Ensuring reliability of measurement results of thickness of metal coatings with the Magneto-Inductive and Eddy-Current methods in the conditions of the Machine Industry

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Abstract

Article is devoted the analysis of the factors defining metrological characteristics Magneto-Inductive and Eddy-Current metal coating thickness gauges and reliability of results of measurements with their use in the conditions of the Machine Industry.

In Russia it is traditionally paid much attention to questions of metrological ensuring of coating thickness measurements, including metal, the most part from which has high cost and small thickness: h = 2 … 20 microns. In the domestic market the big nomenclature of domestic and foreign electromagnetic coating thickness is presented. In the operation manual for each transducer, which is a part of the device, it is necessary to stipulate types of controllable coatings and the bases, a limit of an allowed main absolute error of measurements, a range of measurements of h_{max}, the minimum internal and external radiuses of products, diameter of a zone of measurement and an allowed roughness of $R_{zmax\ bases}$ (coatings), a working temperature range.

Now the majority of leading producers manufacture metal coatings thickness devices with a declared limit of an allowed main absolute error of measurement of $\Delta h \leq \pm(0{,}01h + 1)$ µm in the field of small thicknesses. Thus it is meant that tests of devices carry out on the exemplary bases and working standards (calibration foils), identical subjects on which defined the calibration characteristic in normal conditions. It can mislead unprepared users concerning reliability of results of measurement under production conditions.

Let's analyze compliance of declared and really provided (achievable) metrological characteristics of protective metal coatings thickness devices under production conditions.

Metrological characteristics of coating thickness gauges are determined by a method of measurements, creation of the measuring transducer, used algorithms of transformation and h calculation by the calibration characteristics. Essential influence is rendered by the stirring parameters operating on measuring transducer in processes of graduation, calibration and measurement. Such geometrical parameters are: the base thickness (T), diameter of a zone of measurement (D), radius of curvature (r) and a roughness of a surface (R_z), gap between the transducer and a coating (Z). Physical stirring parameters include: electric conductance (σ_1, σ_2) and relative magnetic permeability (μ_1, μ_2) of coating and basis, temperature (t), external electromagnetic fields, etc.

Influence of geometrical stirring parameters

Roughness and curvature of a surface. Eddy-Current Phase transducers provide with an non-sensitivity of the size of a gap of Z at measurement that almost completely excludes influence of deviation of r and R_z to value about 40 microns.

For the Magneto-Inductive and Eddy-Current frequency transducers the additional error of measurement of thickness of metal coatings depends on Z and an equivalent gap of Z^*, caused by radius r of the product. At their use in the course of measurement on the bases with a regular roughness at normal distribution of value of thickness leave $6S=R_z/2{,}5$, where S – a standard deviation for the normal law of distribution. For example, at $R_z \approx 5$ microns the disorder of results of measurement will be about ± 1 microns.

At coatings measurement in the field of small thicknesses on cylindrical surfaces with radius r the additional error of measurements $\Delta(r)$ has additive character. For transducers with diameter of a zone of measurement D = 1,5... 3 mm $\Delta r \approx (200\ ...\ 220)\ r^{-1{,}07}$, where r is measured in millimeters, $\Delta(r)$ in micrometers. For example, at r change from 10 to 7,5 mm $\Delta(r)$ value will change with 9 to 12 microns.

Diameter of a zone of measurement and regional effect. Sensitive elements of primary transducers are projected with external screens from magneto-soft stales for Magneto-Inductive transducers and high-frequency ferrite for Eddy-Current transducers. Thus it is possible to argue that D is almost equal to the diameter of screen of the transducer, and the minimum distance from the screen to edge of a flat product, at which there is no additional error, is possible to consider equal (0,1 – 0,2)D.

Thickness of the basis. One of the main characteristics of the basis is its minimum thickness T_{min}, not influencing the measurement result. For high-frequency Eddy-Current transducers $T_{min} \approx 2{,}5(\pi f \mu_0 \sigma_2)^{-2}$, where μ_0 – a magnetic constant; σ_2 – an electrical conductivity of object of control; f – frequency of excitement of the transducer. For low-frequency Magneto-Inductive transducers $T_{min} \approx (0{,}3\ ...\ 0{,}4)D$.

