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MEASUREMENT OF THE THICKNESS OF THE SPRAYED NICKEL COATINGS ON LARGE-SIZED CAST IRON PRODUCTS

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Modern industries increasingly use automatic spraying of heat-resistant Nickel coating with a thickness of T = 1-3 mm for large-size parts made of cast iron with nodular graphite. The process of coating application is characterized by time-dependent behavior of its relative magnetic permeability, μ_c, that is a function of relaxation time, which can be as long as 24 hours, and by μ_c deviation from point to point on the surface.

Aspects of eddy-current phase method for measuring the T value are considered. The structure of four-winding eddy current transformer transducers is described and results of calculation and optimization of their parameters are presented. The influence of controlled and interfering parameters is considered. Based on the above results, a two-channel combined transducer is developed providing measurement error of $\Delta T \leq \pm(0.03T + 0.02)$ mm in the shop environment in the process of coating application and in the final product check. Results of tests on reference specimens and of application in production processes are presented.

Key words: eddy current phase method, coating thickness, measuring transducer.

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Spray-applied Nickel coatings provide high heat resistance of large-size products made of nodular cast iron. Most of modern processes used to manufacture the equipment in question include application of coating with a thickness, T, of up to 3 mm to ensure required level of heat resistance.

Applying thick-layer Nickel coating and ensuring specified value of T is a complex task and a quite expensive process.

The method of spraying the coating material is the best suited for this task. However, in the process of coating application heating of the product surface higher than 100-120°C is not allowed otherwise the process of graphite phase recrystallization can be initiated in the cast iron, critical stress fields can be created in it and, hence, its strength properties can be reduced. Therefore the method of electric arc spraying is used, which does not heat the product surface higher than 100°C in contrast to gas-flame methods of coating.

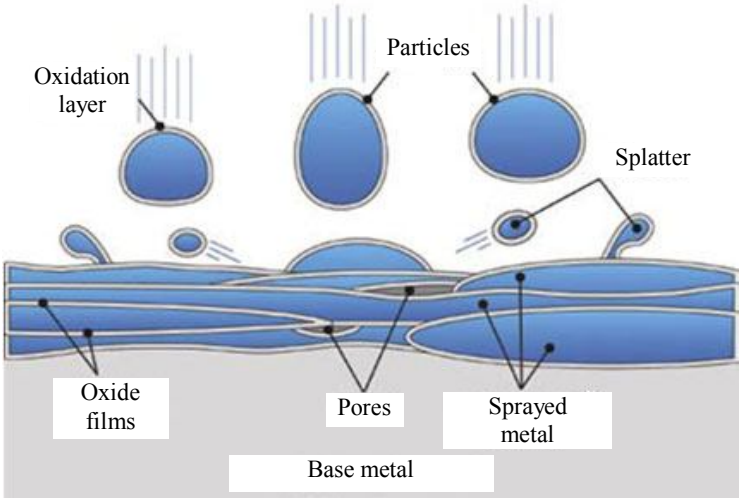


Fig.1. The process of metal sprayed coating build-up and structure of this coating on the product surface

In the process of electric arc spraying molten metal is entrapped by the jet of compressed air flowing out of the spraying gun nozzle and with very high velocity transferred to the product surface in the form of small sprayed particles.

The process of metal sprayed coating build-up and structure of this coating on the product surface are shown in fig.1.

Coating must be applied immediately after removal of preservation lubricant, sand-blasting and cleaning of the surface by blowing, because the activated metal surface becomes covered with oxide film in a very short time.

The coating is applied by special robotic stations. Lets us consider one of typical tasks of Nickel coating application on inner surface of large-size cylinder parts with diameters up to 1500 mm and lengths up to 7000 mm. A special robotic station based on lathe and five-axis robot welding machine is shown in fig.2.

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The product is fixed in the lather chuck. Rotation speed of the product is 3-7 rpm. Control unit of the metal sprayer fixed on the rod is used to control current, air pressure and wire feeding.

Full time of coating application is 24-36 hours depending on required value of T.

The coating is applied by sections (belts) with a length of about 1 m along the product centerline while the product is rotated and the rod with robotic station is moved back and forth. Interruptions longer than 10 minutes are not allowed in the process of coating application to ensure adhesion of layers and to prevent from their cracking. This allowed interruption interval in the coating application process can be used to measure T value with the possibility to apply additional layers without disturbance of coating properties, if necessary. In addition, measurement of final coating thickness is required over the entire surface with specified interval between points of measurement.

