INFLUENCE OF PULSED ELECTRON BEAM PARAMETERS ON THE THICKNESS OF MODIFIED LAYER

Abstract

The problem of metal surface treatment by high-energy electron beams process effectiveness is discussed.

The mathematical simulation of the interaction between the high-energy electron beam and the material shows that a mere increase in specific power of the loaded beam by increasing its current density does not contribute significantly to the thickness of the molten metal layer. Only by increasing the accelerating voltage of the electron accelerator the molten layer about 100 μm thick can be obtained.

Keywords: subsurface modified layer, grain size, cool-down rate, penetration depth, accelerating voltage, melting depth, recrystallization

Introduction

Electron accelerators promise great perspective when applied for surface modification of various metal products. Such features of electron accelerators like the possibility to control the beam current density, accelerating voltage and pulse duration in a wide range and with a high accuracy provides a way of obtaining surfaces with a high corrosion/erosion and wear resistance. These surface characteristics are determined mainly by the *depth* of the modified subsurface layer and the *grain size* of treated material. It is obvious that the thicker is the modified layer and the less is the modified layer grain, the higher is the metal surface hardness and its wear and corrosion/erosion resistance. The latter is defined by the molten layer thickness and its cool-down rate. By selecting appropriate parameters of the beam, like the pulse length, current density and the accelerating voltage, it is possible to control two above-mentioned parameters of the metal surface treatment.

The process of metal surface treatment by high-energy electron beams (100-400 keV) is based on the production of the molten subsurface layer of the required thickness (about 50-100 μm) and its fast cool-down so as to prevent formation of large grains in the crystal lattice of the modified layer which deteriorate the strength properties of the surface. To provide the required cooldown rate of 10^7-10^9 C/s the temperature of the initial molten layer should be as close to the melting temperature as possible, with the temperature in the solid phase remaining low, that would allow a high temperature gradient on the melt/solid phase boundary. It is this gradient that should provide the required cooldown rate of the molten layer. The undertaken researches (among them [1]) revealed that the electron accelerators that are capable to provide the volume heat release in the subsurface layer within a short time interval (pulse length of 20-50 μs) are particularly attractive for metal surfaces treatment.

As mentioned above, the thickness of the molten layer along with a high cooldown rate, determines the quality of the modified surface. The thickness of the molten layer depends strongly on the value of energy deposited into the material. An increase in the beam current density seems to appear the simplest and the easiest way to realize method of the absorbed energy enhancement. But, as it will be shown in the subsequent sections, this increase, with the accelerating voltage remaining unchanged, makes the thickness of the molten layer greater but just slightly. Attempts to increase further the layer thickness further by building up the current lead to the so-called «auto-model» regime when the rates of evaporation and melting fronts become equal with a consequent stabilization of the molten layer.

Thus, only an accelerating voltage increase is the only effective method of the molten layer thickness build-up while providing the required cooldown rate necessary to obtain the high-quality metal surfaces.

Numerical Investigation

To prove the above statement a model problem of Fe sample heat loading by an electron beam should be considerate in more details. In our analysis the e-beam energy is assumed to be equal to 100 keV, since the accelerators with this electron energy are the most typical ones with more complete experimental data base. To solve this problem the non-linear transient mathematical model has been developed. This model includes the following basic physical processes that define the result interaction between high energy flux and metal surface:

- non-equilibrium evaporation of Fe from the sample surface producing a vapour cloud;
- shielding effect by evaporated material;
- melting/solidification inside the solid phase of the Fe sample;
- dependence of Fe thermal physical properties on the material temperature;
- real distribution of the volumetric heat load along the electrons penetration depth.