Influence of physical stirring parameters

Electrical conductivity of basis and coating at measurement of elektro-conducting non-ferromagnetic coatings on the identical bases. Eddy-Current frequency transducers are made according to the auto-generating scheme, their target frequency depends on brought inductance:

$$L_{Br} = {Im\left[J\pi\mu_0 R^2 n^2 \int_0^\infty J_1(\lambda R)^2 e^{-2\lambda z}\chi_0 d\lambda\right]} \Big/ {\omega L_0} \qquad (1)$$

$$\chi_0 = \frac{(\lambda - q_1)(q_1 + q_2)e^{hq_1} - (\lambda + q_1)(q_2 - q_1)e^{-hq_1}}{(\lambda + q_1)(q_1 + q_2)e^{hq_1} - (\lambda - q_1)(q_2 - q_1)e^{-hq_1}}$$

$$q_i = \sqrt{\lambda^2 + j\omega\mu_0\sigma_i}, \qquad i = 1,2,\dots$$

where μ_0 – absolute magnetic permeability; R –equivalent radius of a winding of the transducer; n –number of its coil; $J_1(\lambda R)$ – Bessel's function of the 1st order; λ – transformation parameter; $\omega = 2\pi f$ – circular frequency of a current of excitement; L_0 – initial inductance of the transducer; σ_1, σ_2 – coating and basis electrical conductivity.

The disorder of an electrical conductivity of the basis of real production from non-ferrous metals can reach $\Delta\sigma_2 \approx \pm(0{,}05 \ldots 0{,}1)\sigma_2$. In compliance with (1) for metals and alloys with an electrical conductivity 9 – 60 MSM/m it will lead to disorder of brought inductance of an order $\Delta L_{br} \approx \pm(0{,}012 \ldots 0{,}025)L_{br.}$ From here the error of measurement of thickness of metal coatings will reach $\Delta h(\sigma) \approx \pm 1{,}2$ micron for $\sigma_2 \approx 60$ MSM/m and $\Delta h(\sigma) \approx \pm 2$ micron for $\sigma_2 \approx 9$ MSM/m. The carried-out pilot studies for coatings with the various relation of σ_1/σ_2 confirmed the results received above.

The Eddy-current phase transducers in most cases are carried out according to the three-winding scheme with differential inclusion of measuring and compensatory windings. By means of eddy-current phase coating thickness gauge it is possible to measure at $\sigma_1 >> \sigma_2$ (for example, copper or silver on brass).

Tension on a measuring winding is represented in the form of the sum of the tension $\dot{U}_0$ arising in lack of a controllable product, and the brought $\dot{U}_{Br}$ tension caused by influence of a controllable product: $\dot{U} = \dot{U}_0 + \dot{U}_{Br}$

The relative brought tension of a measuring winding is determined by a formula:

$$\dot{U}_{Br} = \frac{j\pi R_e R_m \mu_0}{M}\int_0^\infty J_1(\lambda R_e) J_1(\lambda R_m) e^{-\lambda(z_e + z_m)}\chi_0 d\lambda \qquad (2)$$

where R_e, R_m – radiuses of windings of excitement and measuring; z_e, z_m – distances from the specified windings to a product surface; M – coefficient of an initial mutual induction between windings.

The phase of relative brought tension is expressed as

$$\varphi = \mathrm{arctg}\left(\mathrm{Im}\left[\dot{U}^*_{\text{вн}}\right] \Big/ \mathrm{Re}\left[\dot{U}^*_{\text{вн}}\right]\right). \qquad (3)$$

Calculations carried-out on (2), (3) show that change of an electrical conductivity of the basis of $\sigma_2 \approx 10$ MSM on ± 1 MSM/m leads to emergence of an error of thickness measurement of a copper or silver coatings ($\sigma_1 \approx 60$ MSM) an order of $\Delta h(\sigma) \approx \pm(1,5…2)$ microns at measured thickness up to $h = 30$ microns.

Magnetic permeability of the basis at measurement electrically conducting nonferromagnetic coatings on the ferromagnetic bases.

The informative parameter of Magneto-Inductive double winding transformer transducers – change of flow linkage $\Psi(h)$, penetrating a measuring (secondary) winding, inversely proportional h and directly proportional μ_2 (the error of measurement doesn't depend on electrical conductivity of basis and coating):

$\Psi(h) = \Psi_0 + \Psi_{br}(h)$,

where Ψ_0 – flux linkage , $h = \infty$; $\Psi_{br}(h)$ – brought flux linkage.

The local spread of magnetic properties is characteristic for steels. In this case the spread of the relative magnetic permeability μ_2 of bases for steels, subjected to quenching and mechanical processing, is more than for soft-iron steels. For the last the spread μ_2 in limits of model by diameter about 50 mm can reach 10 - 20%. In the case of alloy steels, which were subjected to quenching and grinding, the spread μ_2 can compose 40 - 80% [1].

