# Specifics in the Magnetic-Thickness Measurement of Galvanic Nickel Coating

Anatoliy SHUKEVICH, Alexander LUKHVICH, Nadegda KREMENKOVA, Andrey LUKYANOV*,* Vladimir SHARANDO, Institute of Applied Physics of National Academy of Sciences of Belarus, Minsk, Belarus

**Abstract**. Galvanic nickel coatings are widely used and can be deposited both on nonmagnetic and ferromagnetic substrates. Their useful properties (luster, adhesion, density, etc.) are determined by the parameters of the deposition process. Variations of the useful properties and possible violations in the deposition process lead to changes in their magnetic properties, which complicate the nondestructive testing of the thickness of such deposits.

One of the main interfering factors during magnetic thickness measuring of nickel deposits is the level of internal stresses. It is possible to minimize their effect on the results of thickness measurements by increasing the magnetizing field in the informative zone to a magnitude where the material of the deposit is in a near-saturated magnetic state.

In this investigation, we used computer simulation to study the magnetization distribution in the informative zone, the parameters of the zone itself, and the secondary field in interrelation with the parameters of the magnetization source.

We used the following simulation model: the substrate was a plate of thickness *h* with homogeneous properties; the deposit was a homogeneous layer with a maximum thickness of $\delta_m$; the magnetizing-field source had a cylindrical symmetry and consisted of a permanent magnet and a magnetic circuit. The parameters of the permanent magnet corresponded to the NdFeB alloy; the parameters of the magnetic circuit, to a low-carbon steel. The results obtained show that the appropriate geometry of the source of a magnetizing field essentially confines the effect of internal stresses in nickel deposits on the readings of magnetic thickness gages.

## Contents

One of the main interfering factors during magnetic thickness measuring of nickel deposits is the level of internal stresses. It is possible to minimize their effect on the results of thickness measurements by increasing the magnetizing field in the informative zone to a magnitude where the material of the deposit is in a near-saturated magnetic state. This means that, when developing magnetic thickness gages, one must take into account the distribution of magnetization in the informative zone. Experimental studies encounter difficulties [1] caused by the necessity of violating the continuity of an object being tested. Therefore, it seems expedient to use computer simulation for investigation of magnetization in the informative zone. We can compare the results of the calculations, i. e., distribution of the secondary magnetic field, with the experiment, thus verifying the reliability of the results obtained. In this investigation, we used computer simulation to study the magnetization distribution in the informative zone, the parameters of the zone itself, and the secondary field in interrelation with the parameters of the magnetization source.

The magnetization curve of nickel is largely determined by the level of internal stresses and structure peculiarities. However, in this case, the saturation magnetization does not differ considerably from that of pure nickel (500 000 A/m). Hence, if the magnetization of a deposit is close to saturation, the shape of the curve in the range of weak fields is not of great importance. Taking into account the above restriction by saturation, we selected the function $B_{Ni}(H) = 0,3B_{Fe}(H)$ as the magnetization curve for nickel, where $B_{Fe}(H)$ is the magnetization curve for low-carbon steel (both curves were set as tables).

Practically important nickel deposits are those up to 150 μm-thicks. Thus, we assumed $\delta_m$ = 150 μm. Calculations were carried out for deposits 30, 60, 90, 120, and 150 μm-thicks, and the magnetization distribution was calculated at distances of 15, 45, 75, 105, and 135 μm from the surface, correspondently. In the calculations, we used the finite-element and boundary integral equation methods. The first method was used in calculations of the magnetization distribution and secondary field; the second method, in the determination of informative-zone parameters.

Table 1 presents some results obtained for nickel deposits on a nonmagnetic substrate. As follows from the table, for $R \geq 0,5$ mm, magnetization does not depend on the depth and, when $0,5 \leq R \leq 4,5$ mm, it is close to the saturation magnetization. Calculations also show that the dependence of the magnetization on the distance from the axis decreases more slowly for thin deposits than for thick ones. The common behavior of the magnetization distribution is caused by the fact that a thin ferromagnetic plate is mainly magnetized due to the radial component of the field. In the region with $R < 0,5$ mm, the magnetization distribution behaves in an unusual way; i. e., the magnetization decreases with an increase in the distance from the surface where the source is installed. This is due to the fact that in this area $H_z > H_R$ magnetization occurs owing to the field component that is normal to the surface, and the small thickness provides a large demagnetizing factor.

