Modeling and Optimization of Transducers Implementing Technology Magnetic Flux Leakage (MFL)

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Abstract. The physical and mathematical models, optimization criteria, and the main results of the calculations, using the finite element method, development and testing of transducers, implementing technology MFL, to control pitting corrosion damage chemical facilities, are considered.

Introduction

Technology MFL (Magnetic Flux Leakage) is widely used for production of the equipment for identification:

- corrosion walls damages (of pittings or planes) of products from ferrous metals, mainly pipelines and the bottoms of cylindrical tanks (for example, oil storages);
- mechanical damages (longitudinal or cross gaps or cracks with big disclosure) seamless and welded pipes, including thick-walled.

At the location of U - shaped permanent magnet at some distance from the wall of ferromagnetic product the part of power lines interrupts on the border of two environments (a magnet – air and air – product wall) with different values of absolute magnetic permeability μi, and normal H_{ni} a component of intensity of magnetic field H will experience a jump:

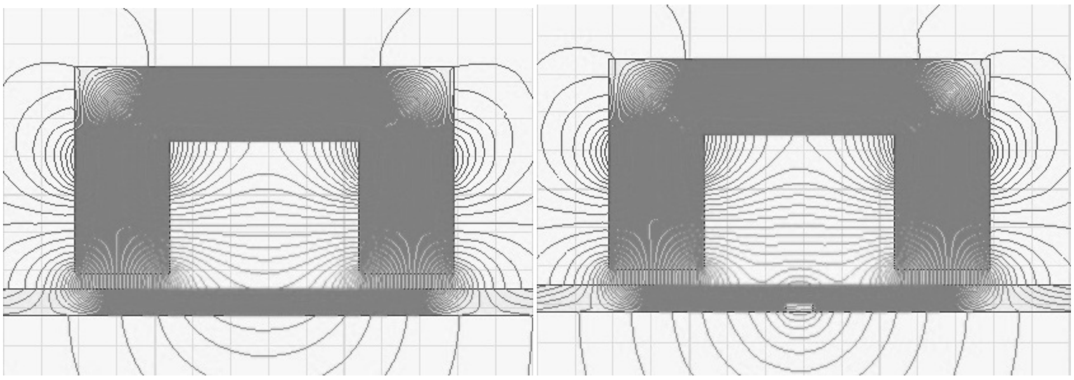
$$\begin{cases} divB = div\,\mu H \\ divB = \mu_1 H_{n1} - \mu_2 H_{n2} = 0 \end{cases} \quad (1)$$

From this it follows that $\mu_1 H_{n1} = \mu_2 H_{n2}$, and refraction of magnetic power lines happens under the law of tangents. When using rare-earth magnets (Nd-Fe-B) with induction B_M ~ 1 - 1,12 T on the border of two environments air/steel magnetic power lines are directed practically perpendicularly to a surface, while in volume of a product they seek to pass practically parallel to a surface that provides the minimum resistance of a magnetic chain. At certain ratios of thickness T of a wall of a product (sheet) and the sizes of a magnet practically all power lines of a magnetic flux will pass inside a sheet, only the insignificant part of them will go beyond a leaf.

In a case when on one of surfaces of a sheet there will be a site with local thinning (for example, pitting corrosion), a picture of a magnetic field will be changed (fig. 1, *b*). Lines-of-force density of power lines around defect will increase and the part of magnetic power lines will leave a sheet both from the side of magnet installation, and from the opposite side (there will be a magnetic flux leakage). This can be fixed by a solid-state sensing element with area S by measuring the normal component of the magnetic field H_n or the magnetic flux Φ_i:

$$\Phi_i = \oint_S B_n dS = \oint_S \mu_0 H_n dS \quad (2)$$

where B_n and H_n – normal components of magnetic induction and intensity of a magnetic field in the point of measurement symmetrized between magnet poles.



a) *b*)

Fig. 1. A settlement picture of power lines of a magnetic field on a faultless site of a steel sheet (*a*) and lines of a magnetic field of dispersion around artificial defect (*b*)