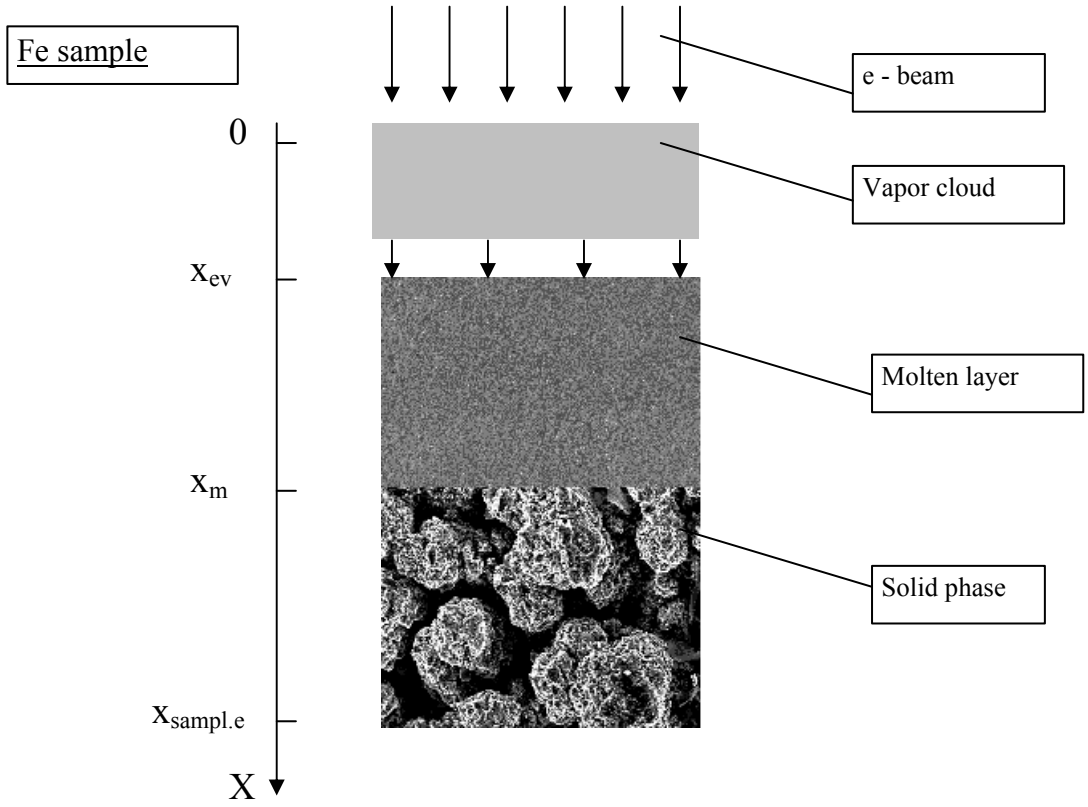

Fig. 1. Calculation model

The governing energy conservation equation that describes the physical model may be expressed as follows:

$$C_p(T)\rho(T)\frac{\partial T(x,\tau)}{\partial \tau} - \frac{\partial}{\partial x}\left(\lambda(T)\frac{\partial T(x,\tau)}{\partial x}\right) = q_v(x,\tau) \qquad (1)$$

The processes taking place on the loaded Fe surface may be written as:

$$-\lambda(T)\frac{\partial T(x,\tau)}{\partial x} = q_{rad} + q_{ev} \qquad at \quad x = x_{ev} \qquad (2)$$

For the back side of the Fe sample we may impose either adiabatic boundary condition or the surface temperature invariability within the whole process:

$$-\lambda(T)\frac{\partial T(x,\tau)}{\partial x} = 0 \quad or \quad T(x,\tau) = T_0 \qquad at \quad x = x_{sample} \qquad (3)$$

A uniform temperature distribution over the entire sample is taken as an initial condition:

$T(x, \tau) = T_0$ for $\forall x \in [0, x_{sample}]$ and $\tau = 0$.

$$-\lambda(T)\cdot\partial T/\partial x\big|_{x=s(\tau)-0} = -\lambda(T)\cdot\partial T/\partial x\big|_{x=s(\tau)+0} + \rho L_{melt}\cdot ds(\tau)/d\tau, \qquad (4)$$

for $x \in s(\tau)$ (melting boundary), where $T(\tau,s(\tau)) = T_{melt}$
The heat lost from the loaded Fe sample surface by radiation may be written as:

$q_{rad} = \varepsilon_{eff}\cdot\sigma\left(T^4(0,\tau) - \vartheta^4\right)$ - if evaporation does not take place yet (5)

We assume for simplicity, that $\vartheta = T_0$, i.e. the environment temperature is the same as the sample initial temperature. When the evaporation becomes evident, correlation (5) should be rewritten as follows:

$$q_{rad} = \varepsilon_{eff}\cdot\sigma\left(T(x_{ev},\tau)^4 - T_{cld}^{\ 4}\right) \qquad (6)$$

The effective emissivity ε_{eff} in equations (5) and (6) is defined as

$$\varepsilon_{eff} = \begin{cases} \left(\frac{1}{\varepsilon_{surf}} + \frac{1}{\varepsilon_0} - 1\right)^{-1}, & \text{for formula (5)} \\ \left(\frac{1}{\varepsilon_{surf}} + \frac{1}{\varepsilon_{cld}} - 1\right)^{-1}, & \text{for formula (6).} \end{cases}$$

The vapour cloud temperature T_{cld} is assumed to be uniform across the cloud and is defined as a mass-average temperature of the evaporated Fe material composing this cloud.

