# NUMERICAL INVESTIGATION OF LOCAL CIRCULAR MAGNETIZATION OF ROUND ROLLED METAL IN MAGNETIC TESTING

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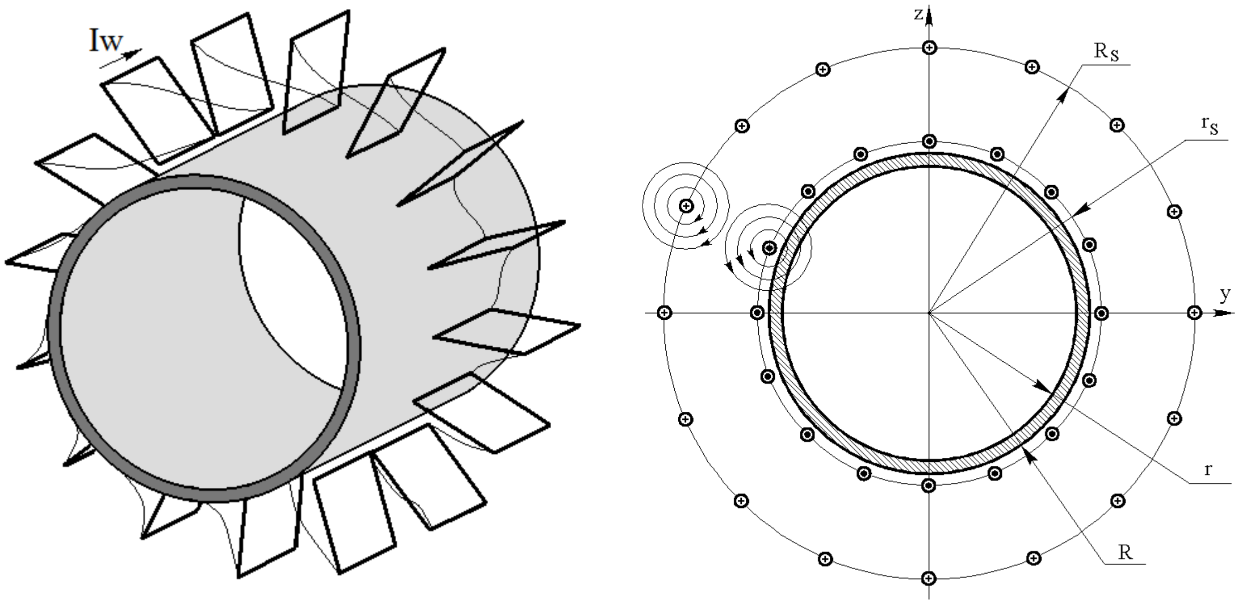
A number of difficulties arises under development of nondestructive testing devices for a magnetic inspection of continuous cylindrical products like a rod, a pipe, etc. One of the difficulties is the design of devices for circular magnetization of such products in a machine unit. The circular magnetization of a stationary product is usually created by an electric current passing through it along the axis. This technique is not applicable for the magnetization of nonstop moving products, e.g. rolled metal, due to difficulties caused by a need to provide a reliable electrical contact. That is why one sometimes applies pole magnetization with the aid of an electromagnet as alternative for the inspection of such products. It is necessary to create the same magnetization conditions in any part of a cross-section perimeter for the complete product testing. It is obvious that passing an electric current is the only way to create a static magnetic field whose lines are closed inside of a product volume. An alternative magnetization way by a system of magnetic poles with an alternating polarity situated near a product surface along its cross-section perimeter may be used. The magnetization is very close to the circular one in regions between the neighbor poles with the different polarities. An axially oriented defect prevents from a magnetic flux passage significantly in such regions of the locally-circular magnetization. But magnetic flux lines are perpendicular to the product surface near the poles that results in an appearance of regions with low quality of detection of such a defect. In order to ensure the same defect detection quality along the product perimeter a magnetic system of the testing device should consist of several units of the same type which are rotated relatively to each other to provide the locally-circular magnetization regions to be overlapped. There is a lot of technical implementations of such magnetization systems, e.g. a multi-pole electromagnet, a system consisting of several attachable saddle shaped solenoids placed in a regular manner, etc.

