Optimization of carbon steel electron-beam hardening

P Petrov

Emil Djakov Institute of Electronics,
Bulgarian Academy of Sciences, 72 Tzarigradsko Chaussee, 1784 Sofia, Bulgaria
E-mail: pitiv@ie.bas.bg

Abstract. A summary is presented of the investigations on the key conditions ensuring electron-beam surface hardening of carbon steels. A numerical model is developed and used to calculate the temperature field caused by high frequency electron beam scanning. The numerical calculation results show that the heating and cooling rate depend weakly on the electron-beam power and are strongly influenced by the sample speed of motion, namely, they increase as this speed is increased. The efficiency of the process of electron-beam hardening of metals increases with the speed of motion of the samples treated.

1. Introduction
The use of high-energy fluxes (HEF), such as electron and laser beams, for surface treatment of metals and alloys is a promising trend with growing application in the industrial production. This treatment ensures enhancement of the physical and mechanical properties and the quality of components made of steels, cast-iron, aluminum, aluminum alloys, copper and titanium alloys, etc. Surface treatment of materials through electron beam and laser energy fluxes is characterized by a number of specific advantages over the conventional methods, such as very small size of the zones treated, precise adjustment and high density of the input energy, high heating rates, good reproducibility and a possibility for a higher degree of process automation. The action of an HEF on a metallic surface induces heat propagation from the surface to the depth of the metallic target during which the rate of heating and cooling may reach up to $10^{10}$ K/s, and, in some cases, even greater [1-5]. In the case of swept-line electron-beam hardening, the cooling and heating rate are in the range $10^3 \div 10^4$ K/s [3] and reach $10^9 \div 10^{10}$ K/s in the case of pulsed electron-beam techniques [4]. In general, the possibility for hardening is determined by the chemical composition of the material. It must be emphasized that the study of the thermal processes (heating and cooling), taking place during treatment of materials by HEF are of considerable theoretical and practical importance with the results finding applications in the optimal control of technological processes.

The aim of this study was to develop a model describing adequately the thermal processes during steel hardening by high-frequency electron-beam scanning (the swept-line electron-beam hardening technique) and identify the important conditions affecting the process.

2. The process of electron-beam surface hardening
The experiment on applying the swept-line electron-beam hardening technique is shown schematically in figure 1. An electron beam focused onto the surface of the sample under treatment is deflected perpendicularly to the direction of its motion. The experiments were performed on
Leybold Hereaus EWS300-15/60 equipment with electron beam power of \( Q = 0.5-3 \) kW, scanning frequency \( f = 1-10 \) kHz, width of the zone treated \( L = 14 \) mm, and speed of sample motion \( V \) of 0.5 to 5 cm/s.

The steel used in this study for experiments and for theoretical calculations was a steel with nominal composition (wt.%): 0.42 %C, 0.96% Cr, 0.6% Mn, 0.37% Si, balance Fe. The samples were machined to the dimensions 60 x 40 x 10 mm and were conditioned as follows: oil hardening at 840-850 °C and subsequent tempering at 560-580 °C.

3. Heat model

The processes of heat propagation during electron beam hardening are studied by using the heat conduction equation:

\[
C(T)\rho(T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left[\lambda(T)\frac{\partial T}{\partial x}\right] + \frac{\partial}{\partial y}\left[\lambda(T)\frac{\partial T}{\partial y}\right] + \frac{\partial}{\partial z}\left[\lambda(T)\frac{\partial T}{\partial z}\right] + Q, \quad (1)
\]

under initial conditions \((t = 0)\)

\[T(x, y, z, 0) = T_0, \quad (2a)\]

or

\[T(x, y, z, 0) = T(x, y, z), \quad (2b)\]

and boundary conditions

\[T(x, y, z)|_{z_i} = T = \text{const}, \quad (3a)\]

\[T(x, y, z)|_{z_e} = T(t), \quad (3b)\]

\[
\lambda\frac{\partial T}{\partial n} + \alpha(T - T_s) = 0 \bigg|_{n_i}, \quad (3c)
\]
in the case of an impenetrable boundary \( \alpha = 0 \), the following condition is obtained

\[
\lambda\frac{\partial T}{\partial n} = 0, \quad (3d)
\]

where \( \rho(T) \) is the density [kg/m³], \( C(T) \) is the specific heat [J/kg K], \( \lambda(T) \) is the thermal conductivity coefficient [W/mm K], \( k = \lambda/c\rho \) is the thermal diffusivity [mm²/s], \( \alpha \) is the heat transfer coefficient [W/mm² K], \( T(x, y, z, t) \) is the temperature [°C], with \( T_0 \) being the initial temperature and \( T_{se} \) the surrounding medium temperature, \( S_1, S_2, S_3 \) are the boundary surfaces, \( n \) is the normal to the surface, \( Q \) is the energy generated per unit volume [W/mm³], \( t \) is the time [s].