**Table 1.** Magnetization distribution ($J \cdot 10^4$, A/m) in a nickel deposit on a nonmagnetic substrate for different range of nickel deposits (Z, mm)

| R, mm | Z=0,015 mm | Z=0,045 mm | Z=0,075 mm | Z=0,105 mm | Z=0,135 mm |
|---|---|---|---|---|---|
| 0 | 47,9108 | 46,2905 | 41,4039 | 34,0123 | 17,0251 |
| 0,5 | 44,5263 | 44,466 | 44,3935 | 44,3504 | 44,3182 |
| 1 | 45,6823 | 45,6456 | 45,6148 | 45,596 | 45,5762 |
| 1,5 | 45,9668 | 45,9599 | 45,5342 | 45,9223 | 45,9084 |
| 2 | 45,922 | 45,9421 | 45,4203 | 45,9173 | 45,9034 |
| 2,5 | 45,7349 | 45,2924 | 45,4161 | 45,7091 | 45,7061 |
| 3 | 45,4343 | 45,4232 | 45,3194 | 45,4135 | 45,4015 |
| 3,5 | 44,9123 | 44,9083 | 44,9024 | 44,8905 | 44,8915 |
| 4 | 44,1901 | 44,1762 | 44,1713 | 44,1723 | 44,1663 |
| 4,5 | 42,5748 | 42,5689 | 42,5619 | 42,556 | 42,556 |
| 5 | 39,407 | 39,4147 | 39,4073 | 39,4287 | 39,4289 |
| 6 | 23,3061 | 23,3378 | 23,3774 | 23,3854 | 23,3932 |
| 8 | 10,1202 | 10,1202 | 10,1281 | 10,1281 | 10,1281 |

The result of calculations influence of the deposit thickness on the normal component of a secondary magnetic flux is shown in Fig. 1. It follows from the figure that the normal component of the flux of the secondary magnetic field linearly depends on the deposit thickness on nonmagnetic substrates. We observe an analogous dependence for the tangential component of the secondary field measured at some distance from the axis.

Let us now consider nickel deposits on a ferromagnetic substrate. In this case, information about thickness can be obtained if the informative zone's depth is larger than the deposit thickness. Hence, the informative volume consists of two ferromagnetic separated by a planar boundary. Since the thickness of a deposit is small, one can expect that the secondary field would be affected by boundary conditions, which include both the tangential component of magnetic-field strength as a boundary is crossed and the retention of the induction component that is normal to the surface. As a result, a jump of the tangential magnetization component takes place at the boundary.

In Fig. 2 the radial distribution of the obtained values of the normal (Fig. 2a) and tangential (Fig. 2b) components of magnetization, induction and intensity of the magnetic field on distance 15 µm from both sides of the boundary in the covering and the basis at total thickness of the covering 150 µm is shown.

It is seen from Fig. 2. that, in the layers adjacent to the boundary, the change in the tangential magnetization component is several times greater than the change in its normal component. Thus, the secondary magnetic field is mainly determined by the tangential component's jump at the boundary.

