Thickness Measurement of Nickel Coatings on Walls of Nuclear Waste Storage Tanks

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Abstract. In one of modern designs of containers for storage and transportation of nuclear waste is carried out automatic spraying of nickel ferromagnetic conductive coating of thickness T = 1 ...3 mm on inner surface of walls from ductile cast iron with spheroidal graphite. The process of coating application is characterised by dependence of its magnetic permeability μ_c on relaxation time, duration of which can reach 24 hours and also deviation of μ_c from place to place on the surface. The work analyses questions of application of eddy current phase method for measurement *T.* A structure of eddy current four-winding transformer transducers, calculation results and optimization of their parameters, the influence of inspected and interfering parameters are given in the work. Based on this a combined dual-channel measuring transducer has been developed that ensures the measurement accuracy $\Delta T \leq \pm (0{,}03T + 0{,}02)$ mm in manufactory conditions in coating application process at the output inspection. The testing results on test specimens and examples of use in manufacture are given in the work.
Keywords: Eddy current, nuclear, coating, storage tank, thickness

Introduction

The containers (transport packaging casks) for storage of nuclear waste analysed in the work are used for transportation and long-term storage of spent fuel assemblies generating heat of power units of nuclear reactors. Transport packaging casks were made in the international cooperation for nuclear industry PRC.

Transport packaging cask (fig. 1) ensures:

- loading the cask with spent nuclear fuel at nuclear power plant;
- transportation of spent nuclear waste by rail, road and water transport;
- storage of spent nuclear fuel in repositories of storage sites;
- service life the tank must be at least 50 years.

Housing of the nuclear-protective container consists of a cast housing and a lid. The housing and the lid are manufactured from ductile cast iron with spheroidal graphite. The necessary technological and inspection and measuring equipment is located inside the container. The weight of an empty container is more than 100 tons.

The internal surfaces of the housing and the lid must have nickel coating of thickness T to 3 mm in dependence on type to ensure the required level of temperature and radioactive

protection.Application of thick layer of nickel coating and ensuring the set value *T* is difficult and very expansive technological operation when manufacturing the containers.
Use of electromagnetic (galvanic) method of application of nickel coating due to the technological difficulties does not seem to be possible. The method of coating material spraying is more acceptable for this application. However, during the application process the product surface cannot be heated over 100-120 °C, because if not maintaining this condition the process of recrystallization of graphite cast iron may begin and an emergence of critical stress fields in its volume will occur that will lead to decrease of strength properties of the transport packaging casks. For this reason it has been decided to use the method of electric arc metallic spraying that unlike gas-flame method does not heat the product surface over 100 °C. During electric arc spraying the molten metal is caught by a stream of compressed air flowing out from central orifice of the sprayer in the form of finely dispersed particles and they are transferred with high speed to the product surface. The metallic coating application process and its structure on the surface of the product are shown on fig. 2.

