Mathematical modeling of magnetic stray fields defects ferromagnetic products

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S u m m a r y . Proposed a method of limiting the area occupied by a ferromagnetic material containing a defect such as "crack" in the calculation of the magnetic stray field defect method of integral equations. Two variants of restrictions are considered: in the numerical solution of the surface integral equation and the solution of the spatial integral equation.
K e y   w o r d s : magnetic field, defect, computational domain.

INTRODUCTION

The simplest method of calculating the stray magnetic fields of the defects is a reference density of fictitious magnetic charges on the surface of their walls followed by calculation of the field on the analytical dependence [2, 13, 14, 15]. This method has several disadvantages. These include the following: density fictitious charges on the surface of defects is given a uniform and is calculated by semi-empirical formulas, leading to considerable error, moreover, in addition to fictitious surface magnetic charge in the vicinity of the defect volume include magnetic charges significant contribution to the magnetic field distribution in the defect. Therefore there is a need to find a method that provides a more accurate calculation of the magnetic stray field of the defect, which is important because by parameters of the magnetic field distribution the means are chosen, which measure the field and form the initial information about it.

MATERIALS AND METHODS

Promising in respect the calculation of the magnetic fields of defects is the method of integral equations [11, 17, 20, 23], which gives the opportunity to calculate the magnetization vector field in the local region containing the defect, and then determine the magnetic stray field defects such as discontinuities of metal. In a number of publications [10, 21, 22, 24] contains information about the used integral equations for calculating the defect fields.

A significant obstacle to the widespread use of the method of integral equations in the field of calculation of defect fields of ferromagnetic products is the uncertainty of the volume limits of the magnetized region, which is a defect. This uncertainty makes it necessary for the implementation of the method of calculation of the field defect of the numerical solution of the integral equation split into elementary volumes of the entire piece, while the defect takes insignificant of its volume. In some cases, the volume containing defect is cut out from the detail and placed in a uniform magnetic field and calculated the

scattering field of the defect together with the field of the selected volume. The magnitude of the magnetizing strength of a uniform magnetic field is connected indirectly with the field strength of real magnetizing field source.

Therefore, for the effective application of the method of integral equations for the calculation of the magnetic stray field of the ferromagnetic part of the defect, we need a method that allows reasonably limit the ferromagnetic region of space in which there is a defect. It is dedicated to the real work.

Development of a method to limit the space of a ferromagnetic region in which the defect is located when calculating its magnetic leakage field by the numerical method of solution of the integral equation. Flaw detection of ferromagnetic production is performed in the applied and the residual magnetic fields. Is considered that if the article material has a coercive force of less than 1500 A/m [3, 5, 15] inspection of defects is advantageously carried out in an applied magnetic field, the magnetization and field measurement in the field of the defect with transmitter (ferroprobes, Hall sensor) to perform the same time. Inspection of defects in the residual field is made by the magnetization of part of the product or the entire product to a state close to saturation, then the source of the magnetic field is turned off, and the product is controlled by the residual magnetization.

The applied field does not lead to saturation of the material and for the calculation of the normal component of the magnetization vector on the surface of the product is used surface integral equation [19, 24]:

$$\sigma(Q) - \frac{1}{2\pi}\lambda \oiint_{S} \sigma(P)\frac{cos\left(\overline{r}_{QP},\overline{I}_{nQ}\right)}{r_{Qp}^{2}}dS_{P} = \tag{1}$$
$$= 2\mu_0\lambda H_{CTn}(Q),$$

wher: $\lambda = \dfrac{\mu - 1}{\mu + 1}$,

$r_{QP} = \sqrt{\left(x_P - x_Q\right)^2 + \left(y_P - y_Q\right)^2 + \left(z_P - z_Q\right)^2}$,

$x_P, y_P, z_P, x_Q, y_Q, z_Q$ − coordinate points of P and Q,

H_{CTn} − normal component of the vector of the magnetizing (probing)field $H_{CTn} = \overline{I}_{nQ}H_{CT}$,

S − complete surface of the part and defect,

μ − relative magnetic permeability.