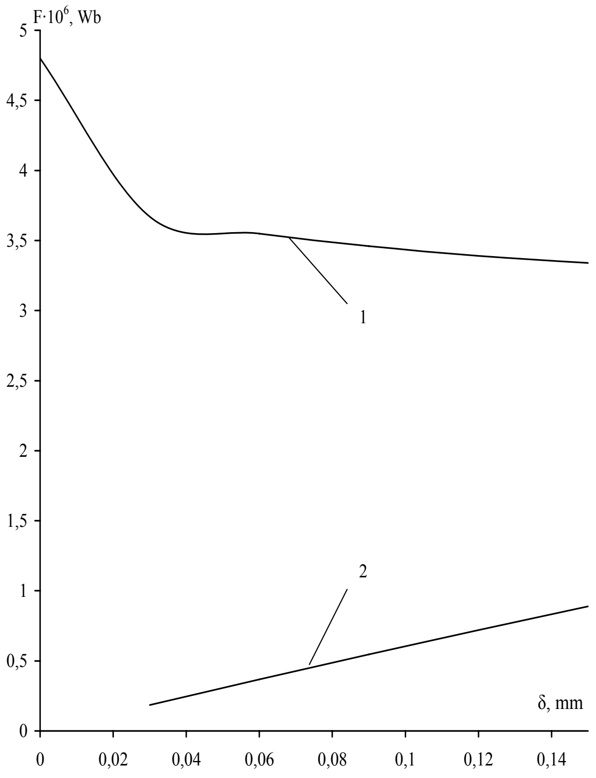

**Fig. 1.** Dependence of the secondary magnetic-field flux on the deposit thickness: 1 - a nickel deposit on a ferromagnetic substrate; 2 - a nickel deposit on a nonmagnetic substrate.

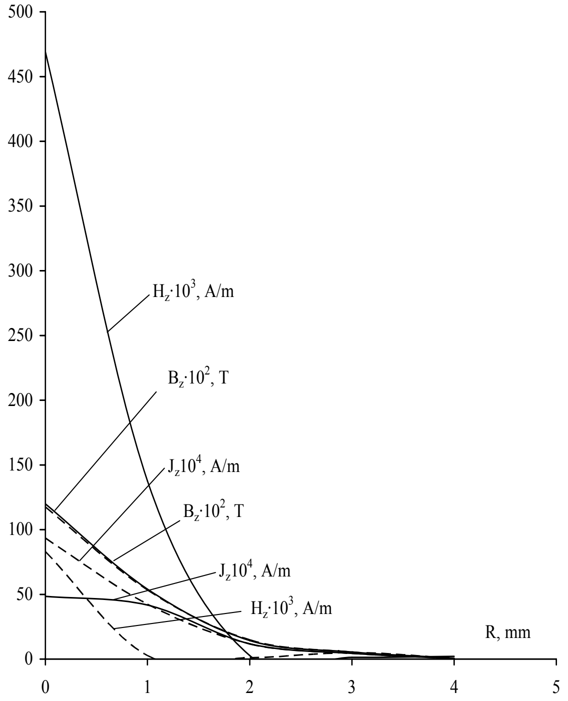

**Fig. 2a.** The radial distribution of the normal components of magnetization, induction and intensity of the magnetic field: —— in the substrate; - - - - in the deposit.

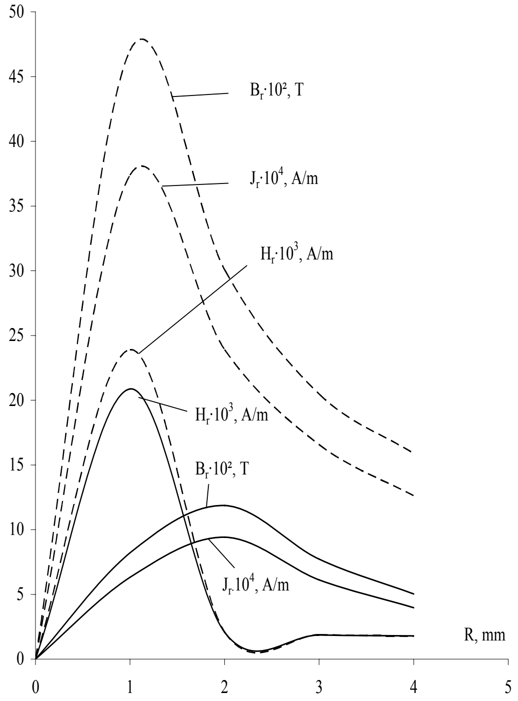

**Fig. 2b.** The radial distribution of the tangential components of magnetization, induction and intensity of the magnetic field: —— in the substrate; - - - - in the deposit.

