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MATHEMATIC MOULDING OF THE ELECTROMAGNETIC INDUCTION HEATING PROCESS FOR SUPERFICIAL HARDENING

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The right mathematical moulding helps reaching the mechanical features as stipulated in the technical documentation of the bench-mark submitted to superficial hardening. The mathematic calculation considers the thermic variation and the magnetic permeability that alter according to temperature variation. The results of superficial hardening through induction depend on the manner of correlating the technological parameters: frequency, heating temperature, specific power, heating duration, type of installation, hardening method.

1. Introduction

Superficial hardening is a thermic treatment in which heating in the austenitic field is carried out only to a certain depth from the surface, due to which the martensite transformation takes place only in the austenized layer during the cooling. The aim of the superficial hardening is to increase parts' surface resistance to wear and to maintain certain high plasticity properties in their unhardened core.

The superficial hardening method is classified and denominated by the energy source, which can be as follows: electromagnetic induction, oxy-gas flame, electronic beam, laser, and so on. For big industry parts, induction hardening and flame hardening are most widely spread.

2. Mathematic Moulding

In order to heat parts to austenitization temperature, we need a certain amount of heat that is determined through the relation 1. [1]

$$Q = m \cdot c \cdot \Delta T \quad \text{[Kcal]} \qquad (1)$$

where:

c – average of specific heat in the intended temperature interval [Kcal/kg·K], and c = c(T).

The values of the heat quantity in the proposed interval are calculated as follows:

$$Q = m\int_{T1}^{T2} c(T)dT \quad \text{[Kcal]} \qquad (2)$$

$$Q = m\int_{T1}^{T2} c(T)dT = m \cdot C(T) \Big|_{T1}^{T2} = m[\,C(T_2) - C(T_1)]$$

where: C(T) is a primitive of the function c(T);

In order to produce the amount of heat Q, we need to introduce electric energy in the part.

$$Q_z = C\frac{\rho \cdot l}{S} I^2 t \quad \text{[Kcal]} \qquad (3)$$

During the heating of the part, the specific resistivity of the material depends on the temperature through the relation:

$$\rho = \rho\,(T)$$

$$Q_z = CI^2 t \frac{l}{S} \int_{T1}^{T2} \rho(T) dT \qquad \text{[Kcal]} \qquad (4)$$

$$Q_z = CI^2 t \frac{l}{S} \int_{T1}^{T2} \rho(T) dT = C \cdot I^2 \cdot t \frac{l}{S} \rho_1(T) \Big|_{T_1}^{T_2} = C \cdot I^2 \cdot t \frac{l}{S} [\rho_1(T_2) - \rho_1(T_1)]$$

where: ρ_1(T) is a primitive of the function $\rho(T)$;

During the inductive heating, the amperage I is divided on the part section according to a function "e". The Amperage at a distance "x" from the surface of the part is calculated as follows:

$$i_x = i_0 e^{-2\pi \cdot x \sqrt{\frac{\mu \cdot f}{\rho}}} \qquad \text{[A]} \qquad (5)$$

with:

$$\rho = \rho(T); \qquad \mu = \mu(T)$$

The amperage at the part surface (x= 0) is i_o. It is divided on the inductor height according to a function arctg.

$$i_0 = \frac{I}{\mu h \delta} arctg \frac{4\frac{a}{h}}{\left(2\frac{y}{h}\right)^2 - 1 + \left(2\frac{a}{h}\right)^2} \qquad \text{[A]} \qquad (6)$$

In the equation, y has values according to the inequation:

$$0 \le y \le \frac{h}{2}$$

According to the relations (4; 5 and 6), the energy introduced by the inductor in the part through induction may be calculated.

During heating, the inductor is fixed, while the part may complete two main movements: rotation, axial, or combined. In order to calculate it, the movement has to be divided into finite intervals. Each interval is granted a part of energy: [2]

$$Q = \int_0^{D/2} Q(x) dx \qquad (7)$$

By introducing energy in the part, a temperature field is produced, whence a $\frac{dT}{dx}$ temperature gradient will result from the surface towards the interior. It is followed by a process of temperature equalising determined by the material's thermic conductibility. This heat equalising process is dependent on the temperature, as λ = λ(T).

