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Analysis of the influence of ferromagnetic contaminations in plastics on the measurements of disturbances of magnetic field of the Earth

***Abstract**. Plastics can be contaminated with small particles or filings with ferromagnetic properties. These contaminations cause significant disturbances in the magnetic field in the case of taking measurements of very low magnetic fields. The analysis of the influence of contaminated plastics on magnetic measurements is presented in this paper.*

Streszczenie**. Tworzywa sztuczne mogą być zanieczyszczone objętościowo lub powierzchniowo przez ferromagnetyczne wtrącenia o bardzo małych rozmiarach posiadające właściwości ferromagnetyczne. Wtrącenia te powodują istotne zaburzenia pola magnetycznego w przypadku pomiarów bardzo słabych pól magnetycznych. W pracy przedstawiono analizę wpływu zanieczyszczonych objętościowo tworzyw na wyniki pomiarów pola magnetycznego. **Analiza wpływu ferromagnetycznych wtrąceń w tworzywach sztucznych na pomiary zaburzeń pola magnetycznego Ziemi

Keywords: magnetic field, magnetic dipole, plastics, magnetometer.
Słowa kluczowe: pole magnetyczne, dipole magnetyczne

Introduction

The paper presents an analysis of ferromagnetic intrusions which represent contamination of structural elements of a measurement site for the measurement of very weak magnetic fields, made of plastics, for example for the purpose of measuring the disturbances of the Earth's magnetic field. This is a highly specialized problem and it is related to the development of very sensitive magnetometric systems. So far, the subject has not been analyzed in detail in the subject literature.

The development of a magnetometric system using precise magnetometers requires appropriate materials to be used for the set-up of the measurement site, most often plastics. Objects built of plastic elements not contaminated by ferromagnetic intrusions do not disturb the magnetic field. During the process of production or technological processing of plastics, the material may be contaminated with ferromagnetic materials. The contaminations may occur in the process of extrusion moulding of plastics in steel forms or during mechanical processing in machine tools. A contaminated component made of plastic creates a disturbance in the magnetic field of the Earth. The disturbance is very small, but it may significantly interfere with the measurement of very small changes of the magnetic field. If ferromagnetic contaminant particles are dispersed over the surface of plastic, it is possible and effective to "clean" the plastic using chemical methods [1, 3].

In the paper a simplified model of spatial contamination of plastic has been assumed, whereby ferromagnetic particles are regularly dispersed throughout the plastic material in the form of revolving ellipsoids for which the directions of longitudinal axes are identical.

Object model

The analyzed object is a plastic cube (Fig.1), including ferromagnetic intrusions of differing density, uniformly dispersed throughout the plastic.

The intrusion model accepted in the paper takes the form of small intrusions shaped as revolving ellipsoids (Fig.2), with the dimensions of *a* =100 μm, *e* = 5 , with no constant magnetic charge (coercive field strength equal zero). Fig.3 shows the position of the object in the rectangular coordinate system. The non-dimensional bulk density has been accepted as the volume ratio of ferromagnetic intrusions to the object volume. For intrusion sizes so small and considerable distances between them, it may be assumed that intrusion self-fields do not interact with each other. The analysis of magnetic field disturbance was carried out, based on the assumption that the distance between the magnetic sensor and the object is 20 cm (Fig. 1).

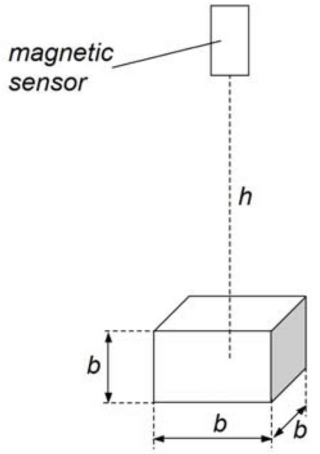

Fig.1. Model object (*b* =15 cm, *h* = 20 cm)

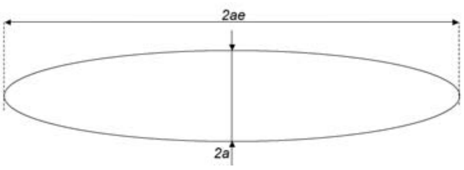

Fig.2. A model of ferromagnetic intrusion (*a* = 100 μm, *e* = 5)