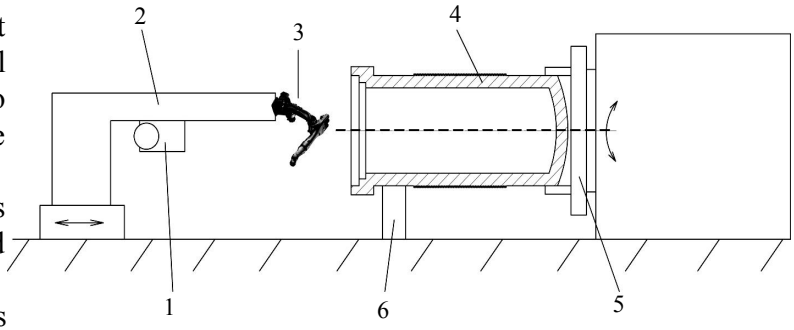


Fig.2. Structure of the special robotic station for applying Nickel coating on inner surface of cylinder products

1 – metal sprayer; 2 – rod; 3 – 5-axis robot welding machine; 4 – product; 5 – spindle with chuck; 6 – steadyrest sprayer

In the measurement task described herein Nickel coating with a thickness of 1-3 mm is a magnetic electrically conductive coating. The substrate is a magnetic electrically conductive material as well. The use of eddy-current phase method [1] is optimum to measure value of T.

Fig.3 shows block diagram of three-winding eddy-current phase transformer transducer that uses voltage of the compensation winding as a reference signal.

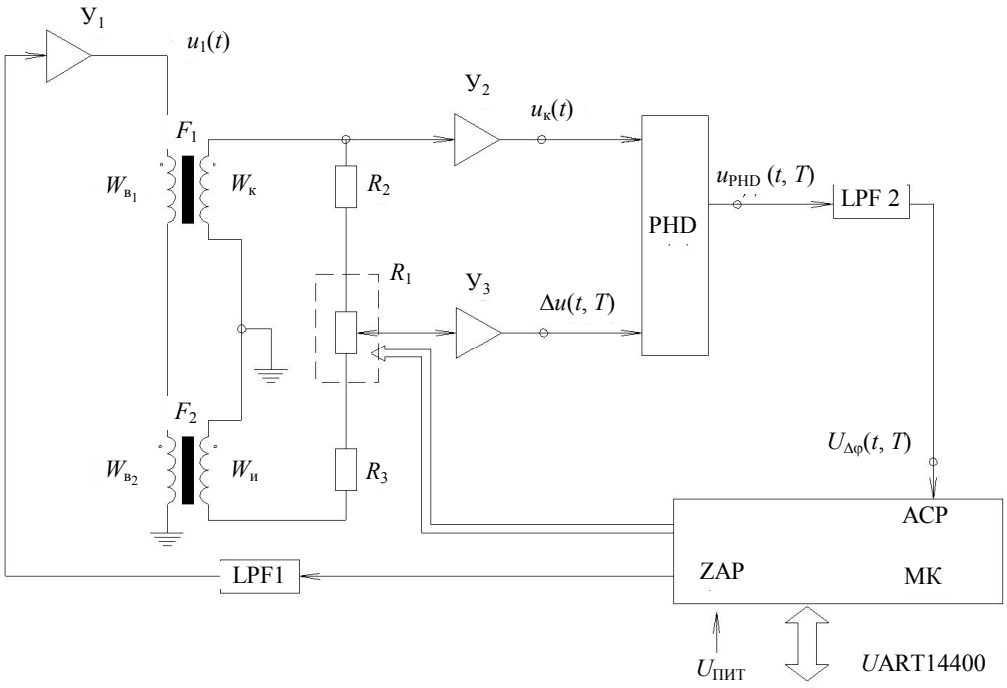


Fig.3. Block diagram of eddy-current phase transducer

A_1-A_3 – amplifiers, PHD – phase detector, LPF1 – LPF2 – low-pass filters, W_{E1}, W_{E2} – excitation windings, W_C and W_M – differentially connected compensation and measuring windings, MC – microcontroller, R_1 – controlled digital balancing potentiometer, F_1, F_2 – ferritic shell cores

W_E winding is supplied with $u_1(t)$ sinusoidal voltage of frequency f. $\Delta u(t, T)$ amplified differential (introduced) voltage is supplied to the PHD phase detector. Phase detector uses $u_k(t)$ from output of W_C compensation winding as a reference signal. Output voltage $U_{\Delta\varphi}(t, T)$ low-pass filter is proportional to the

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phase difference $\Delta\varphi$ between $u_к(t)$ voltage and $\Delta u(t, T)$ differential (introduced) voltage. Windings of the transducer are balanced by the digital potentiometer controlled by the microcontroller [2].

