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Unconventional Methods of Non-Destructive Tests. Part 2

Abstract: Non-destructive tests (NDT) utilise various physical phenomena occurring inside or on the surface of objects subjected to testing. These types of tests do not break continuity or trigger changes in the structure of materials. Non-destructive tests also utilise electromagnetic properties of materials. The article presents methods which, as a result of the effect of electromagnetic field, magnetic field and electromagnetic radiation can be used successfully in industrial applications (e.g. magnetic flux leakage method and potential method).

Keywords: Barkhausen noise testing, potential drop method, low-frequency impedance spectroscopy (LFIS), magnetic flux leakage (MFL)

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Non-destructive tests constitute a key element ensuring the failure-free operation of equipment and machinery. Non-destructive tests make it possible to detect discontinuities formed both at the manufacturing stage and during operation. However, NDTs as such also have their limitations resulting from their nature. Non-destructive tests are mostly indirect methods, where conclusions about the presence of discontinuities are based on the course of specific physical phenomena. Non-destructive tests provide information about properties of a given object. They aim to detect discontinuities and identify their nature.

The first part of the article presented some methods applicable in cases where conventional NDTs do not ensure the detection of discontinuities. In turn, this part of the article discusses electromagnetic tests including methods where the detection of discontinuities is based on the interaction of the electric field, magnetic field and electromagnetic radiation. The aforementioned methods include the following:

– Barkhausen noise testing (BNT) method,
– potential drop method (PDM),
– eddy-current testing method (ET),
– magnetic flux leakage testing method (MFL).

Barkhausen noise testing method

The Barkhausen noise phenomenon consists in the sharp increase in the magnetic induction flux in ferromagnetic materials affected by continuously changing external magnetic field. Ferromagnetic materials are composed of magnetic domains constituting areas characterised by homogenous magnetisation. Tests involve the recording of the signal of the stochastic movements of magnetic domain boundaries during the artificial remagnetisation of the material at frequency restricted within the range of od 0.1 Hz to 120 Hz [1]. The interference of the magnetic field is detected near a given element using a coil or a broadband magnetometer. Voltage spectrum induced in the measurement coil is referred to as magnetic Barkhausen noise (MBN) [2]. The abovenamed signal can be characterised by electric

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parameters including amplitude (AMBN), root-mean-square voltage (RMSMBN), the number of Barkhausen impulses having given amplitude per time unit NT or by geometric parameters and time-related dependences describing the shape of the Barkhausen noise envelope [3]. Barkhausen noise is sensitive to many parameters, including the level of stresses, microstructure, the content of carbon, the condition of the surface layer and the presence of residual stresses or dislocations. In industrial applications, Barkhausen noise is used to assess the level of residual stresses, measure hardening depth or detect damage to the surface layer after grinding. Because of the complexity of factors, a significant issue is the analysis of signal, where the processing of information may not always be performed using simple measures. The technique, involving the processing of signals, is based on the theory of fractals, constituting sets or structures characterised by invariability in scale, incomplete dimension (fractal dimension) and self-similarity [2].

The flowchart of the measurement equipment used in the tests of internal stresses is presented in Figure 1. The measurement equipment is composed of three primary elements, i.e., magnetising module (M), measurement channel (P), and the module of determining MBN parameters. The magnetising module is "tasked with" the generation of current (characterised by specific parameters) to power the winding coiled on a yoke magnetising a given element. The measurement channel is used to separate the noise background and amplify the useful signal of Barkhausen noise voltage (having a value of several microvolts) induced in the measurement winding of the detection coil. The module identifying MBN parameters is used to determine the envelope and amplitude of MBN, the root-mean-square voltage of MBN and the shaping of TTL impulses for single Barkhausen jumps having specific amplitude [3].