Equation (1) does not take into account the processes of convective heat transfer within the molten pool. Conditions (2) and (3) allow one to account for the initial temperature field non-uniformity in the different zones of the hardened zone, and for the heat exchange conditions at the boundaries. Using \( Q \) one can model the heat absorption or release during phase transformations. Thus, the set of equations (1-3) describes the main processes of heat propagation during electron-beam hardening.
In [6,7], an algorithm is presented for solving set (1-3) by applying the finite elements method. The main points in solving the equations in the case of a two-dimensional problem are adopted in accordance with [6] and have to do with finding the minimum of the functional:

$$\chi = \int_V \left[ \frac{1}{2} \lambda(T) \left( \frac{\partial T}{\partial x} \right)^2 + \frac{1}{2} \lambda(T) \left( \frac{\partial T}{\partial y} \right)^2 + \left( 2C(T) \rho(T) \frac{\partial T}{\partial t} - 2Q \right) T \right] dV$$

$$+ \int_S \left[ \frac{1}{2} \alpha(T - T_\infty)^2 \right] dS.$$  (4)

The minimization of functional (4) is carried out with respect to the elements of discretization of the zone considered (triangles with straight sides and three nodes, $i, j, k$). After presenting (4) in a matrix form, minimizing its values at the elements nodes, integrating and substituting the time derivatives by finite differences, the problem is reduced to solving the matrix equation:

$$\begin{bmatrix} C \end{bmatrix} + \partial \Delta t \begin{bmatrix} K \end{bmatrix} \begin{bmatrix} T \end{bmatrix} = \begin{bmatrix} C \end{bmatrix} - (1 - \theta) \Delta t \begin{bmatrix} K \end{bmatrix} \begin{bmatrix} T \end{bmatrix}_{t-\Delta t} + \Delta t \begin{bmatrix} F \end{bmatrix},$$  (5)

where $\{T\}$, $\{T\}_{t-\Delta t}$ are the values of the temperature in the nodes at the current $t$ and previous $t - \Delta t$ moments of time, $\theta$ is a coefficient characterizing the different solution methods ($\theta = 0$, Euler-Cauchy; $\theta = 1/2$, Crank-Nicholson; $\theta = 2/3$, Galerkin; $\theta = 1$, reverse differentiation).

To solve (5) we used the Gauss method – Zenkeevich algorithm [6]. The temperature is calculated at the center of gravity of the elements; the rates of cooling and the momentary structural state of the metal on the seam and in the near-seam zone are determined. The algorithm used to construct the computing process [5,6] is as follows:

1. The cross-section considered is discretized into a finite number of triangular elements. The main principle followed is grid densification in the zones with large temperature gradients.
2. The nodes lying on the boundary are determined for the cases when a boundary condition with heat exchange with the surrounding medium is adopted.
3. The time step $\Delta t$ is determined depending on the current time increase. A step-wise increase ($\Delta t$, $2\Delta t$, $5\Delta t$, $10\Delta t$) increase of the time-step is envisaged that is inversely proportional to the temperature gradient.
4. A scheme is adopted for introducing the heat source, and for the heat distribution on the elements nodes.
5. The matrices of the elements are constructed and introduced in global matrices.
6. The equation set (8) is solved following the Gauss method – Zenkeevich algorithm [6].
7. The temperature and the rates of cooling are calculated at the center of gravity of the elements. The momentary structural state is determined.
8. The temperature and the structural fields are constructed.

The finite-differences scheme used to solve the problem in the time space is built on the basis of the central differences scheme of Crank-Nicholson. This scheme is unconditionally stable, but deviations can still arise of the numerical values from the real values sought [6]. The magnitude of the solution oscillation depends mainly on the material’s properties, the elements size and the time-step size. The material’s properties are usually known and are set specifically for each separate case. The variables, then, that can be varied in order to eliminate the numerical results oscillations are the size of the elements and of the time step. Their simultaneous reduction would reduce the numerical solution oscillation. It is erroneous to change one of the variables while keeping the other constant. For example, in the case of a rough grid and a small time step, one can obtain results that have no physical sense for the particular case considered.

The electron-beam energy is introduced in the elements nodes of an arbitrary element and is defined as:
\[ Q_{\text{net}} = \eta \frac{Q_{\text{source}}}{V t_s} rac{dL}{A}, \quad t_s = \frac{d}{V}, \]

where \( Q_{\text{source}} = UI \) is the energy of the source; \( U \) is the accelerating voltage [kV]; \( I \) is the electron-beam current [mA]; \( \eta \) is the process efficiency; \( d \) is the electron-beam diameter [mm]; \( L \) is the width of the zone treated; \( V \) is the sample's speed of motion [mm/s]; \( t_s \) is the time of action of the source [s]; and \( A \) is unit area [mm²].

The time \( t \) of the heat source action is calculated as the ratio of the electron beam diameter \( d \) in the treated plane to the sample’s speed of motion \( V \).