The primary measuring transducers (further transducers), realizing the considered technology of nondestructive testing, represent U - shaped magnetic circuits with inserts from permanent rare-earth magnets (Nd-Fe-B) and multichannel system of the sensitive elements symmetrized between magnetic conductor poles in the area of a magnetic field of one intensity (fig. 2). Basic transducers of Silverwing firm, one of the founders of this technology, have the following sizes: length of a magnet A = 25 mm, magnet height C = 10 mm, height of a yoke E = 20 mm, height of a pole is D = 25 mm, distance between poles L = 50 mm, a technological gap Z = 5 mm. Width of a magnetic transducer is 40 mm.

Transducers are intended for identification of plane and pitting corrosions of objects with wall thickness T from 6 to 16 mm. At $l \approx T$, the artificial defects with depth from h = 1,8 mm (T = 6 mm) to h = 8 mm (T = 16 mm) are found with guarantee. Used as sensitive elements, the Hall transducers analyzing changes of a component of magnetic induction B_z in a supervision point when the transducer moving concerning defect along an axis x (the beginning of system of coordinates is connected with the center of cross-cut defect.

Effective use of the MFL technology for concrete objects assumes design of the optimum measuring system answering˘ to a specific objective, application of special methods of processing of measuring information and adequate interpretation of results.

It is obviously possible, that not for all points of ranges of change of T and h the sensitivity of transducer, characterized by change of amplitude of *Bz(h)* in a zone of corrosion damage, will be optimum.

The main indicators of the transducers quality:

- the sensitivity of transducer $d/dh(B_z(h,T))$, defining a measurement error $\Delta h(h, T)$, and also the range of measurement of h_{min}- h_{max};

- minimum possible sizes of a magnetic circuit providing set $\Delta h(h, T)$ and h_{min}- h_{max} in the demanded range of thicknesses T_{min}- T_{max};
- mass-dimensional and ergonomic characteristics.

For providing the demanded quality it is necessary to look for the compromise solution since indicators of quality are interconnected.

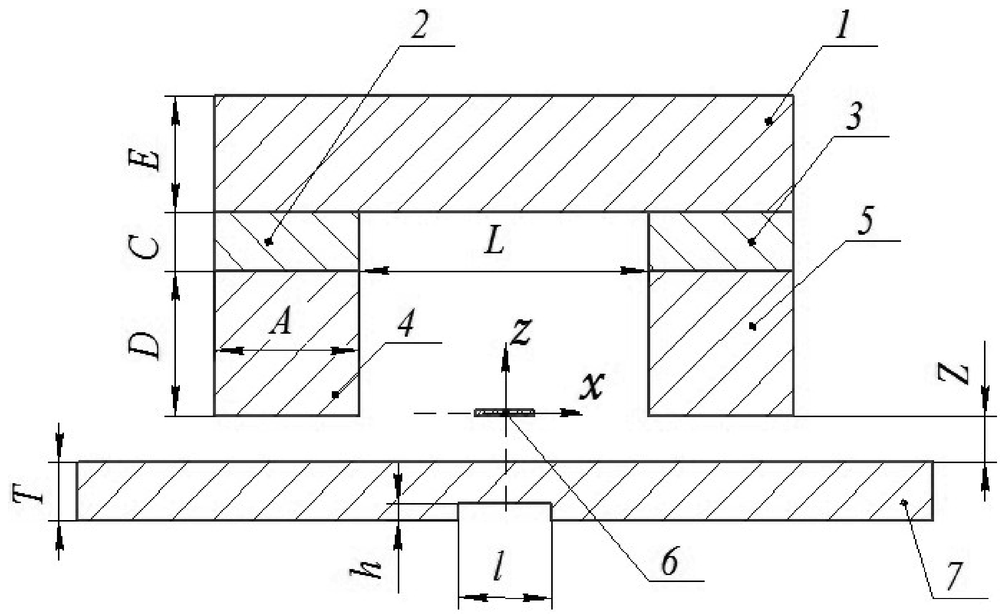


Fig. 2. The primary measuring transducer, realizing the MFL technology, and the object of control with cross-cut artificial defect, imitating corrosion damage of wall (1 – magnetic circuit yoke, 2 and 3 –rare-earth magnets, 4 and 5 – magnetic circuit poles, 6 – sensitive element / point of supervision, 7 – steel sheet with artificial defect).