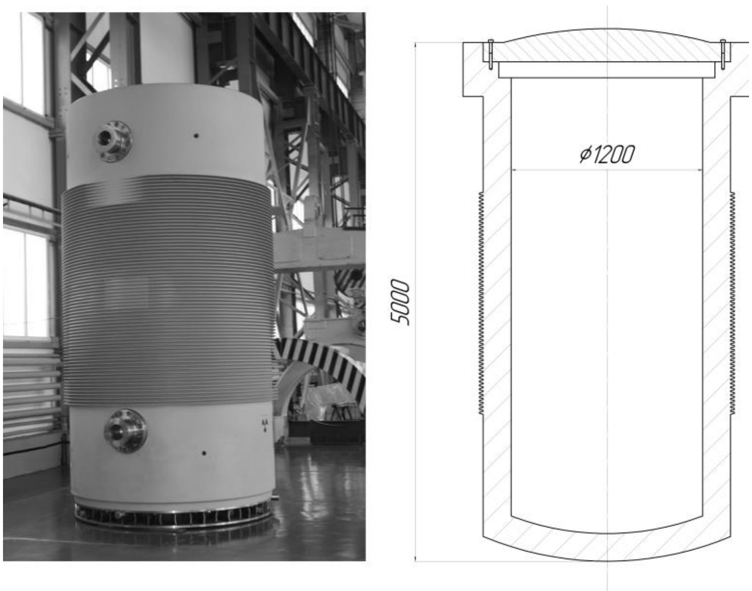

Figure 1. External view of transport packaging cask

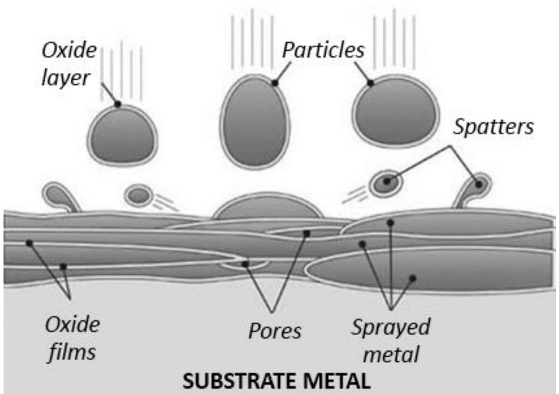

Figure 2. Metallic coating creation process and its structure on product surface

The coating application must be carried out immediately after removal of conserving grease, sand-blasting processing and cleaning of the surface by blowing, because the activated metal surface is quickly covering by oxide layer. The application of coating is carried out by use of a specialised robotised complex manufactured on the basis of a lathe and five-axis welding robot (fig. 3).The product is fixed in the lathe chuck. The turning frequency of the product is 3 - 7 rev/min. Wire feed, current adjustment and air pressure are operated through control unit of the sprayer installed on the rod. Complete time of coating application is 24 - 36 hours depending on the required value *T*. Coating is applied by sections (strips) with a length of 1 m along the product axis during its turing and reverse progressive motion of the rod with the robot. The coating application process must not be interrupted for more than 10 minutes to ensure adhesion of layers and to avoid their cracking. This permissible time interval of interruption of the metal spray process can be used for inspection of *T* with a possiblity of furhter application of addional layers without neccessity of violation of coating properties. Moreover, it is necessary to carry out an output inspection of coating thickness on the whole surface with set resolution.

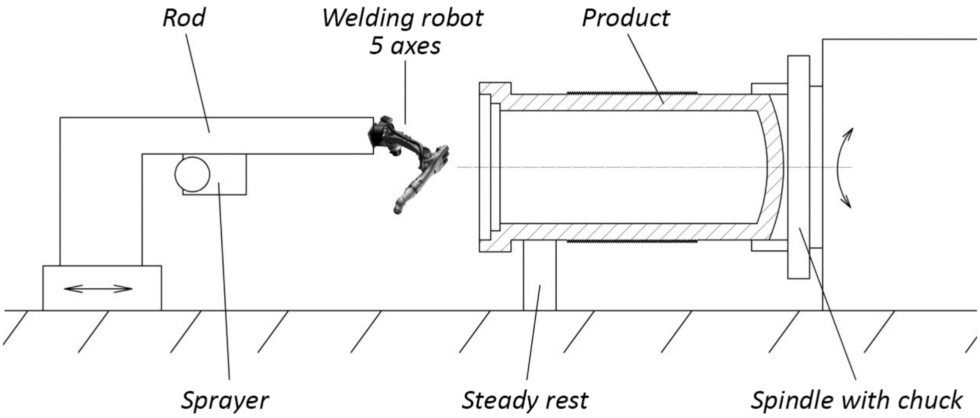

Figure 3. Structure of specialised robotised complex for nickel coating application on the inner surface of transport packaging cask

In the analysed measurement task the nickel coating with thickness from 1 to 3 mm is magnetic conductive. The substrate is also magnetic conductive. It is optimal to use eddy current phase mehtod for *T* measurement.

1. Eddy current measurement of coating thickness

The circuit diagramof four-winding eddy current phase transducer for measuring coating thickness that uses as a reference signal the voltage of the compensation winding is shown on Fig. 4.

