heat-affected zone after moving source  $\eta_{p,st}$  (in the point A) stop practically change. Real calculation is carried out until the quasi stationary regime steadies with given accuracy. The values  $y_T$ ,  $x_T$ ,  $y_m$ ,  $x_m$ ,  $T_{\text{max}}$ ,  $\eta_{p,st}$  depend on technological parameters for soluble and for insoluble particles. Such dependencies were presented in [2] for soluble particles. The  $T_{\text{max}}$  ( $q_0$ ,  $v$ ,  $q_{m0}$ ) etc. for insoluble particles are analogous to [2] and do not presented here.

It is shown from Fig. 1,b, that no solved particles Ni present (for given parameter set) only in the region of their intake; further practically all particles have

time dissolve before melt crystallization. The distribution of particle part  $\eta_p$  in the melt is displayed in Fig. 2 separately for the time moment corresponding to the establishment time.

To evaluate the properties of forming coating, the dependence of the particle part in them depending on the source parameters is the most interest for given material properties. The distribution of  $\eta_p(x, 0)$  for various time  $t$  and various values of capacity density of the heat flux  $q_0$  is given in Fig. 3. Obviously, the higher capacity density of the source, the more part of the particles dissolves in molten pool.

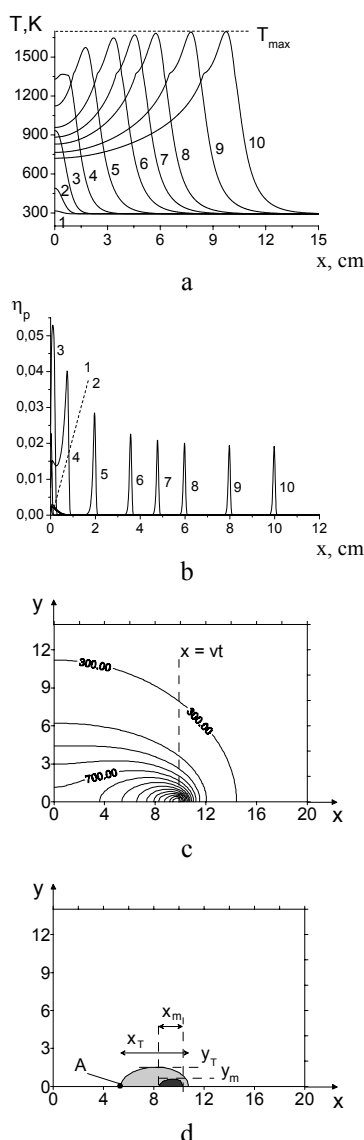


Fig. 1. Distribution of the temperature (a) and the volume particles part (b) along the source moving axis; temperature isolines (c), form and size of the molten pool and heat-affected zone (d) for establishment time; the calculation is carried out for the system Ni+Cu and for the parameters  $q_0 = 10^4$  Vt/cm<sup>2</sup>;  $x_a = 0$ ;  $v = 1$  cm/s;  $q_{m0} = 3$  1/s. The temperature and particle part curves are presented for consecutive times: 1 -  $t = 0.004$ ; 2 -  $t = 0.04$ ; 3 -  $t = 0.2$ ; 4 -  $t = 0.8$ ; 5 -  $t = 2$ ; 6 -  $t = 3.6$ ; 7 -  $t = 4.8$ ; 8 -  $t = 6$ ; 9 -  $t = 8$ ; 10 -  $t = 10$ ;  $T$ - isolines are presented for establishing time

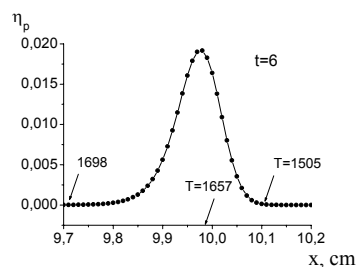


Fig. 2. Distribution of  $\eta_p$  in the melting for establishing time

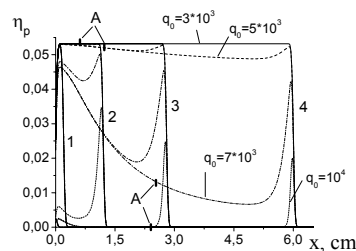


Fig. 3. Distribution of the volume part of the particles for consecutive times (1 -  $t = 0.2$ ; 2 -  $t = 1.2$ ; 3 -  $t = 2.8$ ; 4 -  $t = 06$ ) for different values of the source capacity density  $q_0$ .  $v = 1$  cm/s;  $q_{m0} = 3$  1/s;  $x_a = 0$ ; the calculation is carried out for the system Ni+Cu

It was detected, that the critical value of the capacity density of the source exists and divides the regimes of the homogeneous coating formation and composition coating formation for given value of the motion velocity of the source  $v$  and for given  $q_{m0}$ ,  $x_a$ , etc. If the particles are insoluble, the composition coating is formed always.

The dependencies of particle part in the coating on the mass flux  $q_{m0}$  and on the capacity density of the heat source  $q_0$  are demonstrated in Fig. 4 for different systems (Ni+Cu and W+Cu). If the particles are soluble, the value  $\eta_p$  depends on all parameters; if the particles are insoluble,  $\eta_p$  depends on the velocity  $v$  and mass flux, with these dependences can be taken as linear.