In the analysis of the transducer, presented in fig. 2, we will believe magnetic circuit width much more than its height *C* and length *A*, that allows to exclude its influence at calculations.
Now the method of final elements is widely applied to the solution of the tasks connected with the analysis of electromagnetic fields.
We will count required values of parameters in nodal points (knots) – the general points of final elements. Scalar magnetic potential φ^M of each final element we will present in the polynomial form, with constant coefficients within this element

$$\varphi^M = a_i + b_i x + c_i y. \quad (3)$$

The main aim of calculation by method of final elements is to define coefficients a_i, b_i, c_i. After finding of coefficients there is an opportunity to calculate magnetic potential in any point of space of model. The basic data, added with boundary conditions, and energy dependences lead to system of the algebraic equations which allows to count required coefficients of polynomials in all final elements.
In relation to the considered task under boundary first-order conditions (Dirichlet boundary conditions) the minimized functional is the size proportional to the magnetic energy, reserved in space:

$$W_M = 0,5 \cdot \int \mu\mu_0 H^2 dv \quad (4)$$

as $H = -\text{grad}\varphi^M$, it is possible to write down a minimized functional in a look

$$W_M = 0{,}5 \cdot \int \mu\mu_0 (\mathrm{grad}\varphi^M)^2 dv, \quad (5)$$

and the required (minimizing) function will be $\varphi^M(\xi, \zeta, \eta)$, at which $W_M\{\varphi^M\}$=>min. The sum of the magnetic energies, saved up in all final elements, acts as functional. In this model elements adjoin in the general, nodal, points. Energy of elements is defined by magnetic potentials of nodal points

$W=W\{\varphi_1, \varphi 2, \ldots \varphi_N\}$, where N – number of points.

On the basis of the analysis and determination of magnetic potentials of the general (nodal) points at which W_M is minimum, the system of the algebraic equations is formed, the magnetic potentials, the magnetic induction and intensity of a magnetic field are calculated. Optimum geometrical characteristics of the transducer - such characteristics and their ratios at which the maximum sensitivity, in the demanded area of the measured objects of control(h_{min}- h_{max}) and in the range of wall thicknesses T_{min}- T_{max} at minimum possible dimensions, is reached.

When using the software products realizing a method of final elements it is possible to formulate the following problem definition of calculation of the transducer: two-dimensional, axisymmetric, stationary, generally non-linear, with open borders with the following assumptions:

- in a zone, rather remote from the transducer, the magnetic field created by it is infinitely small;
- there are no external magnetic fields;
- model completely permanent (there is no time and temperature drift of physical characteristics of the transducer).

According to the first two assumptions, it is possible to quote boundary first-order conditions as boundary conditions for models of the considered transducers. In the considered task this boundary condition is applicable for setting of zero value of a normal component of a vector of magnetic induction for symmetry axes (in a supervision point) and for the indication of full attenuation of a field on borders, conditionally infinitely far from the transducer. The varied parameters will be: sheet thickness T, relative coordinate $x^* = x/T$, the relative depth $h^* = h/T$ with a constant relative width of cross-cut defect $l^* = l/T = 1$. At calculations we will accept constructive gap size Z =5 mm, and magnetic induction in magnetic circuit $B_M \approx 1{,}12$ T.

In fig. 3, as an example, are presented the calculated dependences $B_z(h^*, x^*)$ at the symmetric position of the transducer (relatively cross-cut defect), for Z = 5 mm and T = 8 mm, from which it is visible that the maximum value $B_{zm}(h^*)$ is reached at edges of cross-cut defect, when $|x^*| \approx 0{,}5$, and $B_z(h^*, x^* = 0) \approx 0$ - at the central area of cross-cut defect.