(Equation 1) for numerical solution has a bad convergence, because $\lambda \approx 1$, that's why while solving it different methods of regularization are used [6, 8, 18].

If you do not take into account the impact of the defect, then under the influence of the field of the magnetizing device fictitious magnetic charges appear on the surface of the product which equal to:

$$\sigma_{\phi}(Q) = 2\mu_0\lambda H_{CTn}(Q), \tag{2}$$

as on an infinitely smooth flat part $\overline{R}_{QP} \perp \overline{I}_n$ and integral in equation (Eq. 1) equals zero.

The proposed method for isolating the defect is as follows. Around the defect rectangular area S_U is allocated, which has the density of charges $\sigma_{\phi}(Q)$, which creates a magnetic field directly on the surface of the defect equal:

$$\overline{H}_{\phi} = \frac{1}{4\pi}\int_{S_U}\frac{\sigma_{\phi}\cdot\overline{I}_{r\partial}}{\left|\overline{r}_u - \overline{r}_{\partial}\right|^2}dS, \tag{3}$$

where: $\overline{I}_{r\partial}$ − a unit vector directed from a point on the workpiece U, to the point on the surface of defect ∂,

$\overline{H}_{\phi}$ − the vector of the magnetic field created by surface fictitious magnetic charges.

For a geometric model shown in Fig. 1, equation (Eq. 1) can be rewritten as:

$$\sigma(Q) = \frac{1}{2\pi}\lambda \oiint_{S_{\partial}} \sigma(P)\frac{cos\left(\overline{r}_{QP},\overline{I}_{nQ}\right)}{r_{Qp}^{2}}dS_P +$$
$$+ \frac{1}{2\pi}\lambda \oiint_{U_{\partial}} \sigma_{\phi}(P)\frac{cos\left(\overline{r}_{UP},\overline{I}_{nQ}\right)}{r_{Up}^{2}}dS_U + 2\mu_0\lambda H_{CTn}(Q), \tag{4}$$

where: S_{∂} − surface of the defect.

The numerical solution of (Eq. 4) gives the density of the fictitious magnetic charges

in the centers of the elementary areas. Then, according to the formula (Eq. 3) wherein σ_Φ is replaced by $\sigma(Q)$, magnetization vector of leakage field of the defect is calculated.

After calculation values of functon $\sigma(Q)$ space S_U receives an increment ΔS_U and again determined by the value of $\sigma(Q)$. The process of increasing the area S_U is as long as not fulfilled the condition:

$$\left| \sigma^{n+1}(Q) - \sigma^n(Q) \right| < \sigma^n \varepsilon, \qquad (5)$$

wher: ε – given small number.

Condition (Eq. 5) means that the value S_U with a simple layer of fictitious magnetic charges located on it will cease to influence the distribution of the charge density on the surface of the defect.

Mathematical model of the magnetization vector field in a nonlinear medium. Calculation of the magnetic leakage field of the defect in the residual magnetization requires the calculation of the magnetization vector field in a nonlinear medium by numerical solution of the integral equation of the spatial.
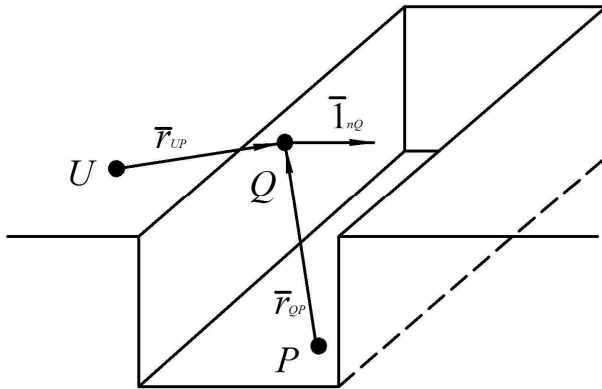

