OPTIMIZATION OF INDUCTION HARDFACING OF THIN DISCS, ALLOWING FOR THERMAL AND ELECTROMAGNETIC SHIELDING

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A mathematical model has been developed to determine the temperature field in the process of disc hardfacing using a two-turn ring inductor with allowance for thermal and electromagnetic shielding. This model enables optimizing the mentioned temperature in the zone of disc hardfacing depending on the parameters of the inductor, disc, electromagnetic and thermal shields, as well as electric current.

Keywords: *induction hardfacing, thin discs, two-turn ring inductor, optimizing the inductor parameters, temperature field, thermal and electromagnetic shielding, investigations, calculations*

In work [1] studies have been performed to optimize the design parameters of a two-turn ring inductor for hardfacing thin round and shaped discs of an arbitrary diameter and width of hardfacing zone, taking into account shielding of just the electromagnetic field, in order to obtain a specified power distribution over the hardfacing zone width. Dimensions of the two-turn ring inductor are selected, depending on disc diameter and hardfacing zone width, as well as allowing for the values of the coefficients of electromagnetic field shielding ($K_{sh} = 1$; $K_{sh} = 0.25$, $K_{sh} = 0$ — full shielding) [1].

It is of interest to study the temperature field in the hardfacing zone with development of a mathematical model to determine the temperature in the disc through the parameters of a two-turn ring inductor, which is used to perform heating, allowing for electromagnetic and thermal shielding simultaneously [2], which significantly affect the temperature distribution in the hardfacing zone. The developed model will allow designing the heating system (inductor, thermal and electromagnetic shields, part) for hardfacing thin round and shaped discs.

Let a round disc (Figure 1) of $2h$ thickness and r_2 radius be heated, using a two-turn ring inductor.

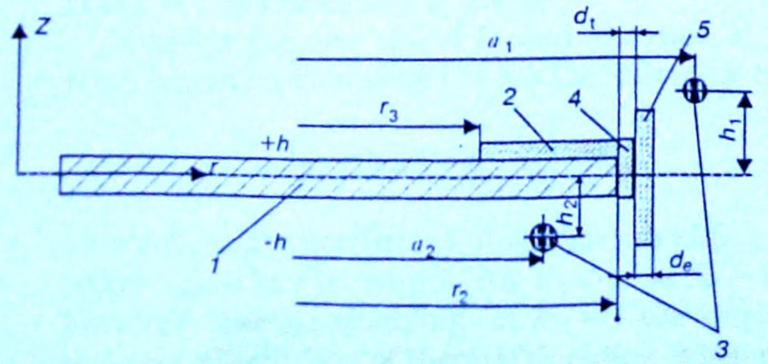

Figure 1. Cross-section of the heating system: *1* — part; *2* — charge; *3* — two-turn ring inductor; *4*, *5* — thermal and electromagnetic shields, respectively

In this case the specific power of the heat sources, which emerge in the disc area under the impact of an electromagnetic field, has the form of [1]

$$w = \frac{\sigma\omega^2\mu_0^2}{128\pi^2 h} \times$$
$$\times [\Delta I_1^2 A^2 a_1^2 + \Delta I_2^2 a_2^2 B^2 + 4ha_1^2 I_1^2 C^2 e^{-2(r_2 - r)/\Delta}], \quad (1)$$

where A^2, B^2, C^2 are the functions of radius r [3], geometrical dimensions of the inductor and disc h_1, h_2, $2h$, a_1, a_2, r_2 (Figure 2), as well as physical parameters of the electromagnetic field; $\Delta = \sqrt{2/(\omega\mu\sigma)}$ is the depth of penetration of the electromagnetic field into disc material (ω is the circular frequency of the electromagnetic field; μ is the magnetic permeability; σ is the electric conductivity); $\mu_0 = 4\pi \cdot 10^{-7}$ H/m.

Temperature field in the disc satisfies the equation of heat conductivity [4]:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} - m^2 T - \frac{1}{a}\frac{\partial T}{\partial t} = -\frac{w}{\lambda}, \quad m^2 = \frac{\alpha}{\lambda h}, \quad (2)$$

where λ is the coefficient of heat conductivity of disc material; α is the coefficient of heat transfer to the