In fig. 4 the calculated dependences $B_{zm}(h^*, T)$ are presented for the considered model of transducer over a ferromagnetic steel 1010 sheet with artificial cross-cut defect, executed according fig. 2.

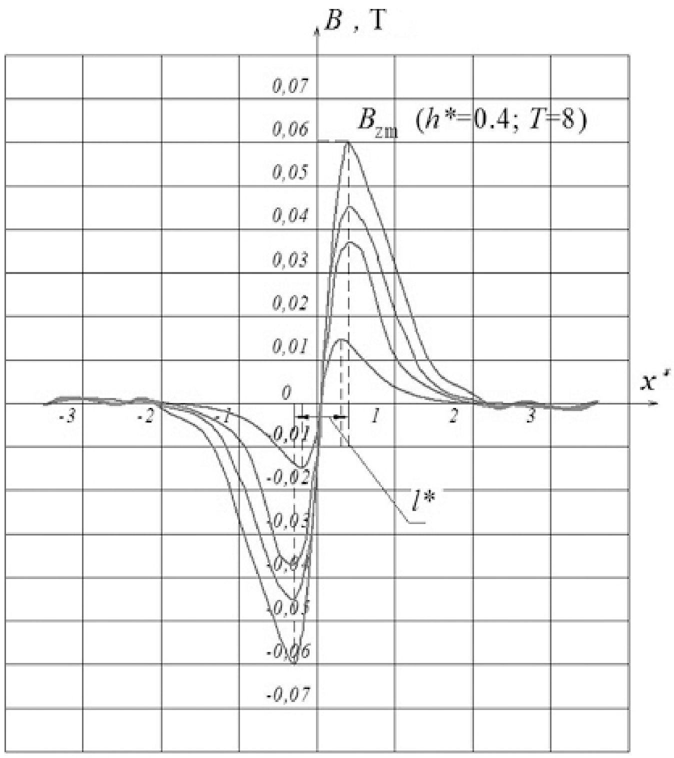


Fig. 3. Dependence $B_z(h^*, x^*)$ for the considered transducer's model over steel 1010 sheet 8 mm thick (T = 8 mm) round the cross-cut defect width l* =1 at Z = 5 mm.

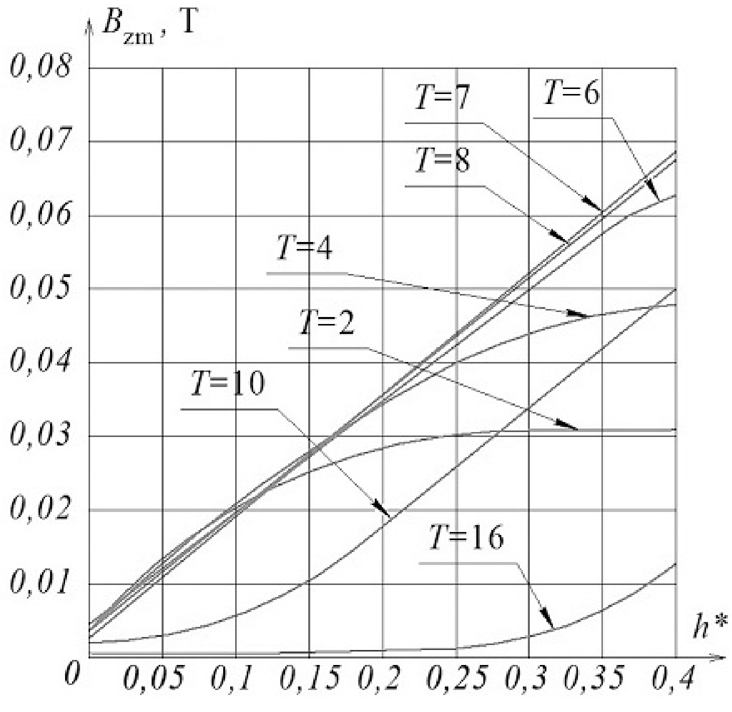


Fig. 4. Dependence $B_{zm}(h^*, T)$ for the considered transducer's model over steel 1010 round the artificial cross-cut defect width l^* =1 at Z = 5 mm