Fig. 1. The geometric model of the defect and the limited plane of the article

The numerical solution is carried out by dividing the area occupied by ferromagnetic materials for elementary volumes (EV). In this case, the spatial integral equation reduces to a system of algebraic equations [4, 12, 15]:

$$\bar{H}_i = -\frac{1}{4\pi} \sum_{j=1}^{N} \sum_{k=1}^{6} \left(\bar{M}_j \bar{1}_{nj} \right) \int_{S_{kj}} \frac{\bar{R}_{ij}}{\bar{R}_{ij}^3} dS_{kj} + \bar{H}_{CT.i}, \qquad (6)$$

$$i = \overline{1, N_1}, j = \overline{1, N},$$

where: i, j – observation point and the source,

$$\left| \bar{R}_{ij} \right| = \left| \bar{R}_i - \bar{R}_j \right| = \sqrt{\left(x_i - x_j \right)^2 + \left(y_i - y_j \right)^2 + \left(z_i - z_j \right)^2},$$

$\bar{1}_{nj}$ – the unit vector normal to the surface j-th EV, $\bar{H}_{CT.i}$ – vector of the external magnetic field at the center *i*-th EV.

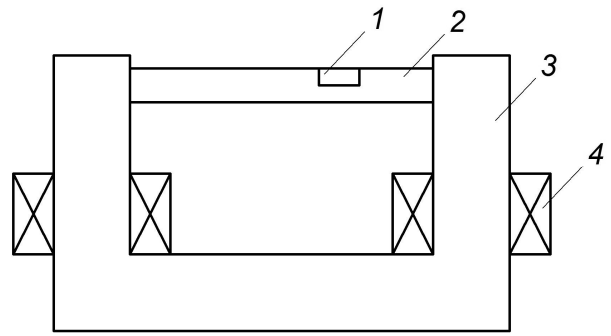It's considered a variant of when the product is magnetized in a closed magnetic circuit (Fig. 2).

Fig. 2. Simplified design of the magnetizing device: 1 – the area of the defect, 2 – controlled part, 3 – magnetic, 4 – reel

When testing the items in a closed magnetic circuit magnetization of the product is equals the residual magnetization M_r. If the control part takes place outside of the magnetic circuit, the magnetic state of the circuit depends on the demagnetization factor modulated by volume. To determine the magnetization at the location of the defect it's necessary to calculate the demagnetization factor in volume adjacent to defect.

Demagnetization factor is calculated for each EV. It is assumed that the product is placed in a sided uniform magnetic field, and the direction of the magnetization vector coincides with the axis of the product. The magnetization of each EV is calculated by numerically solving the system of equations (Eq. 6). As a result of solution we find values M_{xi}, M_{yi}, M_{zx}, as well as the components of the tension field demagnetization H_{pxi}, H_{pyi}, H_{pzi} according to formula:

$$\bar{H}_{pi} = -\frac{1}{4\pi} \sum_{j=1}^{N} \sum_{k=1}^{6} \left(\bar{M}_j \bar{1}_{nj} \right) \int_{S_k} \frac{\bar{R}_{ij}}{\bar{R}_{ij}^3} dS_{kj}. \qquad (7)$$

The known values of the components of the magnetization vectors and field intensity degaussing make it possible to calculate the demagnetization coefficients in each EV. Introduce the concept of vector demagnetization coefficient for each i-th EV, which is written in a rectangular coordinate system in such way:

$$\bar{N}_i = \bar{I}_{xi} N_{xi} + \bar{I}_{yi} N_{yi} + \bar{I}_{zi} N_{zi},$$
$$N_{xi} = \frac{H_{pxi}}{M_{xi}}, N_{yi} = \frac{H_{pyi}}{M_{yi}}, \ N_{zi} = \frac{H_{pzi}}{M_{zi}}. \quad (8)$$

The magnitude of vector $\bar{N}$ is determined by the external field strength, which provides the maximal value of the magnetic permeability of the ferromagnetic material.