It is convenient to use a generic information parameter for analysis of transducer characteristics [3]:

$$\beta = R\sqrt{2\pi f\sigma_c\mu_c\mu_0}\ ,$$

where R – equivalent radius of excitation winding; f – excitation current frequency; σ_c – integrated conductivity of the coating; μ_0 – magnetic permeability of vacuum$ μ_c – relative magnetic permeability of the coating.

To ensure required sensitivity of measurements the following range of generic parameter variation is needed [11, 12]:

$$\beta = 2 - 10\ .$$

In this case the depth of electromagnetic field penetration, δ , will be:

$$\delta = 1/\sqrt{\pi f\sigma_c\mu_c\mu_0}\ .$$

Maximum measurable thickness of coating [ISO 21968 2005] is

$$T_{max} = (0.6 - 0.8)\delta\ .$$

For the coating in question $\sigma_c \approx 1.5$ and $\mu_c \approx 20$, while $T_{max} = 3$. It can be seen from calculations that the above mentioned conditions are met with $f \approx 1$ kHz and $R = 19$ mm.

T must be checked after each next applied section of the coating and during final check of the coating (after the coating is applied over the entire inner surface of the product). Period of check of each next section must not be greater than 10 minutes, because only in this case it is possible to apply additional coating layers, if necessary, without loss of its integrity (by delaminating or cracking) [4]. Since the electric arc spraying method of coating application uses very high rates of metal melting and further coating metal cooling, the temperature gradient results in significant mechanical stresses in the coating. These mechanical stresses, in turn, result in change of mechanical properties of the coating, including change of magnetic properties of Nickel [5, 6, 10].

It is confirmed by investigations that internal stresses really arise in the coating in the process of coating parameters relaxation, resulting in change of μ_c from μ_{cmin} (corresponding to the moment of time immediately after application of the coating) to μ_{cmax} (approximately 24 hours after application of the coating) [15].

Review of publications shows that no any explicit expressions are obtained so far, that describe the relation between magnetic characteristics of ferrimagnetic materials and elastic mechanical stresses aris-

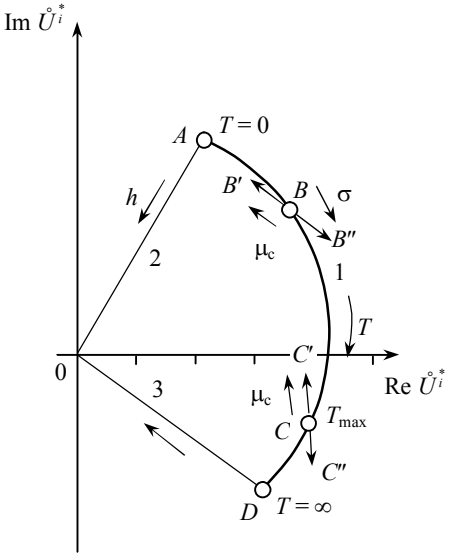


Fig.4. Relative introduced voltage $\mathring{U}_i^* = \mathring{U}_i/|\mathring{U}_0|$ as a function of informative and interfering parameters when measuring T

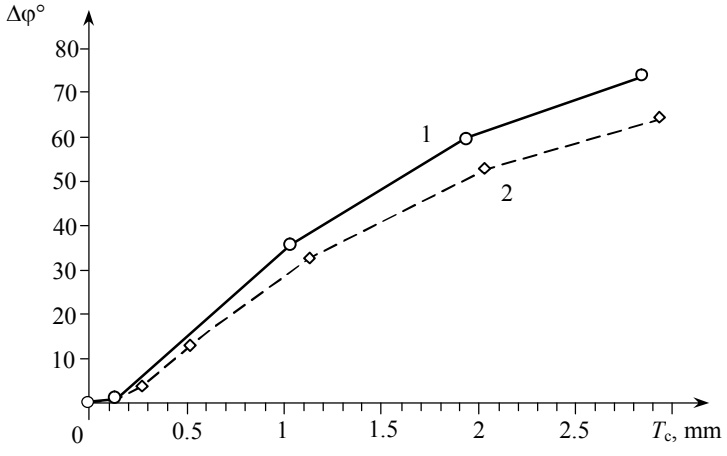


Fig.5. Phase shift as a function of coating thickness
1 – for measurement immediately after application of the coating;
2 – for measurement 12 hours after application of the coating

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ing in them. First of all, this is connected with variable properties of ferrimagnetic materials and their texture. In general:

$$\mu_{c_{max}} = \mu_{c_{min}} / (1 - \alpha\lambda_0 P),$$

where α – constant value, λ_0 – initial magnetostriction of ferrimagnetic material of the coating, P – mechanical load in the coating resulted from mechanical stresses.