Heat spent for evaporation is defined in our model according to the correlation describing a non-equilibrium evaporation process [2].

$$q_{ev} = \rho L_{ev} W_s \cdot \exp\left(-\frac{L_{ev}\cdot\mu}{R\cdot T_{ev}}\right) \qquad (7)$$

In our model electrons generated by the e-beam accelerator are supposed to penetrate the Fe solid phase to the so-called «penetration depth» and distribute their energy over the penetration depth volumetrically. The following equation for the electron penetration depth evaluation was proposed by V. Kovalenko [3] for the electrons with the energy range of 3 – 3000 keV.

$$\delta = \frac{10^{-5}}{\rho}\cdot E^{1,5} \qquad , (8)$$

where, E is expressed in keV, ρ in g/cm^3, δ in cm.
Monte-Karlo method was applied to obtain heat load distribution in the penetration depth. This distribution produced by 100 keV e-beam and normalized for 1 A/cm^2 of current density is shown in Fig. 2.

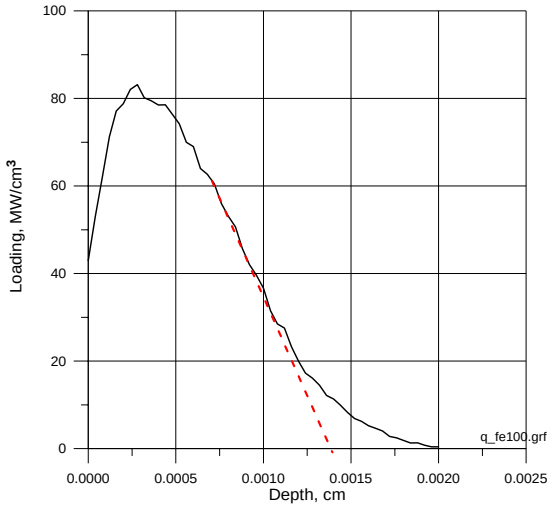

Fig. 2. Heat load distribution in Fe depth (100 keV, 1 A/cm^2)

The Fe properties, such as the thermal conductivity (λ) and heat capacity (c_p), that strongly depend on the material temperature are presented in Fig. 3 and Fig. 4, respectively. These properties are given for Fe produced by recrystallization in vacuum. Due to lack of the reliable data for the temperatures beyond 1100°C, the thermal conductivity and heat capacity were assumed to be constant and equal to those at 1100 °C in this temperature range. Such an assumption will not essentially affect the result of the analysis made in the frame of the stated problem.