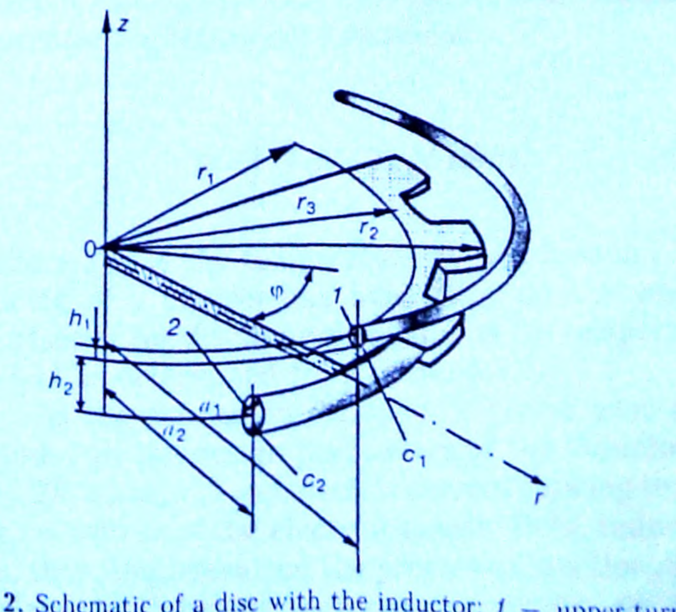

Figure 2. Schematic of a disc with the inductor: *1* — upper turn of the inductor; *2* — lower turn

environment in the absence of a shield; $T = T_1 - T_{en}$ (T_1, T_{en} are the temperature of the disc and environment, respectively); boundary conditions are as follows:

$$\frac{\partial T}{\partial r} = 0 \quad \text{at } r = 0; \tag{3}$$

$$\lambda \frac{\partial T}{\partial r} + \alpha T = 0 \quad \text{at } r = r_2. \tag{4}$$

Analysis of calculations, given in [1], shows that electromagnetic shielding of the specific power of heat sources at disc edge significantly influences the uniformity of its distribution along the radius, particularly over the width of the hardfacing zone ($r_2 - r_3$ = = 10–50 mm). If thermal shielding is also implemented at disc edge (see Figure 1), the heat flow through the edge will be significantly reduced or stopped completely, which will strongly influence the level of temperature distribution in the hardfacing zone, and the heat losses through the edge will also be reduced.

In the case of electromagnetic shielding of disc edge formula (1) may be expressed as follows:

$$w = \frac{\sigma\omega^2\mu_0^2}{128\pi^2 h} \times \left[\Delta I_1^2 A^2 a_1^2 + \Delta I_2^2 a_2^2 B^2 + K_{sh} 4 h a_1^2 I_1^2 C^2 e^{(-2(r_2 - r))/\Delta}\right], \tag{5}$$

where K_{sh}, the coefficient of electromagnetic shielding for a shield, located close to the disc [5], has the following form:

$$K_{sh} = \exp\left(-2\frac{d_{sh}}{\Delta_{sh}}\right), \tag{6}$$

where d_{sh} is the shield thickness; Δ_{sh} = $\sqrt{2/(\omega\mu_{sh}\sigma_{sh})}$ is the depth of electromagnetic field penetration into the shield; σ_{sh} is the electric conductivity of the shield material.

Assuming shield thickness $d_{sh} = \Delta_{sh}$, the power of heat sources on disc edge will decrease e^2 times, if $d_{sh} = 2\Delta_{sh}$, it will decrease e^4 times, at $d_{sh} = 4\Delta_{sh}$ it will decrease e^8 times (i.e. it will be practically zero). At $K_{sh} = 0$ we achieve full electromagnetic shielding, at $K_{sh} = 1$ the shielding is absent.

When a thermal shield is also installed at disc edge, boundary condition (4) has the following form:

$$\lambda \frac{dT}{dr} + K_t \alpha T = 0 \quad \text{at } r = r_2, \tag{7}$$

where K_t is the coefficient of thermal shielding [6], which varies in the range of $0 \le K_t \le 1$. At $K_t = 0$ we have full thermal shielding, at $K_t = 1$ the shielding is absent. Coefficient of thermal shielding, when using a shield of thickness d_t, will be found from the following relationship [6]:

$$K_t \alpha = \frac{\lambda}{d_t}; \quad K_t = \frac{\lambda}{d_t \alpha}, \tag{8}$$

where λ/d_t is the coefficient of heat conductivity of the shield.

If $\lambda/d_t = \alpha$, then $K_t = 1$, i.e. shielding is absent, an intensive convective heat exchange with the environment is in place and boundary condition (7) has the form of equation (4).