The known values of demagnetization allow finding the magnetic field inside the product $\bar{H}$ with certain external field intensity $\bar{H}_{CT}$ according to the formulas:

$$N_x = \frac{\bar{H}_{CTx}}{1 + N_x \chi}, \ N_y = \frac{\bar{H}_{CTy}}{1 + N_y \chi}, \ N_z = \frac{\bar{H}_{CTz}}{1 + N_z \chi}, \quad (9)$$

where: χ – magnetic susceptibility of the material.

By solving the system of equations:

$$M = M(H), \ M = -(1/N)H, \quad (10)$$

the residual magnetization is found for each EV. Next is illustrated by the following example.

The hysteresis loop of the magnetic material in the second quadrant is approximated by a parabola of the form $M(H) = -aH^2 + b$.

Values a and b are found from condition: at $H = 0$, $M = M_c$, at $M = 0$, $H = H_c$, which implies:

$$M = \frac{M_r}{H_c^2} H^2 + M_r. \quad (11)$$

Dependence (Eq. 10) equates the linear function $M = -mH$, where m – permeability form, $m = 1/N$, resulting in a quadratic equation:

$$\frac{M_r}{H_c^2} H^2 - mH - M_r = 0. \quad (12)$$

The solution (12) is analytical relations:

$$H_1 = \frac{m - \sqrt{m^2 + \dfrac{4M_r^2}{H_c^2}}}{2M_r / H_c^2}, M_1 = -m \frac{m - \sqrt{m^2 + \dfrac{4M_r^2}{H_c^2}}}{2M_r / H_c^2}. (13)$$

Equation of the form $H = -mf(H)$ is solved by iteration practically at any approximation curve of the hysteresis loop in the second quadrant.

With the known values of the coefficient of demagnetization $\bar{N}_i$ for each i-th EV according to known values $\bar{H}_{CT}$ it's possible to find the magnetization in each N of EV. For this it is necessary to solve the following three non-linear equations:

$$m_x (H_{CTx} - H_x) = M(H), m_y (H_{CTy} - H_y) = M(H),$$
$$m_z (H_{CTz} - H_z) = M(H).$$

Here $M(H)$ is a function of magnetization.

Solving these equations gives the values of the constituent vectors $\bar{H}_i$ and $\bar{M}_i$ in ferromagnetic material at known value $\bar{H}_{CT}$ in each i-th EV.

When calculating the stray magnetic field in the closed magnet system the module of magnetization vector equals M_c, direction of magnetization vector coincides with the axle of a detail, the area around the defect as a parallelepiped, whose dimensions along the x axis by an order exceeds the size of the defect, and the axes y, z – 5 times (Fig. 3). The selected volume is divided into N EV.

At the ends of the selected volume placed EV whose length tends to infinity. Their quantity equals T. It's considered that magnetization in infinitely long EV equal M_r.
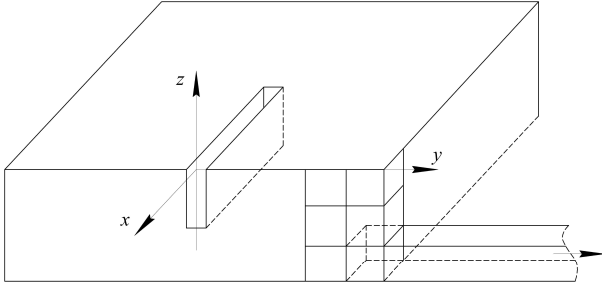
Fig. 3. Isolation of the subregion in the amount of controlled products

Simulating a closed magnetic circuit is performed by connecting to the subdomain EV of infinite length which contains defect. In the absence of a defect fictitious magnetic charges on the faces of the adjacent EO compensate each other, as a result the demagnetization field is missing and $H=H_{CT}$ (Fig. 4).
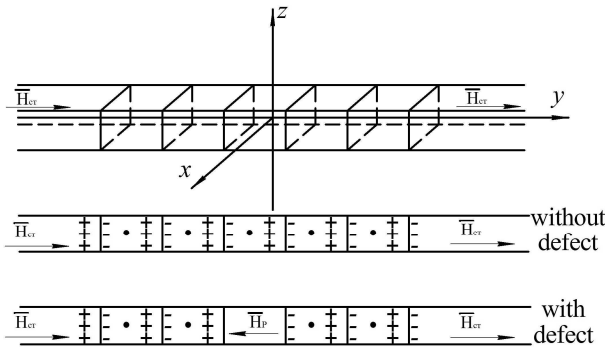

Fig. 4. Simulation of a closed magnetic system

If a defect arises degaussing field strength $\bar{H}_p$, which reduces the external magnetic field adjacent to the defect in the EV.