A toroidal magnetic system consisting of several thin rectangular coils of wire placed on a toroid surface regularly was proposed in the articles [1, 2] for the creation of the locally-circular magnetization regions. However, an influence of the ferromagnetic test product was not taken into account in a field analysis. With other words the researches was aimed at generating the magnetizing field with prescribed properties, but the process of the product magnetization was not considered.

The purpose of our work is an investigation of the process of the continuous cylindrical products magnetization with the aid of the toroidal and multi-pole magnetic systems designed to generate the locally-circular magnetizing field. A magnetic field of nondestructive testing devices is calculated using software designed by authors [3-7]. The software takes into account a geometrical shape of a test product, nonlinear material properties and a field profile for magnetization. This software is based on the volume integral equations method which allows also taking into account peculiarities of testing problems: nonuniform nonlinear magnetic properties of a ferromagnetic material, multi-connected regions with a ferromagnetic product, subsurface arbitrarily shaped defects as well as surface ones. Simulation results can be used for nondestructive testing devices development to increase their efficiency.

More detailed description of the magnetic systems design is given below. The toroidal magnetic system consists of several thin rectangular coils placed in a regular manner relatively to the system axis so that the coils planes contain the axis (see fig. 1). The magnetic system parameters have been chosen for simulation as follows: the radii of inner and outer layers of wire $R_S = 85\ mm$ and $r_S = 55\ mm$, the length $h_S = 50\ mm$, the magnetomotive force of one coil $Iw = 300\ At$. The field of the magnetization system is a sum of the fields generated by the coils. The coil is modeled with $w$ rectangular loops of wire whose sides are placed axially or radially.




a) the general view of the magnetic system b) the parameters of the mathematical model

Fig. 1. The toroidal magnetic system for the locally-circular field creation

There are convenient formulae for description of the magnetic field generated by a current-carrying straight wire of a finite length as those in [1, 2]:

$$a = (x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2;$$

$$b = (x - x_1)(x_2 - x_1) + (y - y_1)(y_2 - y_1) + (z - z_1)(z_2 - z_1);$$

$$c = (x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2;$$

$$G = \frac{1}{4\pi}\frac{1}{ac - b^2}\left(\frac{a - b}{\sqrt{a - 2b + c}} - \frac{b}{\sqrt{c}}\right);$$

$$G_x = z(y_2 - y_1) - y(z_2 - z_1) + y_1 z_2 - y_2 z_1;$$

$$G_y = x(z_2 - z_1) - z(x_2 - x_1) + z_1 x_2 - z_2 x_1;$$

$$G_z = y(x_2 - x_1) - x(y_2 - y_1) + x_1 y_2 - x_2 y_1;$$

$$H_x = IGG_x;\ H_y = IGG_y;\ H_z = IGG_z,$$

where $x_1$, $y_1$, $z_1$ and $x_2$, $y_2$, $z_2$ are the coordinates of the wire ends; $x$, $y$ and $z$ are the observation point; $H_x$, $H_y$ and $H_z$ are the components of the magnetic field strength; $I$ is the current.

A field analysis for the testing of a pipe was carried out. The parameters of the product for simulation: the outer and inner radii of the pipe $R = 51\,mm$ and $r = 47\,mm$; nonlinear material properties are defined as follows [8]

$$M(H) = \chi_i \frac{H_c^2 H}{H^2 + H_c^2} + \frac{M_s}{\pi}\frac{H^2}{H^2 + \alpha H_c^2}\left(\arctan\frac{H_c + H}{H_0} - \arctan\frac{H_c - H}{H_0}\right);$$

$$H_0 = \frac{H_c}{\tan\left(\dfrac{M_r}{M_s}\dfrac{\pi}{2}\right)};\ \alpha = \frac{M_s}{\pi}\frac{\arctan\left(2\dfrac{H_c}{H_0}\right)}{M_c - \chi_i \dfrac{H_c}{2}} - 1,$$