In order to study the influence of h and μ_2 on the flux linkage of small transducers, this parameter of measuring winding was calculated by the method of final elements. Figure depicts the dependence $\psi^*(h) = (\psi_0 + \psi_{Br}(h)) / \psi_0$ in the region of small thicknesses for the transducer with the diameter of measuring zone of $D = 3$ mm with different μ_2. The local spread of magnetic properties ± 50% relative to average value will lead to the deviation of indications from – 1,5 to + 0,7 µm. With smaller μ_2 for alloy steels this spread will be substantially more (depending on brand of material from 1,5 to 4 µm).

Temperature. In the majority of cases operating temperature for the thickness gauges of protective coatings, specified in the operation manual, is from – 10 to + 40 ^{o}C. The temperature effect was studied for the thickness gauges of the chief domestic and foreign producers in the range from – 20 to +40 ^{o}C. In the range of the small thicknesses of coatings the coefficients of additional component of error **$\Delta(t)$,** caused by the temperature effect, were obtained for the thickness gauges of various producers: "Constanta K5" (Russia) – 0,06 microns/ ^{o}C, «Elcometer 456» (England) – 0,13 microns/ ^{o}C and «Positector 600» (USA) – microns/ ^{o}C. It means that at temperature change on 10 ^{o}C Δt will be about 0,6 microns – for "Constant K5"; 1,3 microns – for «Elcometer 456»; 4 microns – for «Positector 600».

External electromagnetic fields. The source of electromagnetic field is a power unit (aiming by frequency of 50 and 100 Hz), transducers of electric drives (pulse aiming by frequency to units of kilohertz) and the communication equipment (high-frequency aiming). In an area of coverage of fields deviation of indications can exceed an allowed absolute error of measurements. Reduction of their influence is reached only by carrying out measurements with averaging.

Submission of the calibration characteristic

The calibration characteristic of transducers of coating thickness looks like the function which is automatically counted on codes $N(h)$, removed on measures of thickness of coatings.

To provide $\Delta h \leq \pm(0{,}01h + 1)$ micron the calibration characteristic optimum to approximate polinom $N(h) = kh^3 + mh^2 + nh + p$ on groups of four points within total number of points. For obtaining the characteristic it is necessary to choose values of measures of thickness from a row 0; 5–10; 16-20; 30; 40; 60; 80; 100; 125; 150; 175; 200; 250 microns. At this range factors of k, m, n, p count for four groups. Thus in the field of small thickness the error of approximation $(\Delta h)_a$ and will be negligible. According to, at confidential probability of P = 0,99 in the field of small thickness at $\Delta h \leq \pm 1$ micron of a measure of thickness of coatings for graduation should be made and certified with an accuracy ± 0,3 micron.

Graduation and checking of transducers as a part of coating thickness gauges

More often transducers in the range of small thicknesses are graduated on measures from metal materials (reference measures of the 2nd category) in normal conditions. Measures of coating thicknesses in a range of 2-1000 microns apply as such measurement standards. Limits of allowed absolute errors of manufacturing and certification of working standards of the 2nd category are calculated according to: $(\Delta h)_{r\ m} \leq \pm((0{,}1\ \ldots\ 0{,}3) + 0{,}025h)$ micron. The basis of a measure should have thickness more $T_{\min}$. Now for certification of step measures of thickness of coverings use the optometric or profile-graphic methods providing an error of measurement at level of ±(0,1 – 0,2) micron in the field of small thickness that is admissible more often.

Sometimes, manufacturing of metal thickness measures on as their characteristics won't correspond to the real for a variety of causes isn't obviously possible. In this situation of a measure of thickness make from samples of real production on technology of manufacturing microsection according to or on a method of a sphere. In the latter case error of measurement of small thickness $\Delta_b \leq \pm(0{,}1\ ...\ 0{,}3)$ micron. The method of a sphere is applicable also for working standards of the 2nd category. Its advantage is that there are no requirements to flat-parallelism of the parties of the bases, necessary in case of use of opti-meters. It is necessary to choose physical characteristics of material of metal thickness measures and bases according to the measurement method, applied in a concrete coating thickness gauge.

When manufacturing metal measures for Magneto-Inductive and Eddy-Current phase coating thickness gauge it is necessary to select the polished steel bases carefully before drawing of coatings. The bases in thickness more $T_{\min}$ should have $\mu_{rel} = \mu/\mu_{max}$ providing in a range of small thickness disorder of indications of "zero" no more ±(0,1 – 0,3) micron. Measures of thickness should be degaussed.

When manufacturing metal thickness measures for Eddy-Current frequency and phase coating thickness gauges it is possible to use as the bases the non-ferrous metals demanding manual operational development. It is more than basis in thickness T_{min}, selected for manufacturing of measures, should have disorder of σ_2 no more ±(0,3 – 0,5) MSM/m. It is necessary to put coatings in a fresh prepared electrolit on the technologies corresponding applied in production where the device will be maintained.