Winding W_m receives sinusoidal voltage $u_1(t)$ with frequency *f*. The voltage on measuring winding W_m is equal to the sum of the voltages $\mathring{U}_0$ emerging in the absence of an inspected product, and brought (differential) voltage $\mathring{U}_i$, emerging due to the influence of the product: $\mathring{U}= \mathring{U}_0+ \mathring{U}_i$. Amplified differential (brought) voltage $\Delta u(t)$ comes to phase detector PD. Voltage $u_c(t)$ from exit of compensating winding W_c serves as a basic signal for the phase detector. Constant voltage $U_{\Delta\varphi}(T)$ on exit of the low-pass filter is proportional to the difference between voltage $u_c(t)$ and differential (brought) voltage $\Delta u(t)$. Balancing of windings of the transducer is done with use of the digital potentiometer R_1 operated by microcontroller MC.

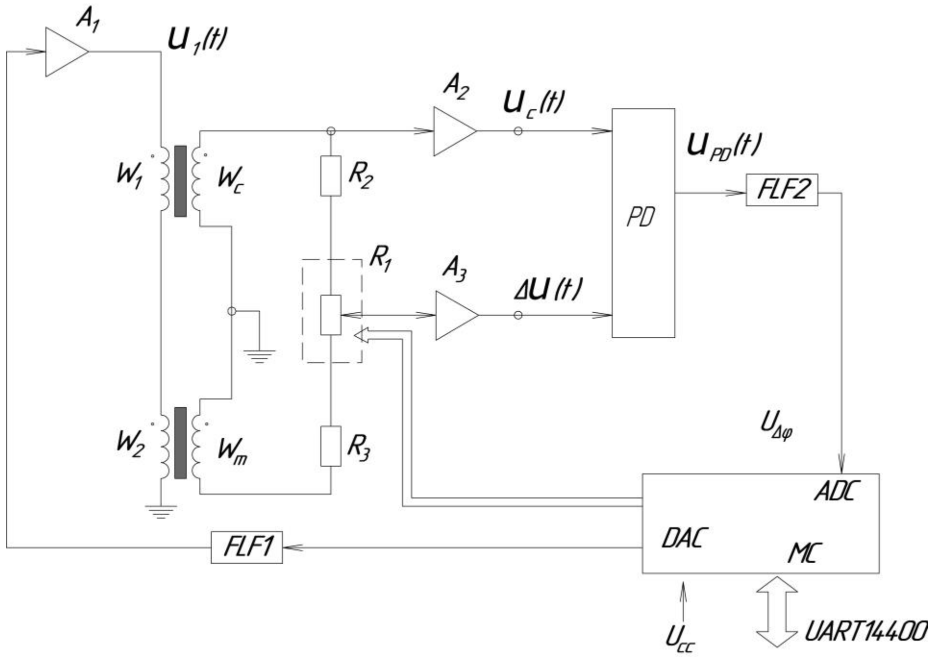

Figure 4. Circuit diagram of eddy current phase transducer:
A_1, A_3 – amplifiers, PD – phase detector, FLF_1 - FLF_2 - low-pass filters, W_1 and W_2 – excitation windings, W_m and W_c – differentially connected measuring and compensating windings, MC – microcontroller, R_1 – digitally operated balancing potentiometer

For the analysis of characteristics of the measuring transducer it is convenient to use the generalized parameter

$$\beta = R\sqrt{2\pi f \sigma_c \mu_c \mu_0} \quad (1)$$

where R – equivalent radius of excitation winding; f – frequency of excitation current; σ_c – integrated electrical conductivity of material; μ_0 – magnetic constant, μ_c– relative magnetic permeability of coating.

For maintenance of comprehensible sensitivity during measurement of conductivity σ_i it is necessary to choose a value of

$$\beta = 2 \dots 10. \quad (2)$$

Generally a depth of penetration of eddy currents δ is equal:

$$\delta = 1/\sqrt{\pi f \sigma_c \mu_c \mu_0} \quad (3)$$

Maximum measured coating thickness [ISO 21968 2005]:

$$T_{max} = (0{,}6 \dots 0{,}8)\delta \quad (4)$$

The analysed coating has $\sigma_c \approx 1{,}5$ MS/m and $\mu_c \approx 20$, $T_{max} = 3$ mm. The calculations demonstrated that the achievement of the above given conditions is ensured when $f \approx 1$ kHz and R= 19 mm.