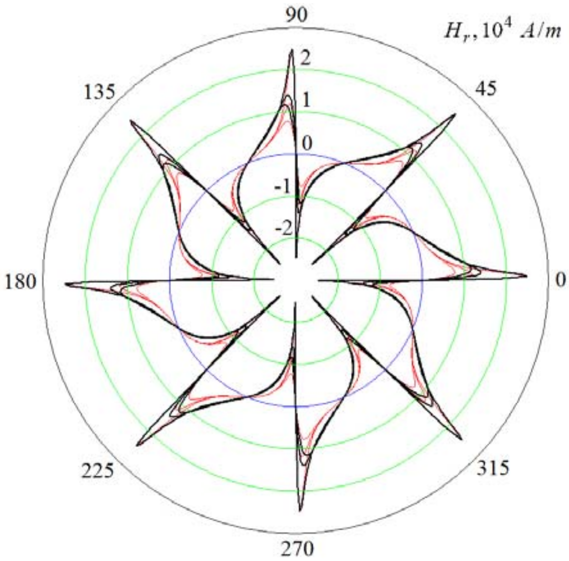
where $H_c$ is the coercivity; $M_s$ is the saturation magnetization; $M_r$ is the remanence; $M_c$ is the magnetization according to main magnetization curve when magnetizing field is equal to the coercivity; $\chi_i$ is the initial magnetic susceptibility (see table 1).

Table 1

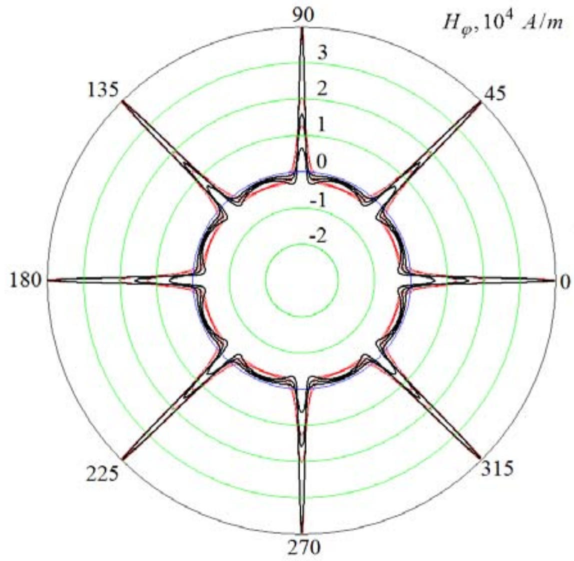
The parameters of the model describing the nonlinear material properties for simulation

| $H_c$, $A/m$ | $M_s$, $A/m$ | $M_r$, $A/m$ | $M_c$, $A/m$ | $\chi_i$ |
|---|---|---|---|---|
| 760 | $1.72 \cdot 10^6$ | $0.97 \cdot 10^6$ | $0.48 \cdot 10^6$ | 89.0 |

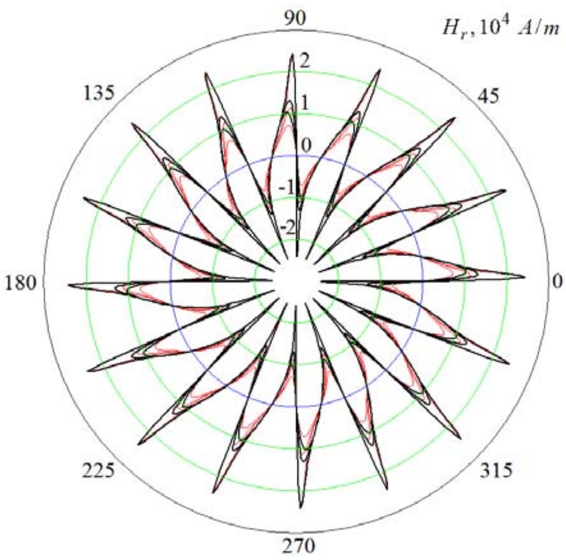
The analysis results of magnetic field at the distance 1, 2 and 3 $mm$ from the pipe surface for magnetization with the aid of the toroidal magnetic systems of 8 and 16 coils are given on fig. 2. The graphs of an angular distribution of radial and circular components of the magnetic field strength are shown on the circular diagrams. The field was calculated for two cases: with the product (thick line graphs) and without it (thin line graphs).