So, conditions of measurement during in-process check within a coating section in the process of coating application will be considerably different from that during final check of sections after all the coating is applied, because of different values of μ_c, which can result in inadmissible measurement error [9].

Shows relative introduced voltage $\mathring{U}^*_i = \mathring{U}_i/|\mathring{U}_0|$ as a function of informative and interfering parameters (fig.4).

Curve 1 in Fig. 4 (hodograph curve of $\mathring{U}^*_i(T)$) reflects the effect of T (point A corresponds to $T = 0$, point C corresponds to $T = T_{max}$, and point D corresponds to $T = \infty$). Curves 2 and 3 (hodograph curves of $\mathring{U}^*_i(h)$) show turning out to mitigate the effect of gap, h, between the transducer and the product surface on the measurement result (when changing h , the informative parameter $\Delta\varphi$ remains unchanged). Curves B'BB" and C'CC" illustrate the effect of μ_c variation in the range from μ_{cmin} (corresponding to points B" and C") to μ_{cmax} (corresponding to points B' and C') [16].

Fig. 5 shows curves of $\Delta\varphi(T)$ for measurement immediately after application of the coating and 12 hours after application of the coating (practically after the end of its parameter relaxation). It can be seen that the value is a function of time. Also, it can be seen from the figure that if this change in the process of relaxation is not taken into account, the error of measurement can be as large as ± 1 mm, depending on the way of transducer calibration in the process of its manufacture.

To evaluate the change of magnetic characteristics of the coating the second eddy-current transducer must be added to the device with $\delta < T_{min} = 1$ mm at ß = 2-4. Concurrently, it can be said that this transducer has its $\Delta\varphi_2$ only dependent on μ_c with constant value of σ_c [14].

The calculations and experiments performed have shown that optimum parameters of this transducer are as follows: excitation current frequency $f \approx 16$ kHz, equivalent radius of excitation winding $R_1 = 3$ mm. See fig. 6 for winding design of the combined two-channel transducer. Compensation and measuring windings of the second eddy-current transducer are equipped with ferritic semi-shell cores improving their sensitivity [15].

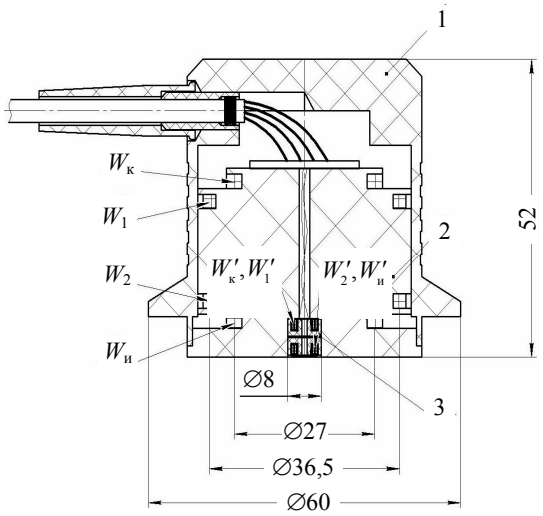


Fig.6. Design of combined two-channel transducer
1 – casing; 2 – transducer sensor to measure coating thickness;
3 – transducer sensor to evaluate magnetic characteristics of the coating

To calibrate and functional test the transducer a reference thickness sample was manufactured in the form of plane-parallel rectangular substrate made of high-strength cast iron with dimensions of 150x150 mm and thickness of 70 mm, on one side of which 4 sectors of coating with different thickness were applied. The coating was applied by the robotic station. Modes and paths of metal sprayer motion were similar to that of the real industrial process of coating application on container case to the maximum possible extent. Coating thickness of sectors was measured by direct measurement method. Functions of $\Delta\varphi(T, t)$ for the first transducer and $\Delta\varphi_2(\mu_c, t)$ for the second transducer were measured over a time interval of 24 hours (from the end of coating application to complete relaxation of coating parameters). Based on results of combined mathematical processing of these functions an algorithm was developed for measurement in each point.

Konstanta K6S, a combined transducer for coating thickness gauge was developed on the basis of the investigation performed. Tests have shown that the device provides measurement error of $\Delta T \leq \pm (0.03T + 0.02)$ mm in the range of coating thickness from 1 to 3 mm in the process of coating application and during final check of the coating (immediately after the end of coating application over the entire surface of the product), suppressing the effect of its magnetic properties variation.

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