Not all the energy introduced in the part will contribute to increasing the temperature. It will be partly lost in the environment through radiation and convection.

$$Q = Q_u + Q_{pr} + Q_{pc} \qquad \text{[Kcal]} \qquad (8)$$

The heat quantity emitted through radiation and convection is dependent on the coefficient of heat transmission, α, for convection and the emission factor, ε, of the radiation. The coefficients α and ε may depend on temperature, too (figure 2), while ε may also depend on the roughness of the surface submitted to thermic treatment.

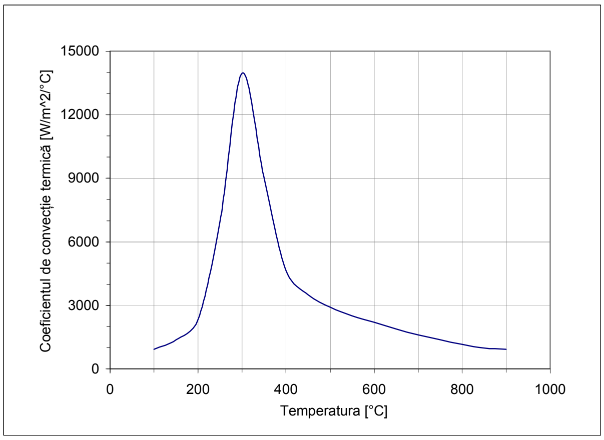

Fig.1. Variation of the convection coefficient with temperature

The part of energy introduced in the induction stage at the moment considered should be calculated by taking into account the conduction, radiation and convection at the respective temperature that will be quantified so that, after adding an energy measure, the equalising processes developing in parallel may be calculated. However, from a mathematic point of view, heating and equalising cannot be conceived at the same time. After introducing the energy and the duration of equalisation, the result is that, through a gradual induction process, the added energy contributes to increasing the temperature of a part. During the induction process, the total energy introduced in the part results from the sum of all energies added at each induction step.

In the relation Q = Q(x) we can determine the temperature of the point belonging to a heat amount Q_x.

From the previous relation, we can determine the heat needed to heat the beginning of the part and to establish the electric power effectively transmitted to the part through the inductor.

$$Ppiesa = 4{,}18\frac{Qpiesa}{t_{inc}}\ [\text{KW}] \qquad (9)$$

The result is that the value of the power needed to harden through induction may be influenced by choosing the heating duration.

The specific power transmitted to the part is calculated through the following relation:

$$Psp = \frac{Ppiesa}{Si}[\text{KW/cm}^2] \qquad (10)$$

where: P_{piesa} – electric power effectively transmitted to the part through the inductors, in KW;

S_i – surface of the part covered by inductors, in cm^2.

Formula number 10 shows that the specific power transmitted to the part determines the hardening penetration, as well as the heating time, provided the hardening temperature is given. Each basic operation of the thermic treatment is characterised by certain technological parameters, variable measures respectively that determine the result of the thermic treatment. Establishing the optimal values for the technological parameters is one of the main issues in drawing up the thermic treatment technological process.

The $\eta_{ind.}$ inductor transfer efficiency depends on the shape of the inductor, but it particularly depends on the free distance between the part and inductor outline.

The symbols used in mathematical moulding are as follows: [2]

S – heated surface;	l – length
a – air gap;	m – mass
b – distance where water splashes (impact of the part surface with the water jet);	Q – heat amount
C – constant	T - temperature
c – specific heat	x- distance from surface
D – part diameter	α_c – convection coefficient
e – basis of the natural logarithm	δ – current depth
f – frequency	ε – emission factor
h – inductor height	λ – thermic conductibility coefficient
I – amperage	μ - permeability
i_o – surface amperage (x_0)	ρ – specific resistivity
I_x – distance x amperage	t – time

The research carried out regarding the physical properties of ferrous alloys revealed the fact that thermic capacity, linear dilatation coefficient, thermic conductivity, magnetic permeability alter depending on temperature variation.

Conclusions

1. From a mathematical point of view, heating and equalising cannot be understood at the same time in the case of austenitization; however, these phenomena may be observed in the analysis through the method of the finite element.
2. The correct mathematical moulding of the heating process for hardening determines the correct assessment of the specific power sent to the part and implicitly the inductor transfer efficiency $\eta_{ind.}$
3. The results of the superficial hardening through induction depend on the manner of correlating the following technological parameters: frequency, heating temperature, specific power, the duration of heating, type of installation, hardening method.

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