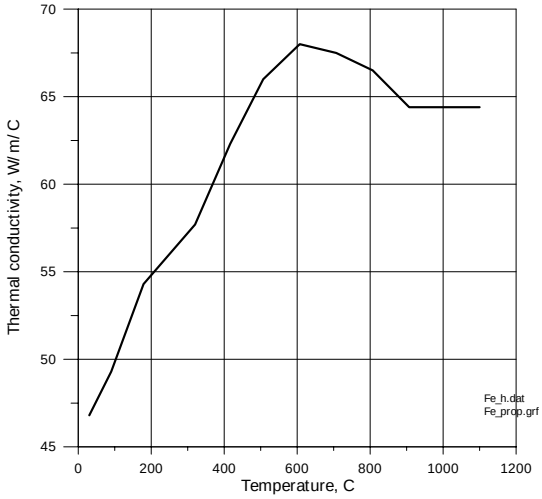

Fig. 3. Fe thermal conductivity vs. temperature

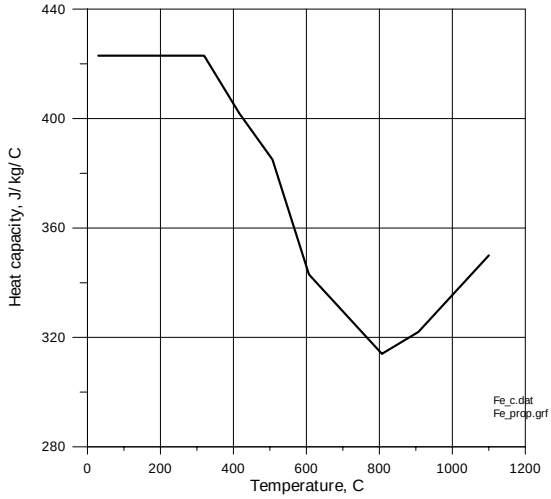

Fig. 4. Fe heat capacity vs. temperature

Other Fe properties, that assumed to be temperature-independent in our analysis, are given below [4]:

Density, kg/m^3	7800;
Emissivity	0.1;
Acoustic velocity, m/s	5180;
Latent heat of evaporation, J/kg	$6.34 \cdot 10^6$;
Latent melting heat, J/kg	$2.77 \cdot 10^5$;

Boiling temperature, °C	2730;
Melting temperature, °C	1530.

Numerical simulation conditions for the postulated problem were taken as follows:

Current density, A/cm^2	5 – 60;
Accelerating energy, keV	100, 200, 300, 400;
Pulse duration, μs	20.

Calculation results

As described above, the main objectives of the presented numerical simulation of e-beam-Fe surface interaction were (1) to determine the molten layer thickness inside the loaded Fe sample and (2) to evaluate an impact of the accelerator regime parameters on the molten layer thickness (current density, accelerating voltage) and different factors characterizing the physical process (accounting or ignoring the melting latent heat).

Thus, the first of the graphs presented below (see Fig.5) shows the results of the numerical investigation on the control of the molten layer thickness by electron beam current density, with constant accelerating voltage (100 keV).

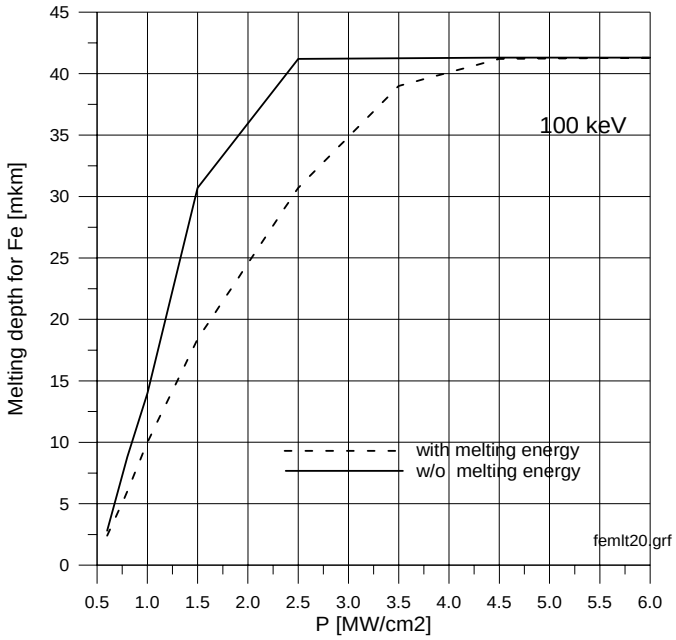

Fig. 5. Fe molten layer vs. power density for 100keV, 20μs pulse.

As may be seen from Fig.5, an increase in the beam density above 4 MW/cm^2, with the energy level (100 keV) retained, does not result in further increase in the molten layer depth of the target materials and, hence, in the buildup of the thickness of the hardened surface layer thickness. The dashed curve in this figure allows to state, that taking into account the melting latent heat does not change the qualitative picture of the process, but results in a reduction of the calculated molten layer thickness.

Similar calculations were carried out with consideration for the energetics of the material melting process for higher energies of incident electrons up to 400 keV. The calculation results

presented in Fig.6 [1] show with a sufficient degree of confidence that the modified layer with an acceptable, regarding practical implementation of hardened surfaces, thickness (100-150 μm) can be produced by beams with an energy of about 300-400 keV.