From fig. 4 it is visible that the transducer has the greatest sensitivity at T ≈ 6 - 8 mm in the range $h^* \approx$ 0,05 – 0,4. If T < 4 mm, it is observed the essential nonlinearity of the characteristic and reduction of sensitivity at h^* > 0,1 - 0,2. When T >10, the transducer almost completely loses sensitivity in the range h^* < 0,15. Calculations show that for $h^* \approx$

0,05 – 0,35 close characteristics are provided in the range $T \approx 5-9$ мм. From this it is possible to draw a conclusion on the size of optimum magnetization of metal for monitoring procedure.

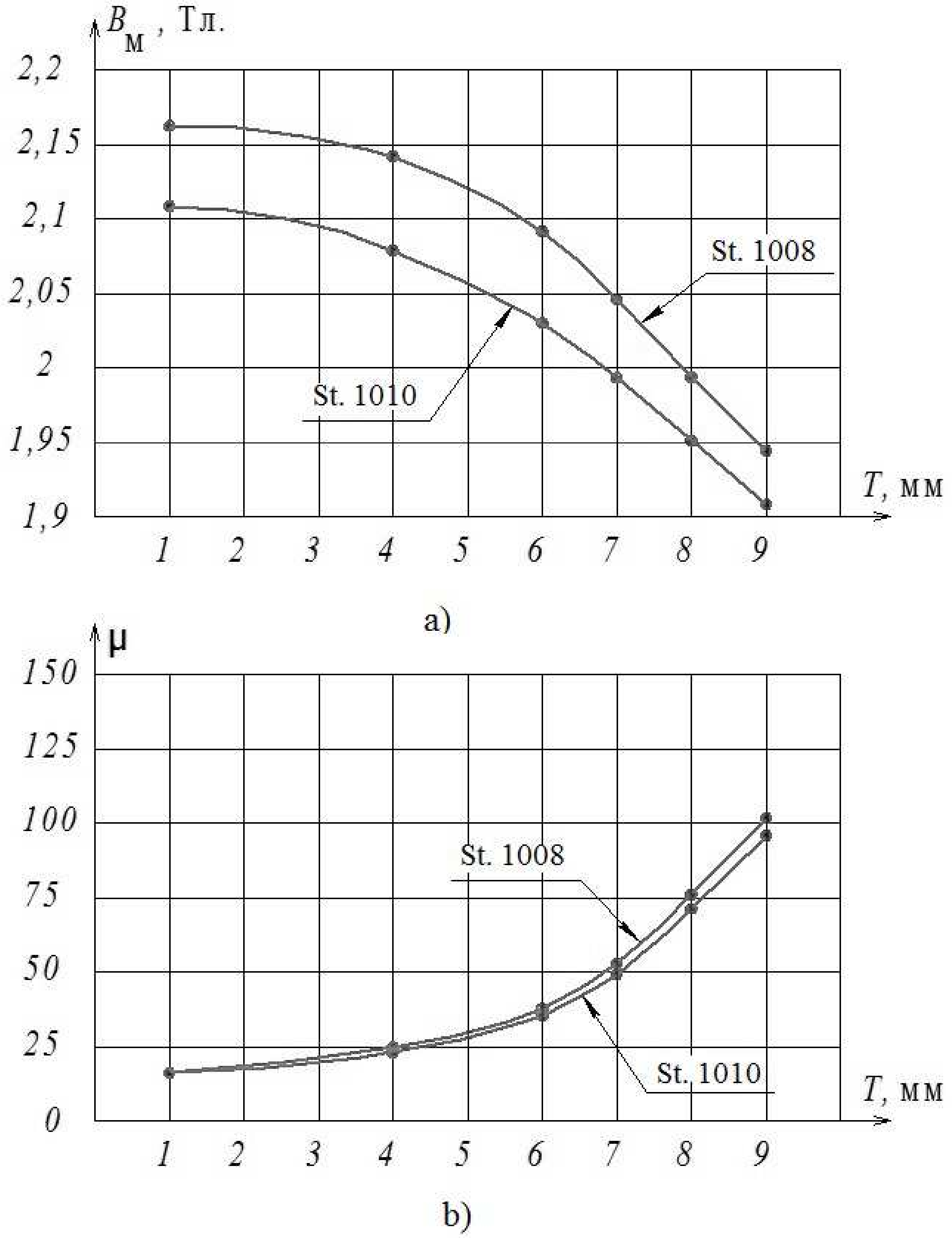


Fig. 5. Dependence of magnetic induction $B_м$ (*a*) and relative magnetic permeability μ (*b*) in metal sheet from its thickness of *T* in a zone of installation of a sensitive element

In fig. 5 The calculated values of magnetic induction $B_м(a)$ and the relative magnetic permeability μ (*b*) of metal sheet at its magnetization by the transducer, depending on *T*, for steels brands 1010 and 1008 in a zone installation of a sensitive element at $h^* = 0$ are given. In view of the aforesaid, the size $1{,}9 < B_м < 2{,}05$ T is optimal. For monitoring procedure metal should be magnetized up to $30 < \mu < 70$.
We will enter the relative sizes of the transducer: $^* = A/T$, $C^* = C/T$, $E^* = E/T$, $D^* = D/T$, $L^* = L/T$, $Z^* = Z/T$. At $T_0 = 7$ mm we will designate for the considered transducer as optimum: $A_0^* = 3{,}57$, $C_0^* = 1{,}43$, $E_0^* = 2{,}86$, $D_0^* = 3{,}57$, $L_0^* = 7{,}14$, $Z_0^* = 0{,}71$. In the control range ΔT from 5 to 9 mm the relative sizes of the transducer will change in limits:

ΔA^*~ (5 – 2,77), ΔC^* ~(2 – 1,11), ΔE^* ~(4 –2,22), ΔD^*~(5 – 2,77), ΔL^*~(10 – 5,55), ΔZ^*~(1 – 0,55).

According to fig. 2, on condition of geometrical similarity of magnetic systems of transducers, it is possible to break all range of controlled thickness T into subranges, for each of which the relative sizes of transducers will correspond to the optimum and change in the limits, set for them. The calculated values of the sizes of magnetic system of transducers and ranges of measurement conforming to the formulated requirements are given in tab. 1.

Table 1. Calculated values of the transducer's magnetic system sizes and ranges of controlled thickness

№	T_0, mm	A, mm	C, mm	E, mm	D, mm	L, mm	Z, mm	ΔT, mm
1	3,8	13,6	5,4	10,8	13,6	27,2	2,7	2,7 - 5,3
2	7	25	10	20	25	50	5	5 - 9
3	12	42,8	17,1	34,3	42,8	85	8,5	9,2 -15,9

At identification of areas with pitting corrosion damages of large-size objects of control, for example, of oil tanks or the main pipelines, one of the key disturbing parameters is the local deviation Δμ of the relative magnetic permeability which can lead to decrease in reliability of results of control [1]. For an assessment, calculations of $B_{zm}(h^*, T)$ for steels 1010 and 1008 (fig. 6), which difference of magnetic properties comparable to possible local deviation Δμ for the stated above objects of control, were carried out. In this case in the course of scanning of a surface, deviation $\Delta B_{zm}(h^*, T)=|B_{zm}(h^*,T)_{st1010} - B_{zm}(h^*, T)_{st1008}|<$ 0,002 T practically in all range of h *, that won't led to essential decrease in an error of measurements of depth and the sizes of pitting corrosion damages.