**Fig. 2.** Magnetic parameters in the near-boundary layer of nickel–low-carbon steel

The distribution of the magnetization module in the deposit on a ferromagnetic substrate (columns 2 – 4) and in the substrate (columns 5) is demonstrated in Table 2**.**

**Table 2.** Magnetization distribution ($J \cdot 10^4$, A/m) in a nickel deposit on a ferromagnetic substrate for different range of nickel deposits (Z, mm)

| R, mm | Z=0,015 mm | Z=0,075 mm | Z=0,135 mm | Z=0,165 mm | Z=0,135 mm |
|---|---|---|---|---|---|
| 0 | 48,9033 | 48,5734 | 48,5033 | 93,341 | 48,4049 |
| 0,5 | 48,2712 | 48,1319 | 48,0245 | 79,12 | 48,4049 |
| 1 | 46,9936 | 45,5999 | 42,1398 | 56,4718 | 48,3945 |
| 1,5 | 26,7667 | 24,7372 | 25,6151 | 38,2651 | 48,364 |
| 2 | 15,9368 | 15,5482 | 15,0546 | 26,6664 | 48,2877 |
| 2,5 | 10,8276 | 10,6449 | 10,3586 | 20,4227 | 47,8151 |
| 3 | 7,9662 | 7,7268 | 7,4766 | 16,8113 | 39,8243 |
| 3,5 | 5,879 | 5,5878 | 5,3168 | 14,3613 | 26,9012 |
| 4 | 4,9258 | 4,4775 | 4,0221 | 12,5714 | 20,042 |
| 4,5 | 4,8836 | 4,491 | 4,1239 | 11,458 | 14,316 |
| 5 | 5,738 | 5,4503 | 5,2159 | 9,6208 | 10,7799 |
| 6 | 3,8513 | 3,725 | 3,6066 | 4,0177 | 7,0235 |
| 8 | 0,7009 | 0,7051 | 0,7095 | 1,0495 | 2,01 |
| 10 | 0,3565 | 0,3579 | 0,3593 | 0,5695 | 0,7157 |

It follows from this table that the deposit is magnetized almost homogeneously through its thickness, which is a similar feature of a nickel deposit on a nonmagnetic substrate. However, a strong difference in the radial distribution of magnetization is observed. Since the results present in table 1 and 2 have been obtained using the same source of the primary magnetizing field, the difference is only caused by the presence of a ferromagnetic substrate. Owing to the interaction with the substrate, the strong-magnetization region in the deposit decreases almost 4.5 - time. This is caused by the demagnetizing effect of the tangential component of the ferromagnetic substrate. Additionally, there is no dependence of magnetization on the thickness near $R = 0$.

It is important to determine the dependence of the structure and internal stresses on the readings of the thickness gage remains unclear. At first, we need to determine the parameters of the informative zone.

The radius of the informative zone was determined by the method of finite integral equations in accordance with the expression:

$$\frac{F - F_{R_0}}{F} \le \alpha, \tag{1}$$

where $F$ - at distance z from the surface, is the normal component of the secondary field's induction flux, which is generated by all portions of the deposit whose magnetization is not zero; $F_{R_0}$ - is the same value in the case when only regions with $R < R_0$ are considered; and $\alpha$ -is the required accuracy of the deposit-thickness measurement.

Using the magnetization distribution calculated by the finite-element method and the method of boundary integral equations, $F_{R_0}$ we determined as a function of variations in the limit of integration by R. Fig. 3 presents results of these calculations.

At $R > 15$, the magnetization is on the order of $10^5$ of its maximum value; thus, we did not take into account these areas in our calculations. If the measurement accuracy is set equal to 2%, it follows from the table that the radius of the informative zone is approximately 5 mm at $z = 1$mm and approximately 8 mm at $z =$ 3 mm. Therefore, for both non-