In the formula (Eq. 6) the integration is over the faces (planes) EV, so:

$$\left| \bar{r}_i - \bar{r}_j \right| =$$
$$= \sqrt{\left(x_i - x_j \pm \Delta x_j \right)^2 + \left(y_i - y_j \pm \Delta y_j \right)^2 + \left(z_i - z_j \pm \Delta z_j \right)^2}. \tag{14}$$

In (Eq. 14) the sign in front Δx, Δy, Δz selected in accordance with the face on which the integration is performed. For EV infinite length $y_i \to \infty$; $\Delta y \to \infty$ (Fig. 5).

Therefore, the point t is transferred to the center of an infinitely long edge of EV which faces the selected volume with defect.

Consequently, for the edges of EV of infinite length can be written:

$$\left| \bar{r}_i - \bar{r}_j \right| = \sqrt{\left(x_i - x_t \right)^2 + \left(y_i - y_t \right)^2 + \left(z_i - z_t \right)^2}.$$

For the calculation of the field in the selected volume in the mode of the external field $\left(\bar{H}_{CT} = 0 \right)$, (Eq. 6) is rewritten as:

$$2\pi \bar{H}_i = -\sum_{j=1}^{N} \sum_{k=1}^{6} \left(\bar{M}_j \bar{I}_n \right) \int_{S_k} \frac{\bar{I}_r}{\left| \bar{r}_j - \bar{r}_i \right|^2} dS_k +$$
$$+ \sum_{t=1}^{T} \left(\bar{M}_{rt} \bar{I}_n \right) \int_{S_t} \frac{\bar{I}_r}{\left| \bar{r}_t - \bar{r}_i \right|^2} dS_t. \tag{15}$$

Thus, in (Eq. 15) the field source is magnetized volume of ferromagnetic material with the magnetization M_r. System of equations (Eq. 15) is solved iteratively. Start of iterations should be done with the value $M_1 = M_r$.

After determination of M_1 values of M_1 are compared in EV, located at the border of the selected subdomain, which contains defect with the value M_r according to the formula: $M_1 = M_r$.
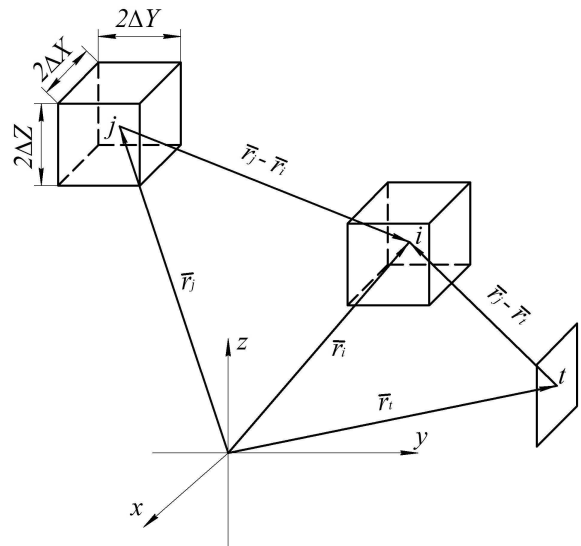

Fig. 5. To solving the system of equations (Eq. 15)

If this inequality is not satisfied, there is an expansion in subdomain containing the defect, by the amount $2\Delta x$, $2\Delta y$, $2\Delta z$ and calculation of magnetization is repeated.