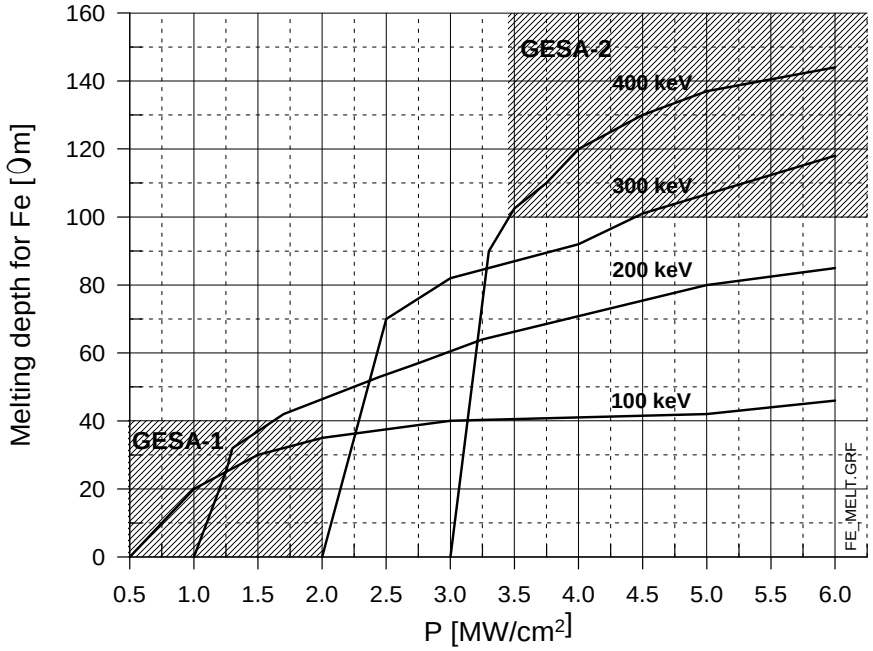

Fig. 6. Fe melting depth vs. heat load density
at different e-beam energies and 20μs pulse duration

Summary

Pulse duration in the present work is corresponded to adiabatic condition of material heating only. The calculations have revealed that an increase in the accelerating beam voltage is the only effective method for attainment of the required thickness of the thermally hardened surface layer of treated material. This conclusion has been confirmed by not presented here additional calculations and analysis for a wide range of metals characterized by various thermophysical properties, e.g. copper, titanium, nickel, chromium, aluminum, etc.

As the subsequent analysis of the calculation results has shown, the main reason for this phenomenon is an intensive evaporation of the sample material and, hence, an entrainment of material and energy from the treated surface and the shielding effect of the evaporated cloud absorbing the beam energy and moderating the fraction of energy absorbed by the condensed phase. Further increase of the energy flux density, with the accelerating voltage remaining unchanged, results in the so-called automodel regime at when the boundary of the evaporating material front on the sample surface and the melting front boundary within the material thickness move with the same velocity without increasing the resulting depth of the molten layer. This conclusion is confirmed by the results of calculation of the simplified model problem (not taking into consideration the temperature dependence of the material properties, energy exchange of the evaporated material cloud with the condensed phase surface, surface heat load) given in [5]. This fact was verified experimentally by the results of heat treatment of metal surfaces on the GESA I (100 keV) and GESA II (400 keV) electron-beam facilities.

This study also shows that taking into account the energetics of the material melting processes has a marked effect on the calculation results: for the parameters of the considered problem the energy absorption for melting phase transition can decrease the molten layer by 50%. Therefore, in most cases to obtain correct results it is necessary to take into account latent melting heat of material.

Nomenclature

$c_p(T)$ - temperature-dependent heat capacity, J/kgK;

$\rho(T)$ - temperature-dependent density, kg/m^3;

$\lambda(T)$ - temperature-dependent thermal conductivity, W/mK;

$T(x, \tau)$ - node current temperature, ^{o}C;

$q_v(x, \tau)$ - volumetric heat flux due to penetrated load, W/m^3;

q_{rad} - heat flux by radiation from the loaded surface to the vapour cloud or to environment before evaporation takes place, W/m^2;

x_{ev} - moving coordinate of the Fe sample surface, m;

x_{sample} -total thickness of the Fe sample;

σ - Stefan – Boltzmann constant ($5.67 \cdot 10^{-8}$ W/m^{2}K^4);

L_{ev} - evaporation heat, J/kg;

μ - molecular mass, kg/kmole;

R - universal gas constant, J/(kmole·K);

T_{ev} -surface temperature, C;

W_S -acoustic velocity in condensed phase, m/s;

ε_{surf} ,ε_o, ε_{cld} - loaded surface, environment and vapor cloud emissivities correspondingly.