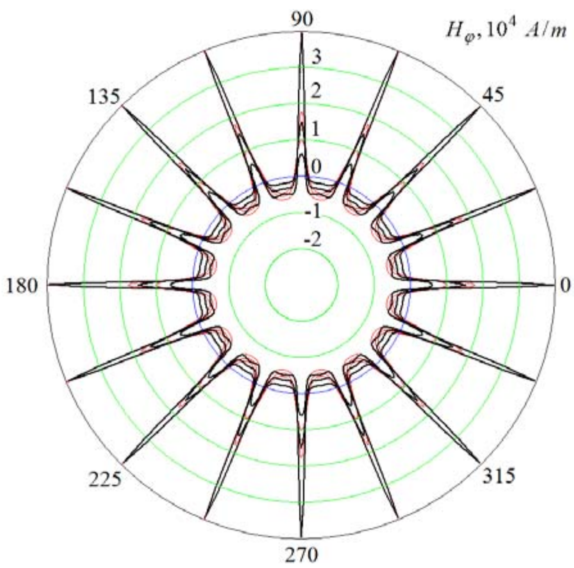

a) the radial component




b) the circular component




c) the radial component




d) the circular component

Fig. 2. The calculation results of magnetic field near the pipe surface in the case of magnetization with the aid of the toroidal magnetic system

As it can be seen on diagrams the absolute values of both components increase when the distance from the pipe surface increases and the distance from the inner layer of the magnetic system decreases. The test product influence becomes essential near its surface while far away from it the thick and thin lines are not distinguished almost. The field distribution is periodical along the perimeter. The radial component changes its sign at the angles matching the magnetic system coils positions, but the circular one has maxima. Thus, the locally-circular magnetization regions are situated closely to coils that may cause difficulties in a registering indicators placement in a testing region.

The multi-pole magnetic system (fig. 3) may be chosen as an alternative.

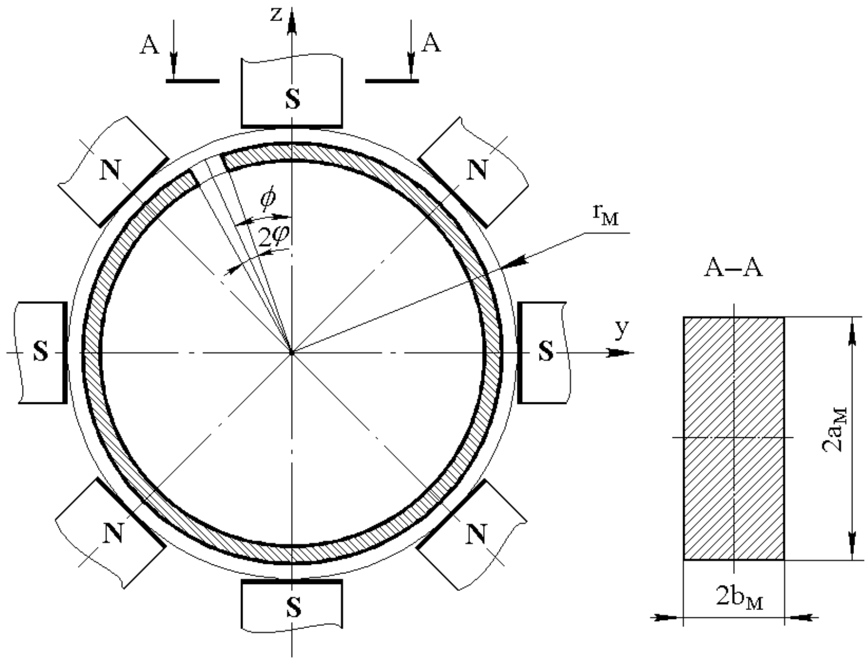
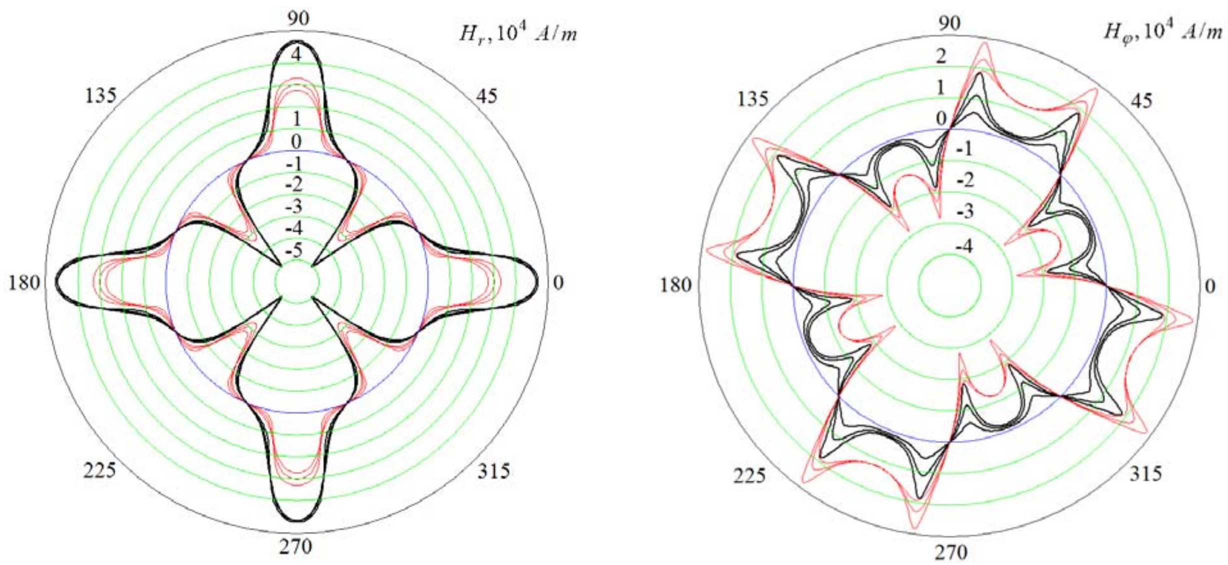