Using theories known from continua mechanics, we can evaluate the mechanical properties of formed coating. So, in the simplest case, when the form of particles and the nature of internal boundaries do not taken into consideration, the modulus of elasticity can be evaluate by formulae

$$E_a = E_p \eta_p + E_b (1 - \eta_p) \quad (11)$$

or

$$\frac{1}{E_L} = \frac{\eta_p}{E_p} + \frac{(1 - \eta_p)}{E_b}, \quad (12)$$

where  $E_a$  is the upper evaluation;  $E_L$  is the lower evaluation. In the case of insoluble tungsten particle, we have  $E_b = E_{Cu}$ , and we take  $E_b = E_p \xi_p + E_{Cu} (1 - \xi_p)$  (the elasticity modulus for the solution) for the case of soluble nickel-particles, where  $E_p$  is the elasticity modulus for the particles. Correspondingly to [3] we

have:  $E_{Ni} = 210$  GPa,  $E_W = 375$  GPa,  $E_{Cu} = 120$  GPa. The results are shown in Fig. 5,a,b.

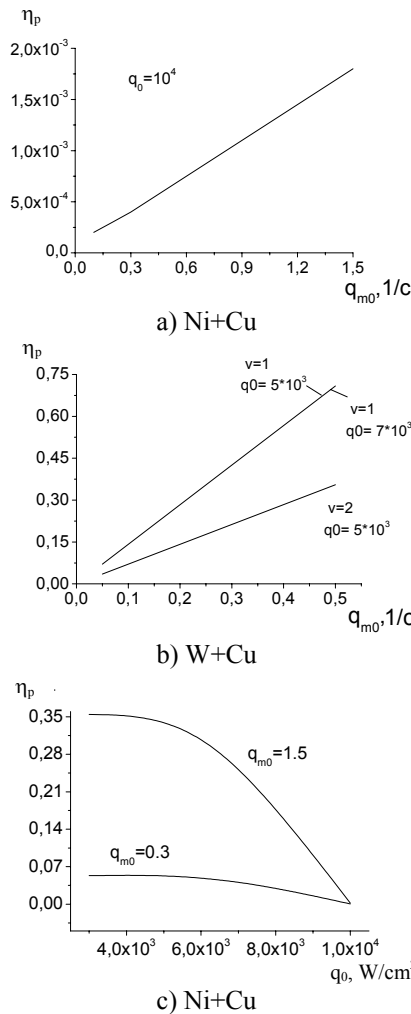


Fig. 4. Dependence of particles fraction in the coating for different systems (Ni+Cu and W+Cu) depending on the mass flux  $q_{m0}$  and the source power density  $q_0$

For values  $q_0$ , when nickel particles dissolve actively in copper melt, the particle part in the coating is not too large. That explains the coincidence of the modulus values calculated by different formulae (Fig. 5,a). If the particles are insoluble, the upper and lower evaluations can be different essentially. In the case of the system Ni+Cu, the dependence of modulus on the capacity density of the heat source takes a place, with this dependence is nonlinear essentially (Fig. 6). The upper and lower evaluation coincide again for the large values  $q_0$ , that connects with the homogeneous coating formation.

### Conclusion

Let us notice in conclusion, that the suggested model and their particular variants allow to investigate the influence of the distribution of the particles in sizes, the place of their intake in the melt on the kinetics of

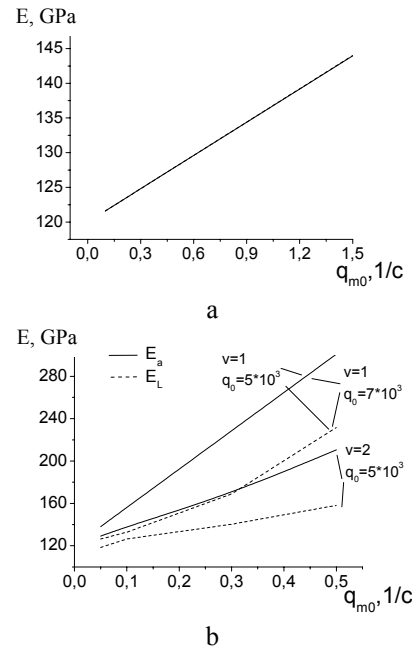


Fig. 5. Dependence of the elastic modulus on the mass flow  $q_{m0}$ : a -  $E_p + E_{Ni}$ ; b -  $E_p + E_W$

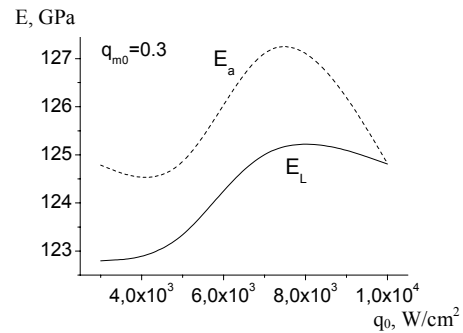


Fig. 6. Dependence of the elastic modulus on the source capacity density  $q_0$ ,  $E_p + E_{Ni}$

their redistribution in the molten pool and the solution kinetics; the critical conditions of the solution depending on the technological parameters etc. That can be interested for optimization of the technology of electron-beam surfacing.

The work was supported by Russian Science Foundation, grant No. 02-01-81034 Бел 2002\_a.

### References

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