The inspection of T is carried out after application of each regular section of coating and during the output inspection (after coating application on the whole inner surface of the product). The time of inspection of each regular section cannot exceed 10 min, because only in such case it is possible to apply the additional layers of coating, if necessary, without violation of continuity (exfoliation or cracking). Since during the electric arc method of coating application the time of melting and successive cooling of the metal of the coating is very short so the temperature gradient leads to an emergence of considerable stresses in the coating. The mechanical stresses in their turn change physical parameters of the coating including change in magnetic properties of nickel. Research confirmed that during process of relaxation of coating parameters indeed internal stresses occur in it that lead to change of μ_c from value μ_{cmin} (corresponding to the moment immediately after the coating application) to μ_{cmax} (approximately after 24 hours after the coating application).

An analysis of publications demonstrated that no evident analytical dependencies have been found so far connecting magnetic characteristics of ferromagnetics with emerging elastic mechanical stresses in them. Primarily it is related to variable properties of ferromagnetic itself and its texture. Ingeneral

$$\mu_{cmax} = \mu_{cmin}/(1 - \alpha\lambda_0 P), \qquad (5)$$

where α — constant, λ_0— initial magnetostriction of ferromagnetic material of coating, P— mechanical load in coating that emerges due to mechanical stresses.

Accordingly, the conditions of measurements during technological inspection within a section when applying the coating and during the output inspection by sections after the whole coating application will significantly vary due to different value μ_c that can cause unallowable measurement error.

The dependence of complex relative brought voltage $\mathring{U}^*_i = \mathring{U}_i/|\mathring{U}_0|$ is presented on fig. 5. Line 1 onfig. 5 (hodograph $\mathring{U}^*_i(T)$) demonstrates the influence of T (point A corresponds to $T = 0$, point C corresponds $T = T_{max}$, and pointD corresponds to $T = \infty$).

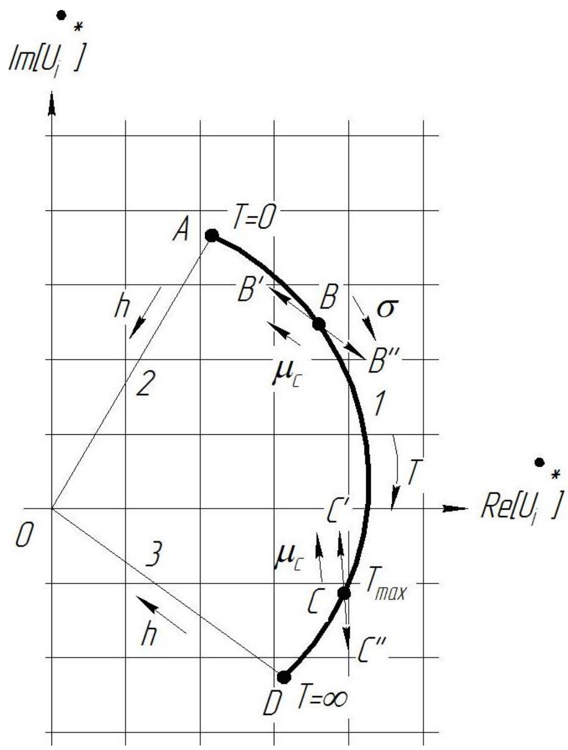

Figure 5. Dependence of complex brought voltage $\mathring{U}^*_i$on inspected and interfering parameters during$T$ measurement

Lines 2 and 3 (hodographs $\mathring{U}^*_i(h)$) demonstrate the tune out of influence of gap h between transducer and product surface on measurement result (when h changes the informative parameter Δφ does not change). Lines B'BB" and C'CC" illustrate the influence of variation of μ_c inrange from value μ_{cmin} (corresponding to points B" and C") to μ_{cmax} (corresponding to points B' and C').