Let us assume that at the initial moment of time the disc temperature is equal to that of the environment. Then, initial condition for equation (2) will be expressed in the following form:

$$T = 0 \quad \text{at } t = 0. \tag{9}$$

Solution of equation (2) at boundary condition (7) and initial condition (9) in the case, when the specific power is determined from formula (5), has the following form:

$$T = \frac{a}{\lambda_y} \sum_{\nu=1}^{\infty} \left(e^{-a\lambda_\nu^2 t} \int_0^t \frac{\int_0^{r_2} w(r, t) J_0(l_\nu, r) r dr}{\int_0^{r_2} J_0^2(l_\nu, r) r dr} e^{a\lambda_\nu^2 t} dt \right) J_0(l_\nu, r), \tag{10}$$

where $l_\nu^2 = \lambda_\nu^2 - m^2$; $\lambda_\nu = \sqrt{l_\nu^2 + m^2}$; $J_0(l_\nu, r)$ is the Bessel function of the first kind of zeroth order of the real argument; a is the thermal diffusivity; l_ν are the roots of the characteristic equation

$$\lambda l_\nu J_1(l_\nu, r_2) + \alpha K_t J_0(l_\nu, r_2) = 0. \tag{11}$$

Thus, a mathematical model is obtained of determination of temperature in the disc through the source of its induction heating, using electromagnetic and thermal shielding of disc edge. This allows determination and optimizing the above temperature in the zone of disc hardfacing, depending on the parameters of the inductor, disc, electromagnetic and thermal shields, as well as electric current.

To optimize the parameters of the inductor and electric current, flowing through it, it is necessary to optimize the following functional:

$$\Phi = \int_0^{\tau} \int_{r_3}^{r_2} (T - T_{h.d})^2 \, r dr dt, \tag{12}$$

where $T_{h.d}$ is the temperature at which sound hardfacing of a powder-like hard alloy on the working surface of the disc is performed; T is the temperature, which is determined from formula (10).

As the expression for specific power $w(r, t)$ includes all the design parameters of the inductor (h_1, h_2, $2h$, a_1, a_2, r_2) and electric current flowing through it, as well as of the electromagnetic field, induced by it, then, implementing the process of functional minimizing (12) by the required parameters, we obtain the optimum variant of the design of the inductor and electric current source to provide the technological process of induction heating simultaneously over the

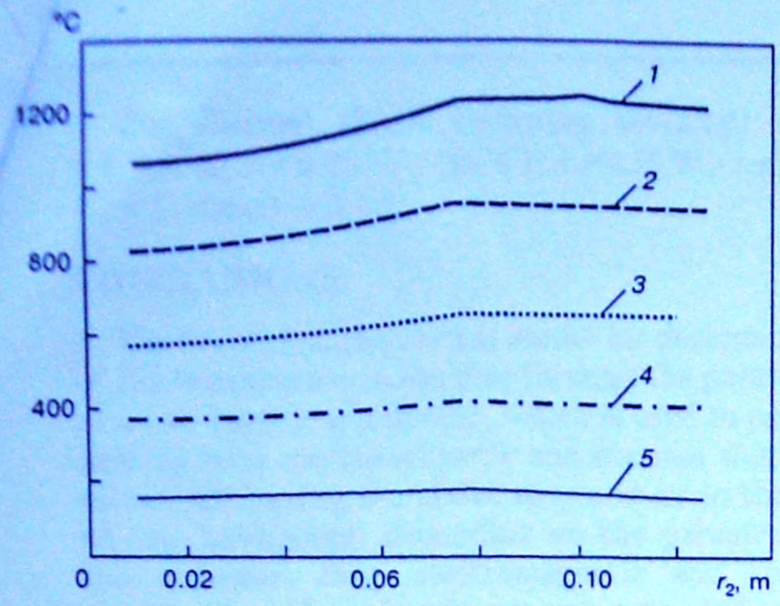

Figure 3. Temperature distributions around disc radius: r_2 = = 0.125 m for different moments in time: *1* — 22; *2* — 19; *3* — 15; *4* — 11; *5* — 5 s

Results of temperature calculation (°C) in different moments of time, depending on disc radius

r_2, m	τ				
	5	*11*	*15*	*19*	*22*
0.010	129.82	347.82	543.63	792.95	1023.71
0.020	131.79	352.20	550.40	802.74	1036.20
0.030	133.33	357.25	558.69	815.69	1052.42
0.040	137.38	367.11	573.66	836.58	1079.77
0.050	140.55	376.76	589.08	859.19	1108.96
0.060	145.98	390.55	610.06	889.09	1146.96
0.070	150.74	402.31	627.75	914.10	1178.64
0.075	155.25	412.48	624.39	934.13	1199.76
0.080	154.59	410.35	639.98	931.55	1202.21
0.090	154.01	411.21	641.67	934.36	1204.68
0.095	152.86	411.99	641.96	935.54	1205.64
0.100	154.90	413.08	644.25	937.72	1205.64
0.105	154.57	412.16	642.79	935.57	1205.93
0.110	154.62	411.99	641.96	934.56	1201.72
0.120	156.55	413.50	642.76	933.56	1201.99
0.124	157.89	414.78	643.65	933.87	1201.74
0.125	157.67	414.10	642.54	932.22	1199.59

entire working surface of a thin round and shaped disc.