4. Results and discussion

The microhardness distribution measured within the depth of the layer is shown on figure 2. It is seen that the hardness reaches values of 550-650 HV₀₁ to a depth of 400 µm. As the depth is increased, the hardness decreases rapidly down to the matrix hardness ~300HV₀₁. The total depth of the hardened layer reaches 550 µm. Figure 3 shows the maximum temperature (defined on the basis of the thermal cycles calculated within the depth of the hardened zone) as a function of the sample’s speed of motion. It is seen that the maximum temperature decreases with the increase of the sample’s speed of motion. The layers within the depth reach a temperature maximum later than the layers that are closer to the surface, the rates of heating and cooling of surface layers being higher than these in depth. The temperature field is nonstationary and highly inhomogeneous. Very high temperature gradients are observed within the depth of the hardening layer in the processes of both heating and cooling.

![Figure 2. Microhardness distribution along the hardened layer depth.](image1)

![Figure 3. Maximum temperature calculated vs. distance from surface.](image2)

The principal electron beam hardening process variables are the beam power and speed of motion of the sample treated. The heating and cooling rates are investigated as functions of the electron beam power and the sample’s speed of motion. The average rates of heating and cooling within the temperature interval of 800 to 500°C are defined on the basis of the thermal cycles calculated within the depth of the hardened zone (with power of the electron beam of 0.5 to 3 kW, speed of motion of the sample treated \( V = 0.5 \div 5 \text{cm/s} \), width of the zone treated \( L = 14 \text{mm} \) and electron beam diameter \( d = 0.1 \text{mm} \)). The data for the temperature dependence of the thermo-physical parameters of the steel were taken from [8].

Figure 4 and figure 5 show the heating rate calculated depending on the sample’s speed of motion and on the electron-beam power. As one can see in figure 4, the heating rate increases with the speed of motion (for a constant electron-beam power of \( Q = 3 \text{kW} \)). For rates higher than 3 cm/s, the curve is reaching saturation, which means that a further increase of the speed of motion of the sample under treatment influences weakly the rate of heating. Further, the heating rate increases linearly with the electron-beam power (figure 5). This is mainly connected with the very fast processes of electron-beam energy transfer from the surface layers of the sample under treatment.
Figure 4. Calculated heating rate depending on sample’s speed of motion.

Figure 5. Calculated heating rate depending on electron beam power.

Figure 6 and figure 7 show the cooling rate as a function of the sample’s speed of motion and the electron-beam power. The cooling rate depends weakly on the electron beam-power (figure 4), but is strongly influenced by the speed of motion of the sample processed (figure 5). The cooling rate increases with the sample’s speed of motion. This effect may be used for electron-beam treatment, since the hardening effect is mainly determined by the rate of cooling. Therefore, the process of electron beam hardening of metals should be performed at higher speeds of motions of the samples to be hardened. The results of the experimental measurements of the microhardness of the hardened zones and the calculated hardening temperature $T_h$ and rate of cooling $W_{800-500}$ allowed us to construct curves that can be used to determine the optimal conditions of carbon steel samples hardening by swept-line electron-beam hardening. Figure 8 shows the dependence of the experimentally measured microhardness on the temperature of hardening at a cooling rate of $3 \times 10^4$ K/s. An increase of the microhardness is observed up to the temperature $\approx 900$ °C, after which the microhardness practically does not increase. One can observe two characteristic values of the temperature, namely, $T_{hs}$ and $T_{hm}$. The former temperature, $T_{hs}$, at which hardening of the layer treated is observed, is determined by the carbon content (% C) in the initial material. The latter temperature, $T_{hm}$, is the temperature after which no rise is observed in the experimentally measured microhardness of the hardened layer. $T_{hm}$ is higher than the temperature of $A_{C3}$ transformation and decreases from $\approx 1200$ °C (at C = 0.2%) down to $\approx 900$ °C (at C = 0.4%).
Figure 8. Measured hardness vs. calculated heated temperature.

Figure 9. Maximum hardness measured vs. calculated cooling rate.

Figure 9 presents the dependence of the experimentally measured microhardness on the cooling rate in the range between $2 \times 10^4$ K/s and $5 \times 10^4$ K/s. As one can see, the microhardness does not change as the rate of cooling is raised. A change in the microhardness could be expected at considerably higher rates of cooling, up to $10^7 \div 10^9$ K/s, which are typical for the pulsed electron-beam hardening. The dependences $HV = f(T_h)$ and $HV = f(W_{800-500})$, allow one to determine the optimal conditions for hardening of carbon steel samples by swept-line electron-beam hardening.

5. Conclusions
A numerical thermal model is developed in view of studying the processes of heating and cooling during swept-line electron-beam hardening. The numerical calculations demonstrate that the heating and cooling rate increase with the speed of motion (constant electron-beam power) and electron beam power (constant specimen speed of motion). Efficiency of the process of swept-line electron-beam hardening of carbon steels increases with the increase of the sample’s speed of motion.

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