In processes of graduation and checking it is necessary to maintain constant temperature of samples $t = (20 \pm 2)$ °C, and also to provide probably minimum level of electromagnetic fields.

Performance of the specified conditions of manufacturing and certification of thickness measures, approximation of the calibration characteristic and conditions of graduation will provide $\Delta h \leq \pm(0{,}01h + 1)$ microns in the field of small thickness in normal conditions.

Research of an average resource of metal coating measures of thickness by their repeated measurements by means of Magneto-Inductive coating thickness gauge showed that to 3000-5000 measurements the characteristics of metal coatings practically don't change.

It is desirable to test coating thickness gauge on thickness measures similar to measures which were used for their graduation when manufacturing.

Calibration and measurements

Coating thickness gauge calibrate by means of working measuring instruments – coating thickness measures with various combinations of materials of the bases and the coatings grouped to destination, with a limit of an allowed absolute error of manufacturing $(\Delta h)_{wmi} \leq \pm ((0{,}2 \ldots 0{,}3) + 0{,}05h)$ micron.

For calibration of the Magneto-Inductive coating thickness gauge in the field of small thickness often apply simulators of coatings – films from polyethylene-teraftalat, imposed on samples of products without coatings. The minimum thicknesses of simulators (on the basis of polyethylene films) are about 5-10 microns. By means of selection of films it is possible to provide manufacturing of simulators with disorder no more ±0,3 micron of thickness on a zone in diameter about 6-10 mm. To exclude influence of wear of films it is necessary to replace them after carrying out 30-200 measurements (in dependence on thickness of the simulator).

At measurement of thickness of electro-conducting non-ferromagnetic coatings on ferromagnetic and non-ferromagnetic bases with the help a Eddy current transducers the quantity of measures of thickness for calibration can be not justified big. Now conducting producers solve this problem as follows. The transducer build in the non-volatile memory of the transducer in which write down the calibration characteristics "coating - basis" removed on working standards of the second category. An error of Δh is almost additive depends on influence of parameters of the basis in the field of small thickness and it is eliminated with "zero" installation on a product sample without coating.

In the process of calibration and measurement the measuring transducer is influenced practically by all influencing factors defined by parameters of a coating, the basis and environmental conditions. With the account of told above for Magneto-Inductive and Eddy-Current phase coating thickness gauge the local disorder μ_2 of the basis causes disorder of indications of an order of ± (1-3) micron in the field of small thickness; temperature change on 10 degrees can lead to a measurement error at level of 0,5-3 microns; wearing of simulators can cause an uncontrollable error at calibration. For Eddy-Current frequency and phase coating thickness gauges the great influence on result of measurements renders disorder of σ_1 of bases and σ_2 of coatings (it is possible to ± (1-2) micron). For reduction of influence of variations of σ_2, μ_2 и R_z the it is recommended to carry out calibration and measurements with averaging of the results of a zone of control or on a lot of products.

Conclusion. Coating thickness gauge manufacturing now and used in the industry can't provide the error of measurement $\Delta(h) \le \pm(0{,}01h + 1)$ microns, declared in the operation manual, in the conditions of technological disorders of physical and geometrical parameters of products and environment of the majority of machine-building productions.

For carrying out annual checking in the field of small thickness the certificated metrological services should be completed with coatings thickness measures of demanded combinations of materials of coatings and the bases – the working standards of the 2nd category made on uniform technology according to design documentation, corresponding to controllable objects.

Performance of measurements with averaging on the set zone of control or within a certain quantity of products at the specified stirring parameters allows to receive the value of thickness, characterizing technological process of drawing of a coating with suppression approximately $\sqrt{n}$ times of disorder of indications, caused by stirring parameters. At n = 10 … 15 it is possible to say about possibility of carrying out measurements of technological thickness of metal coatings for the considered methods of measurement with $\Delta h \le \pm 2$ micron the field of small thickness with confidential probability of P = 0,95 … 0,99 that proves to be true operating experience of devices

Before the beginning of operation it is necessary to carry out tests of devices for determination of temperature and temporary stability of their indications by results of which periodicity of calibration is regulated at work in shop conditions.

It is impossible to appoint technological admissions to thickness of a coating - proceeding from specified in recommendations about operation of the majority of modern coating thickness gauge $\Delta h \le \pm(0{,}01h + 1)$ microns in the field of small thickness as they won't be provided with demanded confidential probability. At establishment of admissions it is necessary to carry out research of stirring parameters and to consider their influence and only after that to develop a technique of performance of measurements and to define necessary confidential probability for admissions for coating thicknesses.