The dependencies $\Delta\varphi(T)$ during measurements immediately after coating application and after 12 hours (practically after the end of relaxation of its parameters) that are presented on fig.6 show that they are dependent on time. It can be seen from the figure that if not taking into account such change in the process of relaxation, the measurement error can rise up to ± 1mm in dependence on how the calibration of the transducer was carried out during its manufacture.

The second eddy current measurement transducers has to be included in the device composition for evaluation of change of magnetic characteristics of coating, which has $\delta<T_{min}$= 1 mm when ß= 2... 4. It can be claimed that $\Delta\varphi_2$ of this transducer will depend only on μ_c when constant σ_c.

Figure 6. The dependence of phase shift on coating thickness: 1 – during measurements immediately after coating application; 2 – during measurements after 12 hours since coating application

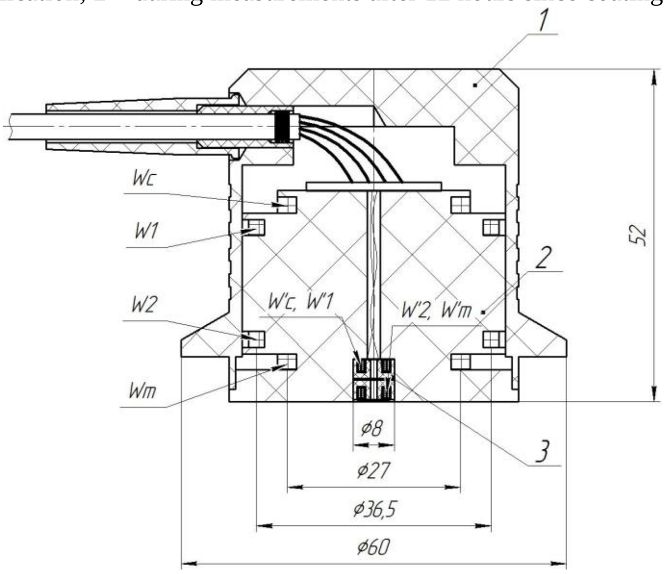

Figure 7. Design of combined dual-channel measuring transducer: 1- housing; 2 - sensitive element of transducer for coating thickness measurement; 3 - sensitive element of transducer for evaluation of magnetic characteristics of coating

Calculations and experiments accomplished demonstrated that the optimum parameters for this transducer will be as follows: frequency of excitation current $f \approx 16$ kHz, equivalent radius of excitation winding $R_1 = 3$ mm. The design of the windings of combined dual-channel measurement transducer are shown on fig. 7. Compensational and measuring windings of the secondary eddy current transducer have ferrite half-armoured cores, which increase its sensitivity.

A coating thickness specimen for calibration and testing of work of the transducer has been made. It is 150x150 mm, 70 mm thick rectangular substrate with parallel planes, it is made of ductile cast iron. Four sectors of coating with different thicknesses were applied on one surface by robotised equipment. Modes and motion trajectory of the sprayer were maximally close to the technological ones when applying coating on container housing. The coating thickness in sectors was measured by method of direct measurements. Dependencies $\Delta\varphi(T, t)$ for the first transducer and $\Delta\varphi_2(\mu_c, t)$ for the second transducer were created in time interval of 24 hours (from the moment of the end of application up to full relaxation of coating parameters). According to the results of joint mathematical processing of dependencies an algorithm was developed, during which at each point of inspection are first measured $\Delta\varphi_2$ and $\Delta\varphi$, after that with use of dependency $\Delta\varphi(T, t)$ corresponding to the measured value $\Delta\varphi_2$ is calculated T.

3. Conclusions

Based on the accomplished research a combined transducer for coating thickness gauge Constanta K6C has been developed. The coating thickness gauge is used in a plant that serially manufactures the transport packaging casks. The experiments revealed that the device ensures measurement error $\Delta T \leq \pm (0{,}03T + 0{,}02)$ mm in the range of coating thicknesses $T$from 1 to 3 mm in the process of its application and during the output inspection (immediately after the end of coating application on the whole product surface) suppressing the influence of variation of its magnetic properties