A ferromagnetic intrusion with the proposed shape placed in a uniform magnetic field is subject to induced magnetism, resulting in a disturbance of that field. In the calculations, the intrusion in a shape of a revolving ellipsoid has been treated as a magnetic dipole. Specific components of magnetic induction created by intrusion (a magnetic dipole) are [4]:

$$B_x = \frac{\mu_0}{4\pi r^3}\left(\frac{3R_m(x-x_o)}{r^2} - M_x\right) \tag{1}$$

$$B_y = \frac{\mu_0}{4\pi r^3}\left(\frac{3R_m(y-y_o)}{r^2} - M_y\right) \tag{2}$$

(3) $$B_z = \frac{\mu_0}{4\pi r^3}\left(\frac{3R_m(z-z_o)}{r^2} - M_z\right)$$

where:

(4) $$r = \sqrt{(x-x_o)^2 + (y-y_o)^2 + (z-z_o)^2}$$

(5) $$R_m = (x-x_o)M_x + (y-y_o)M_y + (z-z_o)M_z$$

x_o, y_o, z_o - position of the intrusion (it is assumed that the magnetometer sensor is at the origin of the coordinate system), M_x, M_y, M_z – components of the vector of the magnetic moment.

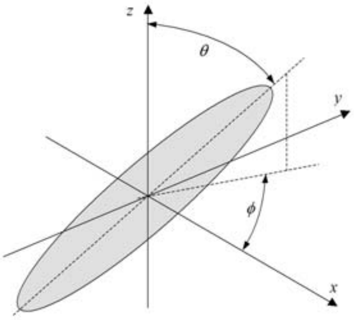

Fig.3. Object location in the rectangular coordinate system

Disturbance of magnetic induction measured with the help of a scalar magnetometer equals:

(6) $$\Delta B_m = |\mathbf{B}_T| - |\mathbf{B}_E|$$

(7) $$\mathbf{B}_E = \begin{bmatrix} B_{xE} \\ B_{yE} \\ B_{zE} \end{bmatrix}$$

(8) $$\mathbf{B}_T = \begin{bmatrix} B_{xE} + B_x \\ B_{yE} + B_y \\ B_{zE} + B_z \end{bmatrix}$$

where: components of the magnetic field vector of the Earth are as follows B_{xE} = 17 μT, B_{yE} = 0 μT, B_{zE} = 47 μT.

The magnetic moment vector in the coordinate system is described by the relationship [4]:

(9) $$\mathbf{M} = \begin{bmatrix} B_{xE}(f_1 + f_{31}\sin^2\theta\cos^2\phi) + B_{zE} f_{31}\cos\theta\sin\theta\cos\phi \\ B_{xE} f_{31}\sin^2\theta\cos\phi\sin\phi + B_{zE} f_{31}\cos\theta\sin\theta\sin\phi \\ B_{xE} f_{31}\cos\theta\sin\theta\cos\phi + B_{zE}(f_1 + f_{31}\cos^2\theta) \end{bmatrix}$$

the shape coefficients of the assumed object are [4]:

(10) $$f_1 = \frac{\mu_D - 1}{1 + A_1\dfrac{\mu_D - 1}{2}}$$

(11) $$f_{31} = f_3 - f_1$$

where:

(12) $$f_3 = \frac{\mu_D - 1}{1 + A_3\dfrac{\mu_D - 1}{2}}$$

(13) $$A_1 = \frac{(e + 0{,}5E)e}{e^2 - 1}$$, (14) $$A_3 = -\frac{2 + eE}{e^2 - 1}$$

(15) $$E = \frac{\ln\left(\left|\dfrac{e - \sqrt{e^2 - 1}}{e + \sqrt{e^2 - 1}}\right|\right)}{\sqrt{e^2 - 1}}$$

where: μ_D - relative magnetic permeability of ferromagnetic intrusion equal 100, *e* = 5.

Results of the numerical analysis

Numerical calculations have been developed for the uniform distribution of ferromagnetic intrusions (magnetic dipoles) with relative intrusion volume ratio of:

(16) $$\rho_{bn} = \frac{n\frac{4}{3}\pi a^3 e}{b^3 - n\frac{4}{3}\pi a^3 e}100\%$$

where: *n* - number of intrusions (*b, a, e* - see Fig.1 and Fig.2).

Calculations performed in MathCad. Fig.4 shows the distribution of ferromagnetic intrusions within the object for *n* = 27. It was assumed in the calculations that the sum total of distance between intrusions along each of the axes is *b* (Fig.1).