When calculating the stray magnetic field defects in the product, which is out of the magnetizing device, it is also allocated the region in the vicinity of the defect. Outside this region, the magnetization is determined by solving the system of equations (Eq. 10) and the definition of the vector demagnetization factor for the EV. The equations are solved:

$$H_x = -N_x M(H), H_y = -N_y M(H),$$
$$H_z = -N_z M(H) \quad (16)$$

relatively to H_x, H_y, H_z values M_{1x}, M_{1y}, M_{1y} are determined. This value of the magnetization takes place in an infinitely long EV. The system of equations (Eq. 15), where M_{1t} is used instead of M_{rt} is solved. With these values of the magnetization begins an iterative process of solving a system of algebraic equations (Eq. 15). As a result of solutions are used vectors $\bar{M}$ in each EV of subdomain. After that the procedure of comparing the magnetization on the boundary of subdomain is held. If the inequality is satisfied for $|M_1 - M| \le M_1 \varepsilon$, where ε – given small number, then expansion of the defect at value $2\varDelta x$, $2\varDelta y$, $2\varDelta z$ begins.
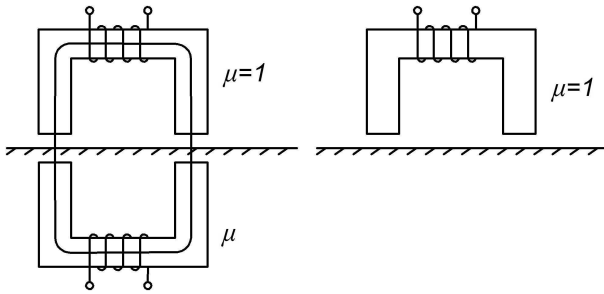

Fig. 6. Calculation of the field by mirror images (Searle basis): a – calculated magnetic scheme in air, b – the design scheme of the magnetic system in a ferromagnetic material

Mathematical model of the magnetization vector in locally magnetized region containing the defect. Calculation of the magnetic stray field of the defect is divided into two stages. On the first stage is a preliminary calculation of the field in a ferromagnetic material on the basis of Searle [1, 7, 9, 16]. As a result of the calculation

performed in the first stage, pre-determined area in which the magnetization vector module exceeds a preset value M_c.

By the method of calculation of the magnetic circuit is calculated field strength in the air and magnetizable material Fig. 6. In the equivalent magnetic circuit:

$$Iw_3 = \frac{\mu - 1}{\mu + 1} Iw, \ R_C = R_{C3} = \frac{l_C}{\mu_0 \mu(H) S_C},$$

where: Iw – magnetizing force of the magnetic circuit,
R_C – the reluctance of the core.

The magnetic flux in the magnetic circuit is:

$$\varPhi = \frac{Iw + Iw_3}{2R_C + R_B} = \frac{Iw + Iw_3}{\frac{2l_C}{\mu_0 \mu(H) S_C} + \frac{2l_B}{\mu_0 S_C}},$$

where: R_B – the reluctance of the air gap at twice the length $R_B = 2l_B / (\mu_0 S_C)$.

The flux is calculated using an iterative method depending $M(H)$. The calculated value of the magnetic flux allows finding induction and the magnetization of the core $B_C = B_B = \varPhi / S_C$, $M = B_C / \mu_0 - H$.

In the second phase calculation of the field is held by the method of the numerical solution of the integral equation in the highlighted area in the first phase, which is divided into EV. The area is complemented with EV of infinite length (Fig. 7), which have a magnetization equals $\bar{M}_t = \chi \bar{H}_{CT}$, wher: χ – the average value of the magnetic susceptibility, $\bar{H}_{CT}$ – the vector of magnetic field strength of magnetizing device.