As an example of calculation of the inductor, allowing for the design features and optimization capabilities, let us assign the geometrical dimensions of the heating system: radius of the inductor external turn a_1 = 0.131 m (see Figures 1 and 2), criterion B_i = 0.27 for a thermal insulation material on the external contour of the disc of asbestos sheeting of thickness d_t = 0.004 m, radius r_3 = 0.075 m (see Figure 1), hardfacing time τ = 22 s, λ = 0.35 W/(m·°C).

Experimental data confirms that hardfacing temperature T_1 = 1220 °C. Then, at T_{en} = 20 °C we have $T_{h.d}$ = 1200 °C. If the electromagnetic shield is made of copper, at circular frequency ω = 2π·440 kHz the depth of the electromagnetic field penetration into the shield is Δ_e = 0.1 mm.

Let us assume a_2, h_2, h_1, A, K_e to be the optimization parameters. Performing the procedure of functional minimizing by these parameters, we obtain their values: a_2 = 0.0945 m; A = 165.20; K_e = 0.655; h_2 = = 0.0315 m; a_1 = 0.131 m; h_1 = 0.01 m; r_3 = 0.075 m.

Results of temperature calculations in the disc area at these values in different moments of time are given in the Table, and their graphic representation — in Figure 3. It can be seen from the Figure that the temperature is almost the same across the width of the hardfacing zone (in this case $S = r_2 - r_3$ = 0.125 − 0.075 = 0.05 m), deviation from the specified temperature being 0.5 %, and it is equal to 1200 °C over time τ = 22 s (which is highly important at induction hardfacing). As the hard alloy (for instance, PG-S1) melts from the surface of the base metal, the thickness of the deposited metal is uniform over the entire working surface.

It follows from the conducted analysis that the final (at τ = 22 s) temperature in the hardfacing zone in this case deviates from the required one by not more than 0.5%. For implementation of the found optimum coefficient of electromagnetic shielding K_e = = 0.655 it is sufficient, according to formula (6), to use a copper plate of thickness d_e = 0.021 mm, i.e. spraying of copper powder onto the thermal shield or pasting of copper foil of the same thickness on it can be performed in practice.

The following data are assumed in calculations:

- for disc: $2h$ = 3 mm; c = 846 J/(kg·°C); λ = = 40 W/(m·°C); γ = 5969.2 kg/m^3; $\sigma = 1.25\cdot10^{-6}$ 1/(Ohm·m); r_2 = 0.125 m; α = 455 W/(m^2·°C); r_3 = = 0.075 m; τ = 22 s; $T_{h.d}$ = 1200 °C. Base metal is steel St3, deposited layer is of alloy PG-S1, thickness of deposited metal is 0.8–1.5 mm;
- for inductor (copper): $\mu = 2.75\mu_0$; ε_0 = = $8.854\cdot10^{-12}$ F/m; $\mu_0 = 4\pi\cdot10^{-7}$ H/m; ω = = $2.763\cdot10^{-6}$ Hz; c_1 = 5.0 mm; c_2 = 8.0 mm; ρ = = $0.17\cdot10^{-7}$ Ohm·m;
- for electromagnetic shield (copper):

$$\sigma_e = \frac{1}{\rho} = \frac{1}{0.17\cdot10^{-7}} = 58.8\cdot10^6 \text{ 1/(Ohm·m)};\quad \mu_e = \mu\mu_0 = 1\cdot4\pi\cdot10^{-7} = 12.56\cdot10^{-7} \text{ H/m};\ K_e = 0.655.$$

For thermal shield (asbestos sheeting): $d_t = 0.004$ m; $\lambda = 0.35$ W/(m·°C); $\alpha = 455$ W/(m²·°C); $K_t = \lambda/(d_t\alpha) = 0.192$.

CONCLUSIONS

1. The derived mathematical model for determination of the temperature in the disc through the parameters of a two-turn ring inductor, which is used to perform heating with electromagnetic and thermal shielding, allows optimizing the above temperature in the zone of disc hardfacing, depending on the parameters of the inductor, disc, electromagnetic and thermal shields, as well as electric current in the inductor.

2. Developed algorithm also allows designing the heating system (inductor, thermal and electromagnetic shields, part), which provides the required conditions for performance of the technological process of hardfacing.

3. The developed heating system ensures the required temperature in the hardfacing zone with the accuracy of up to 0.5 %.

4. A procedure has been developed for finding the coefficients of the electromagnetic and thermal shields, which are used for temperature regulation across the width of the hardfacing zone with a complex geometrical shape of the surface.

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