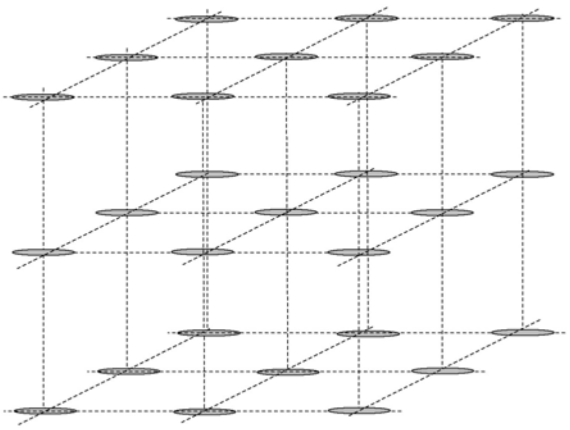

Fig.4. Distribution of ferromagnetic intrusions for *n* = 27

Fig. 5 shows disturbance distribution of magnetic induction module Δ*B* (17) for *n* = 27, and Fig. 6 for *n* = 1331 (for ϕ = 0°, θ = 90° — dipoles situated horizontally along the NS direction).

(17) $$\Delta B = \Delta B_{m\max} - B_{m\min}$$

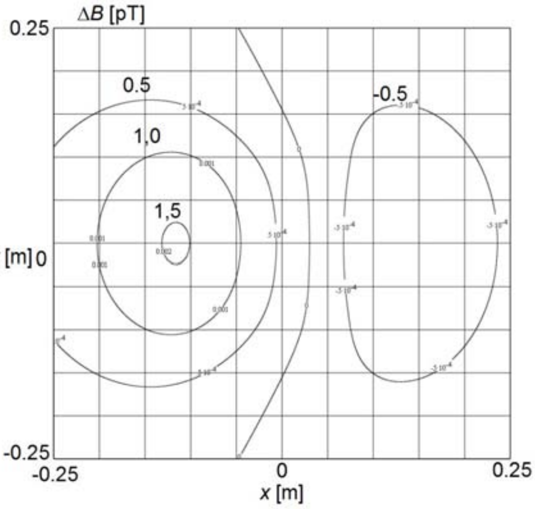

Fig.5. Disturbance distribution of magnetic induction module Δ*B* (2) for *n* = 27 at the sensor position of (*z* = 0.2 m, Fig. 1, ϕ = 0°, θ = 90° - dipoles situated horizontally along the NS direction)

Fig.7 and Fig.8 show, respectively, disturbance distributions of magnetic induction module Δ*B* for *n* = 27 and for *n* = 1331, for dipoles situated along the WE direction (for ϕ = 90°, θ = 90°). In this case the disturbance of the magnetic field is characterized by one extreme, which is considerably stronger than the other extreme. At the same time, disturbance values are almost twice as low as the disturbance for the NS dipole direction.

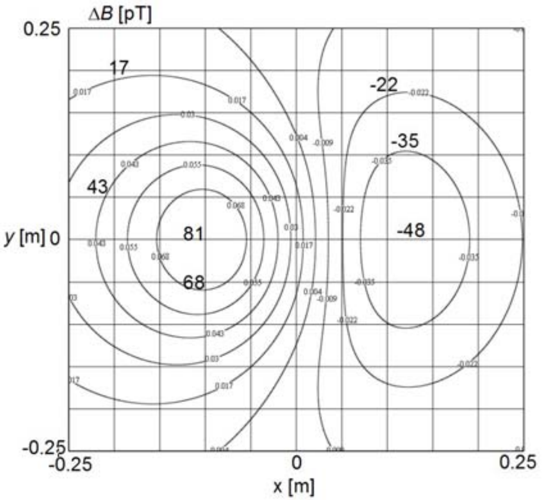

Fig.6. Disturbance distribution of magnetic induction module ΔB (2) for n = 1331 (ϕ = 0°, θ = 90° — dipoles positioned horizontally NS)