Fig. 3. The multi-pole magnetic system for the locally-circular field creation

The field of such a system is described with a superposition of the poles fields on which a simple layer of magnetic charges of density $\sigma = \pm\mu_0 M$ with an alternating sign is placed. Here $M$ is the magnetization in a magnetic circuit. The rectangular poles of sizes $2a_M \times 2b_M$ are placed along the perimeter of cylindrical surface of the radius $r_M$. The parameters of the magnetic system for simulation: $r_M = 55\,mm$, the pole sizes $2a_M \times 2b_M = 50\times16\,mm$, $M = 70\,kA/m$, the poles pairs number $n = 4$. The analysis results of magnetic field at the distance 1, 2 and 3 $mm$ from the pipe surface are given on fig. 4.




a) the radial component b) the circular component

Fig. 4. The calculation results of magnetic field near the pipe surface in the case of magnetization with the aid of the multi-pole magnetic system

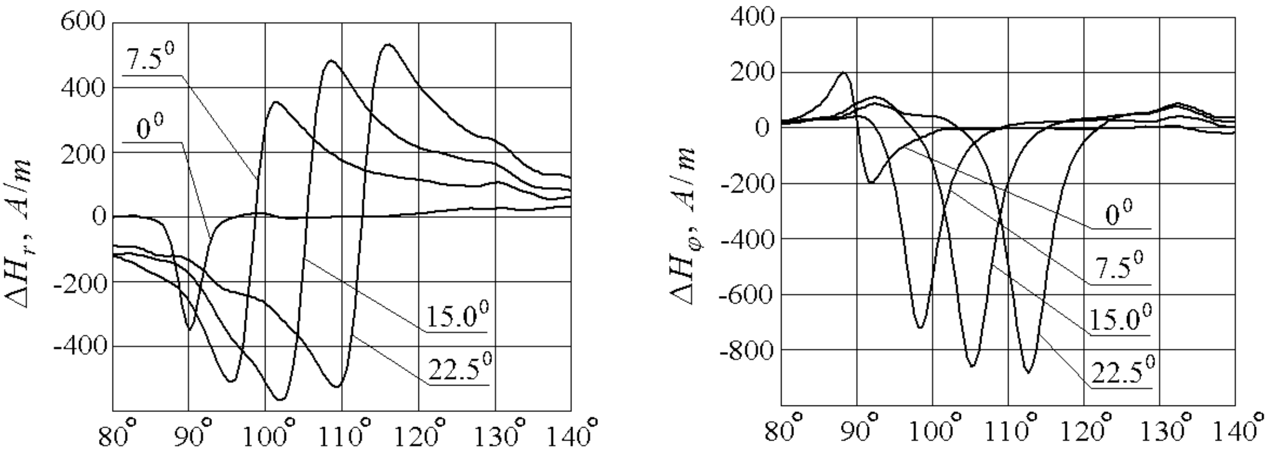
As it is shown on the diagrams the radial component reaches its maxima at poles centers, but the circular one is zero. Hence, the field is almost perpendicular to the product surface near the poles. The locally-circular magnetization regions are between the poles where registering indicators may be placed freely. Increasing the poles pairs number essentially causes a mutual compensation of their fields and as result decreasing the absolute value of the magnetizing field components. Thus, such increasing is not efficient.