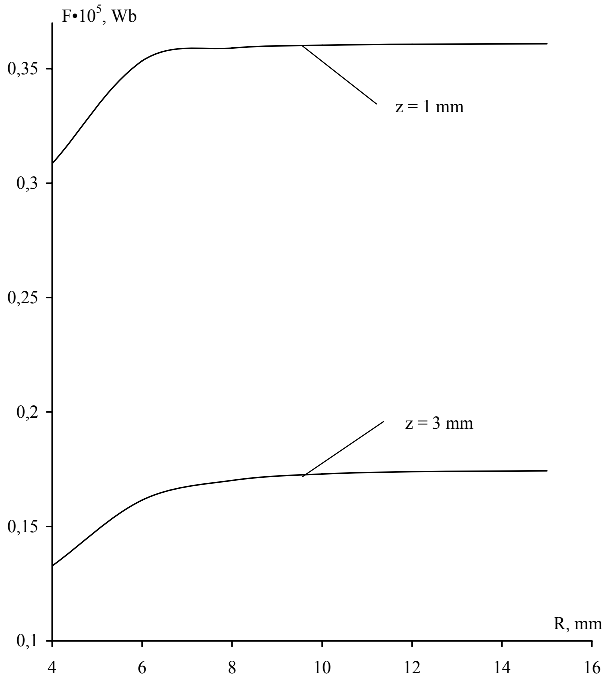

**Fig. 3.** Dependence of the secondary-field flux on the radius of integration

magnetic and magnetic substrates, the entire informative zone is not in a state close to magnetic saturation. Hence, we can expect a considerable effect of internal stresses on the thickness gage readings. This imperfection can be eliminated by expanding the area of maximum magnetization of the deposit by increasing the radius of the magnet and the tip, using a planar magnet end, or creating a close magnetic circuit with simultaneous contact of the magnet tip and the ferromagnetic screen with the deposit. All the above methods were checked by calculations. During the process of switching to a planar magnet tip, 1 the area of weak magnetization near *R* = 0 increases and, in the case of a close magnetic circuit, the radial distribution of magnetization has a saddle shape; i. e., an area lacking magnetization between the tip and the screen appears. A simultaneous increase the radius of the magnet and the tip leads to an expansion of the maximum magnetization area and, to a smaller degree, to an increase in the informative zone's radius. Therefore, this method can be used to reduce the effect of stresses on the readings of a thickness gage that has a pickup coil serving as a measuring element. However, it was found more efficient to place a measuring element into the blind pocket at the tip's axis while simultaneously increasing the radius of the magnet and tip. As calculations show, when radius *R* of the pocket is 1,5 mm, the magnetizing field of the source decreases by no more than 2,5% while the maximum magnetization area increases (Table 2, last column).

Let us demonstrate that condition (1) is satisfied in the simple case of stepwise uniform magnetization of a surface. In this case, we obtain

$$\alpha = \frac{\sum_{i=2}^{N} \sigma_i \cdot z \cdot \left(1\Big/\sqrt{z^2+R_{i-1}^2} - 1\Big/\sqrt{z^2+R_i^2}\right)}{\sigma_1 \cdot \left(1 - z\Big/\sqrt{z^2+R_1^2}\right) + \sum_{i=2}^{N} \sigma_i \cdot z \cdot \left(1\Big/\sqrt{z^2+R_{i-1}^2} - 1\Big/\sqrt{z^2+R_i^2}\right)}, \qquad (2)$$

where $\sigma_i = J_n$ - is the normal magnetization component in the area $R_{i-1} \le R \le R_i$. Let us assume that $z = 1$; $\sigma_1 = 1$; $R_1 = 3$; $\sigma_2 =$ 0,5; $R_2 = 4$; $\sigma_3 =$0,1; $R_3 = 10$, for $R > 10$, let us assume $J = 0$. As follows from (2), a $\alpha$ = 0,067 in this case. If $R_1 = 6$, $R_2 = 7$, and all the other parameters remain unchanged, then $\alpha =$ 0,017. That is, the first case provides an accuracy not worse than 6,7%; the second case, not worse than 1,7%. The above example demonstrates that there exists a possibility to equalize the radius of the informative zone and that of the maximum magnetization area. In turn, if the informative zone and the maximum magnetization area coincide for deposits with maximum stresses, this should nearly eliminate or considerably weaken the effect of internal mechanical stresses (parameters of deposition technology) in a deposit on the readings of a magnetic thickness gage.

Thus, the obtained results show that the appropriate geometry of the source of a magnetizing field essentially decreases the influence of internal stresses in nickel deposits on the readings of magnetic thickness gages.

## References

[1] Tabachnik, V. P., Fedorishcheva, E. E., and Chernova, G. S. Induction Distribution in a Bulky Article during Magnetization by a Bar Electromagnet. – Defektoskopiya, 1986, No. 1, pp. 33-40.