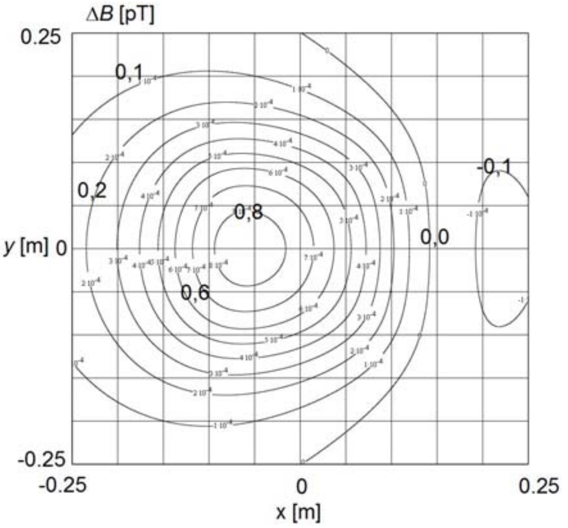

Fig.7. Disturbance distribution of magnetic induction module ΔB (2) for n = 27 (ϕ = 90°, θ = 90° — dipoles positioned horizontally WE)

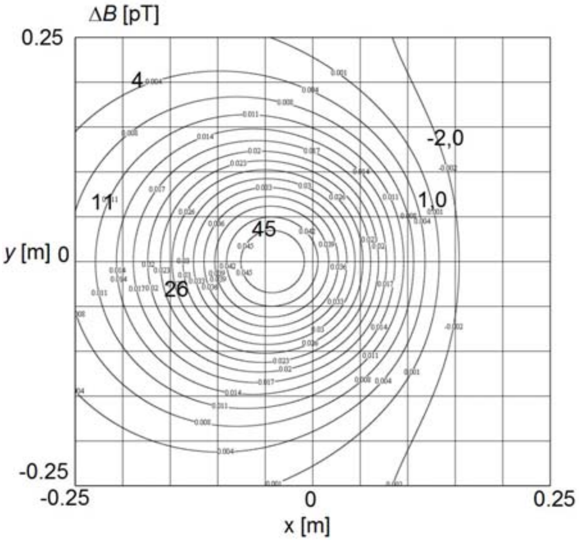

Fig.8. Disturbance distribution of magnetic induction module ΔB (2) for n = 1331 (ϕ = 90°, θ = 90° — dipoles positioned horizontally NS)

Fig.9 shows the relationship between magnetic induction disturbance and relative density of ferromagnetic intrusions, for various positions relative to the direction of the Earth's magnetic field. For the largest accepted number of intrusions at the equivalent relative density of $\rho_{bn} \approx 0.83{\cdot}10^{-3}$% the disturbance is about 375 pT (for dipole direction consistent with the Earth's magnetic induction vector). If the direction of intrusions (dipoles) is perpendicular to the $\mathbf{B}_E$ vector, the value of the disturbance is 123 pT (for ϕ = 90°, θ = 70°). When measuring the Earth's magnetic field with two scalar G823A magnetometers, it is possible to achieve measurement sensitivity at the level of 10 pT [2]. The analysis indicates that even trace levels of ferromagnetic intrusions present in a plastic element used in the construction of a magnetometric system may cause disturbances whose impact will significantly influence the result of measuring very weak magnetic fields.

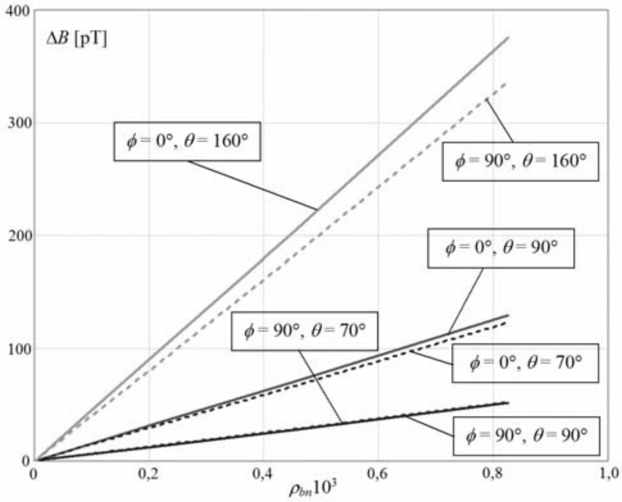

Fig.9. Relationship between the disturbance of magnetic induction module and the relative intrusion volume density.