The measurement transducer (presented in Figure 2) applied in Barkhausen method-based tests is responsible for the generation of the variable magnetic field (having a value of several A/m) in a given element and the detection of Barkhausen jumps, characterised by changes

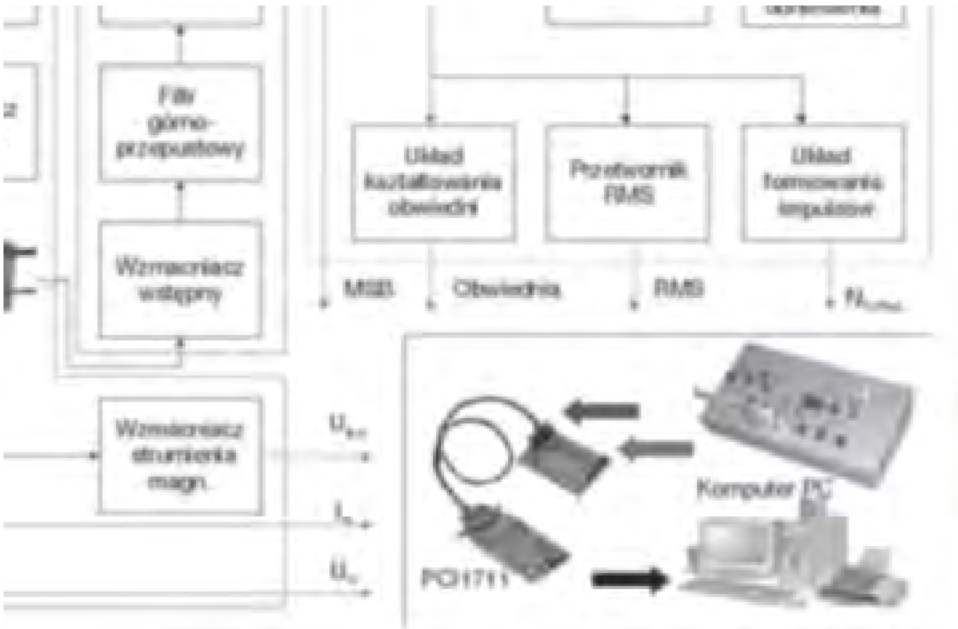

Fig. 1. Magnetic equipment flowchart [3]

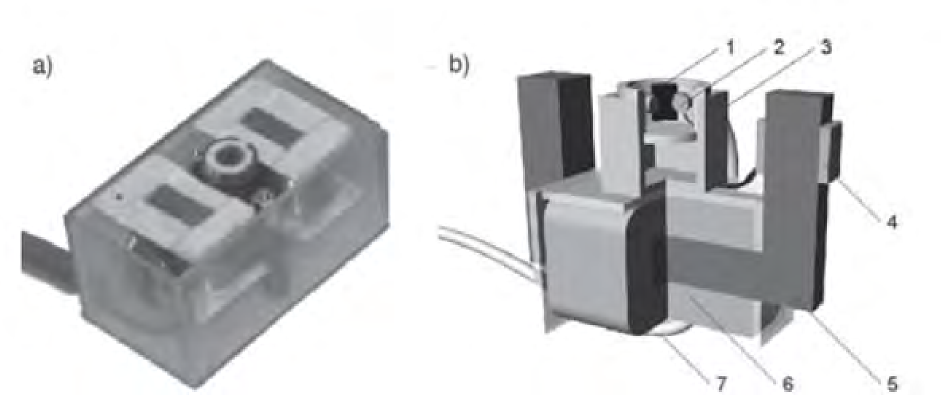

Fig. 2. Equipment element used in the Barkhausen method: a) measurement transducer, b) schematic diagram of the measurement transducer: 1 – detection coil core, 2 – measurement winding, 3 – screening casing, 4 – flux control windings in the core, 5 – magnetising yoke, 6 – magnetising windings and 7 – signal cable [3]

in the magnetic flux resulting from changes in magnetisation.