It is obvious from simulation results that it is impossible to distinguish the fields of the defect product and the defectless one due to the locally-circular magnetization regions location and their very small sizes that are specific in the case of magnetization with the aid of the toroidal magnetic system. This prevents from a robust defect detection. But the magnetization with the aid of the multi-pole magnetic system is able to provide an enough defect magnetic flux leakage magnitude as it will be shown below.

In order to investigate the defect detectability situated at different angles relatively to the magnetization system the field of the test product with a through axially oriented defect of the length $2a = 40\,mm$ and the opening angle $2\varphi = 1^0$ was analyzed for several cases of a defect allocation relatively to the vertical axis at the angles $\phi = 0^0$, $7.5^0$, $15.0^0$ and $22.5^0$.

A magnetic flux leakage of a discontinuity defect is defined by subtraction the field of the defectless test product from the field of one with a defect: $\Delta H_r = H_r^* - H_r$ and $\Delta H_\varphi = H_\varphi^* - H_\varphi$.

The defect magnetic flux leakage at the distance $3\,mm$ from the pipe surface in the case of magnetization with the aid of the multi-pole magnetic system is given on fig. 5.



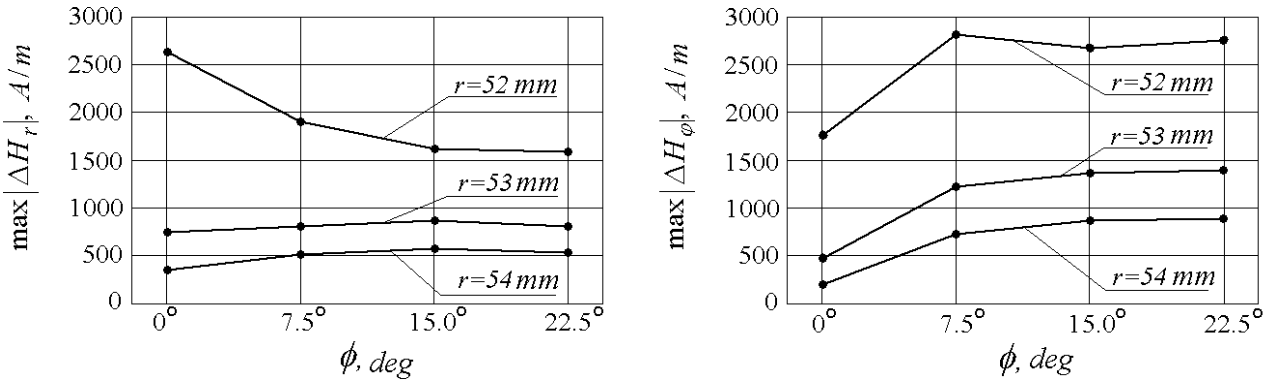

a) the radial component b) the circular component

Fig. 5. The defect magnetic flux leakage for several cases of its allocation relatively to the magnetic system

When $\phi = 0^0$ a defect is situated under the pole of the magnetic system. The magnetizing field is perpendicular to the test product surface; the radial component distribution has an unipolar pulse; the circular component distribution has a bipolar pulse. In the locally-circular magnetization regions ($\phi = 7.5^0$, $15.0^0$ and $22.5^0$) the radial component changes its sign above the defect, but the circular one has bell shaped pulse as well as in the case of circular magnetization by a current.

The graphs of the defect magnetic flux leakage dependence on its allocation angle at different distances from the pipe axis are given on fig. 6. As it is shown on the graphs the magnetic flux leakage magnitude is enough to register it robustly for any position of the axially oriented defect.

Thus, it is proven with simulation results that usage of multi-pole magnetic systems for magnetization in the magnetic testing of round rolled metal is more effective.




a) the radial component b) the circular component

Fig. 6. The maxima of the defect magnetic flux leakage at different angles relatively to the magnetization system

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