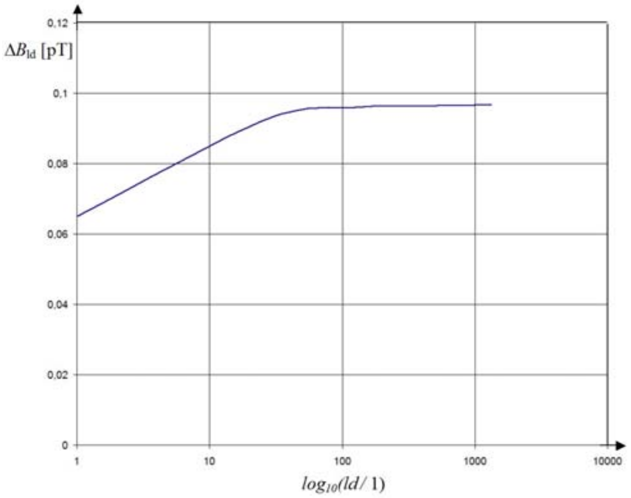

Fig. 10. Relationship between magnetic induction module disturbance per number of intrusions, depending on the number of intrusions—(ϕ = 0°, θ = 90° — intrusions (dipoles) situated horizontally at the NS axis).

Fig.10 shows the relationships between magnetic field disturbances and the number of ferromagnetic intrusions inside the plastic, relative to the number of intrusions:

$$\Delta B_{ld} = \frac{\Delta B}{n} \tag{18}$$

As shown, for the number of intrusions exceeding 27, the relationship becomes practically represented by a flat line. Thus, the relationship between the value of magnetic field disturbance (17) and relative intrusion volume density (Fig.9) is linear. If intrusion dimensions increase twice, the magnetic field disturbance will increase approximately 8-times. Correspondingly, for dimensions two times smaller, the disturbance is 8 times smaller. Fig.11 shows an example of an item made of plastic (bakelite) with no metal components. It is an anti-infantry mine (type PMA-1) with the following dimensions: length - 140 mm, width - 50 mm, height - 30 mm. It is hard to detect with typical metal detectors. Measurements made with a magnetometric differential system [2] using scalar G823A magnetometers, indicated a significant value of disturbance to the Earth's magnetic field, at the level of about 1300 pT (Fig.12).

Fig. 11. The PMA-1 anti-infantry mine made of bakelite

Measurements were made over the mine, at the distance of 20 cm. The readings indicated that the bakelite was contaminated with ferromagnetic intrusions.

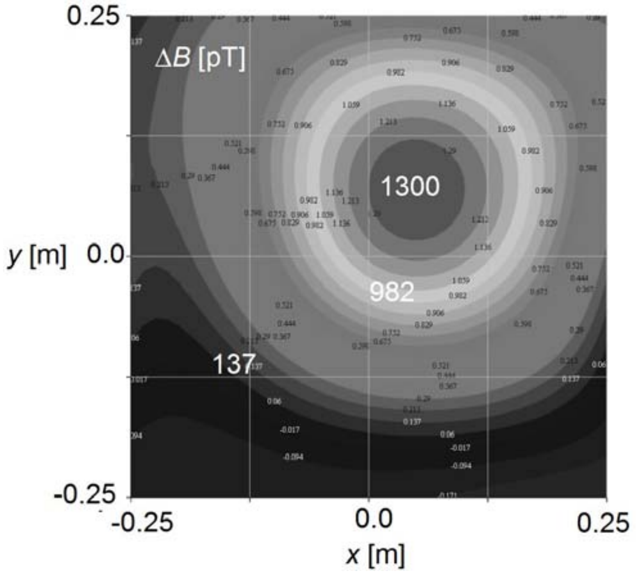

Fig. 12. Distribution of disturbances of the Earth's magnetic field measured over a PMA-1 mine.

Conclusions

The paper presents an analysis of the impact of very small-size ferromagnetic intrusions in the ~~object~~ element made of plastic on the results of measurements of the Earth's magnetic field. The analysis has shown that plastics contaminated with small ferromagnetic intrusions may significantly disturb the results of measurements of very weak magnetic fields. This is of specific importance when materials need to be selected for the construction of a magnetometric system in which precise magnetometers are used, e.g. optically-pumped or SQUIDs. In the case of materials contaminated with intrusions included within the material, their use for the construction of a magnetometric system is not recommended. An example of such a material is textolite [1, 3]. When an element made of plastic with no ferromagnetic contaminations is mechanically processed with tools made of steel, this results in contamination of the material surface with ferromagnetic intrusions. In this case a special chemical treatment technology can be used to remove the intrusions, i.e. clean the surface of the contaminated material [3]. Experimental studies have confirmed a significant impact of certain plastics on precise measurements of weak magnetic fields [3].

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