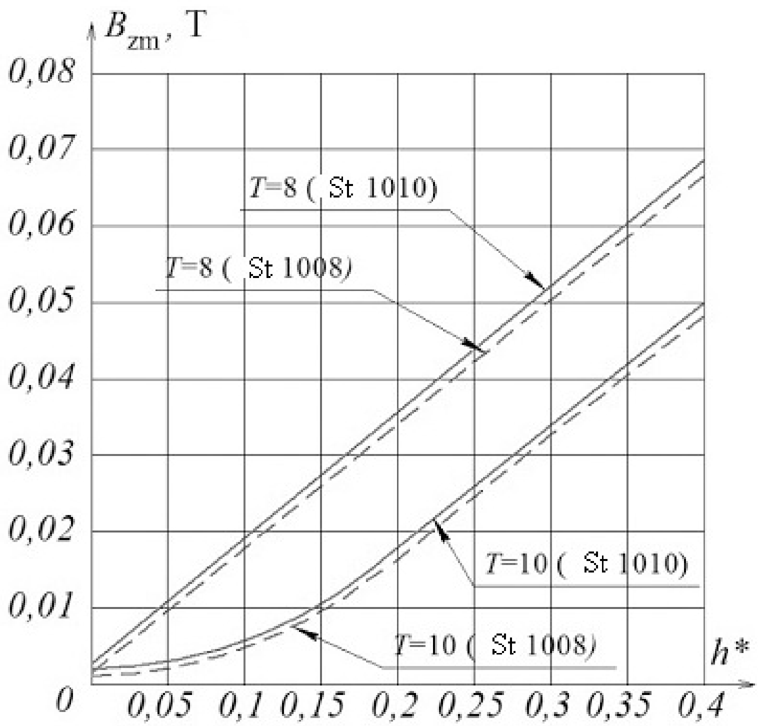


Fig. 6. Dependence $B_{zm}(h^*, T)$ for the considered transducer's model over steel 1010 and 1008 round the artificial cross-cut defect width l* =1 at Z = 5 mm

Deviation of a gap of Z (for example, coating thickness) will also lead to change of sensitivity and uncertainty of the transducer at an assessment of depth of pitting corrosion, as $B_{zm} \sim 1/Z$ with other conditions being equal [2].
In the petrochemical industry control samples are used for calibration of the measuring transducers, realizing the MFL technology, for settings of the equipment and high reliability identification of pitting corrosion. Until recently samples were represented by metal sheets similar on thickness and structure to real object of control, with conic drillings with a corner 120^0 from 0,2T to 0,8T in depth (fig. 7, a). However, the experiments executed by the leading producers, showed that more perspective is to use control samples with artificial defects of a step conic form with a corner 136^0 and from 0,2T to 0,8T in depth, made with use of milling cutter. In this case diameters of artificial defect are: Ø = T for h * = 0,2 and Ø = 2T for h * = 0,4.

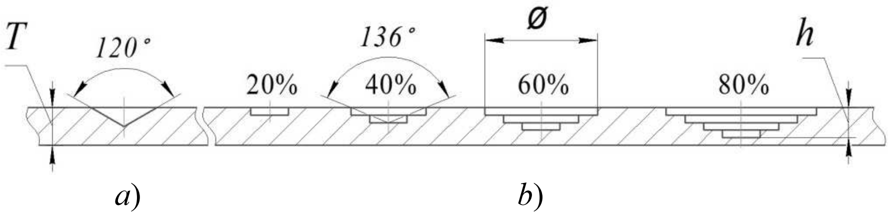


Fig. 7. Control samples with artificial defects: conic, 0,4T in depth (a) and step conic, 0,2T - 0,8T in depth, imitating pitting corrosion damages (b)

Use of the last generation of tiny integrated transducers of the Hall (for example, A1395 of Allegro firm) with an installation step about 1 mm provides possibility of identification of corrosion damages by depth of h * = 0,15 for objects of control with wall thickness $T_{min} \geq$ 2,7 mm.
Simulation of measuring transducers showed the convergence of results of modeling and calculations with experimental data, in particular, the reduction $\Delta h(h, T)$, at expansion of ranges of h * and T. Setup of transducers with use of control samples before work allows to control products with wall thickness T from 2,7 to 16 mm and to measure depth the pitting corrosion damages to h* range from 0,15 to 0,4 with an absolute admissible error $\Delta h \leq 0{,}1h$, comparable with an error at an ultrasonic coating thickness measurement [3].

References
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