The system of algebraic equations corresponding to the integral equation takes the form:

$$H_i = -\frac{1}{4\pi} \sum_{j=1}^{N} \sum_{k=1}^{6} (\bar{M}_j \bar{I}_n) \int_{S_k} \frac{\bar{I}_r}{|\bar{r}_j - \bar{r}_i|^2} dS_k +$$
$$+\bar{H}_{CT} + \sum_{t=1}^{T} (\bar{M}_t \bar{I}_{nt}) \int_{S_t} \frac{\bar{I}_{ir}}{|\bar{r}_t - \bar{r}_i|^2} dS_t. \quad (17)$$
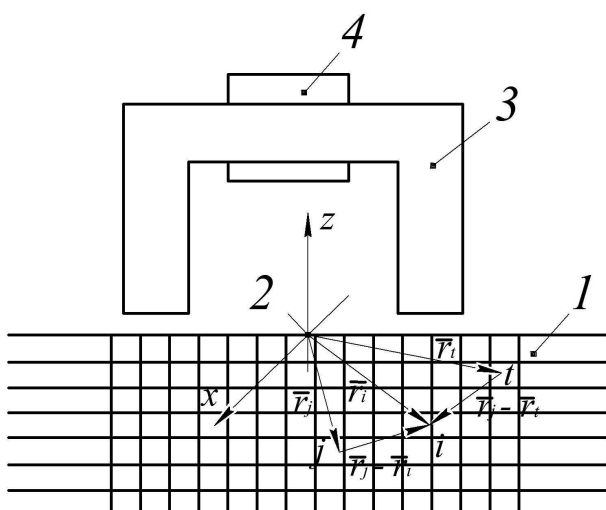
Fig. 7. The magnetizer of local type: 1 – controlled product, 2 – defect, 3 – magnetic circuit, 4 – inductor

The solution of the system (Eq. 17) is the value of the magnetization in each *i*-th EV. Equation (Eq. 17) is solved with the geometry of the defect, located in the subdomain.

After determining values $\bar{M}_i$ in EV, adjacent to the boundary of subdomain, there is a comparison $\bar{M}_i$ with the value $\bar{M}_t$ in accordance with the following relationship:

$$\left| M_t - M_i \right| \le M_t \varepsilon. \qquad (18)$$

If the direction (Eq. 18) is not satisfied, expansion occurs in subdomain in the direction of vector $\bar{H}_{CT}$ for one linear dimension of EV and the whole calculation of the field vector $\bar{M}_i$ is repeated again.

Known values $\bar{M}_i$ and $\bar{M}_t$ allow the calculation of the magnetic field vector of the scattering defect according to formula (Eq. 16), in which $\bar{H}_{CT} = 0$.

Equal importance is normal component of the magnetization on the surface of the poles of the core of the magnetizing device facing the plane of the controlled product. To calculate the field created by the poles in a ferromagnetic medium, it is necessary instead of M in the formula for the calculation of the field substitute $M' = M \cdot 2 / \left(\mu + 1 \right)$.

Calculated values $\bar{M}_i$ correspond to the applied magnetic field at the included current

in the windings of the magnetizing device and allow you to find the magnetization vectors of the demagnetization factor for each EV according to formulas (Eq. 8).

Furthermore, by solving the nonlinear equations (Eq. 16) found the values of the vector $\bar{M}_i$ at the disconnected and remote field of verification of magnetizing device. The known values of the magnetization vector components make it possible to calculate the magnetic stray field of the defect.

CONCLUSIONS

1. Closed surface of the ferromagnetic part, on which the defect of "crack type" in the calculation of the magnetic field, its scattering the method of numerical solution of the integral equation can be restricted to the local rectangular platform with a simple layer of magnetic charges.

2. In the calculation of the field defect in nonlinear ferromagnetic medium proposed to localize the area surrounding the defect, by the introduction of infinitely long elementary volumes.

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МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ МАГНИТНЫХ ПОЛЕЙ РАССЕЯНИЯ ДЕФЕКТОВ ФЕРРОМАГНИТНЫХ ИЗДЕЛИЙ

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Аннотация. Предложен метод ограничения области, занятой ферромагнитным материалом, содержащей дефект типа "трещина", при расчете магнитного поля рассеяния дефекта методом интегральных уравнений. Рассмотрены два варианта ограничения: при численном решении поверхностного интегрального уравнения и при решении пространственного интегрального уравнения. Ограничение области расчета производится путем использования элементов бесконечной длины, которыми охватывается область.

Ключевые слова. Магнитное поле, дефект, область расчета.