The measurement transducer is composed of a core with magnetising winding (coiled on the core) and the primary winding (located between the pole pieces), used for the monitoring of the magnetising flux in the magnetising yoke [3].

Potential drop method

Crack depth measurements performed using the potential drop method involve measurements of electric resistance between two measurement points on the surface of a metallic object. Surfaces containing cracks are characterised by higher electric resistance than that of crack-free surfaces. The above-named resistance is a crack depth-related measure. Crack depth measurements are based on the quadripolar technique. A transducer with four contact pins is placed in a given element transversely to a crack. Figure 3 presents the manner in which the depth of a given crack is measured. Direct current flows through external poles S1 and S2. Voltage U generated between poles M1 and M2 is proportional to electric resistance between these poles. As a result, it is possible to identify the depth of a crack [4].

The potential drop method utilises the phenomenon of skin effect. In terms of alternating current, the skin effect is manifested by the fact that, in a conductor, current flows closer to conductor edges. Current density decreases along with a growing penetration depth (towards the centre of the conductor). The higher the signal frequency, the higher the intensity of the skin effect. In cases of higher frequencies, current density decreases more significantly along with greater depths. In cases of very high frequencies, current only flows in a very thin layer, close to the surface of the conductor. In cases of low measurement current values, the determination of the depth of a given crack necessitates the application of alternating current. Low voltage avoids contact traces and protects transducer poles and an element being tested. The correlation between the depth of a crack as well as measured voltage and frequency is of non-linear nature. Important test-related factors also include the electric and magnetic properties of a given material.

Presently used straight and angular transducers also enable the performance of measurements in relation to bent surfaces or small areas. Figure 4 presents exemplary measurement transducers.

Fig. 4. Examples of straight and angular transducers used in tests based on the potential drop method [4]

The potential drop method requires the use of a calibration module with artificially made cracks having a depth restricted within the range of 0 to 10 mm. As a result, it is possible to verify the calibration of the transducer and of measurement equipment. Steels characterised by low penetrability (e.g. austenitic steels) and non-magnetic materials characterised by high electric conductivity (e.g. copper and aluminium) can be tested with

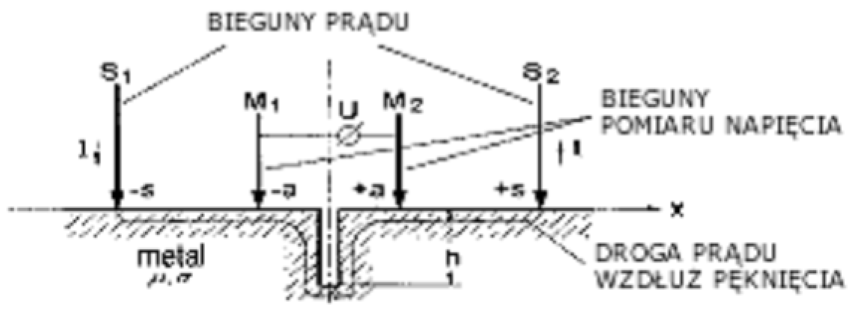

Fig. 3. Crack depth measurements based on the potential drop method [4]

Fig. 5. Measurements performed using straight and angular potential transducers [4]

sufficient accuracy. Figure 5 presents an exemplary measurement involving the use of a potential transducer.

Low-frequency impedance spectroscopy (LFIS)

The method of low-frequency impedance spectroscopy (LFIS), also referred to as the (multi-frequency) eddy-current testing method, can be used in relation to materials conducting electric current, e.g. ferromagnetic, paramagnetic and diamagnetic materials [5]. The low-frequency impedance spectroscopy method is one of non-destructive testing methods and involves the measurement of the magnetic field of eddy currents. Inhomogeneities or discontinuities present in a material being tested trigger changes in the magnetic field. The distribution of magnetic induction is measured using magnetic field sensors. Figures 6 and 7 present the idea of the eddy-current testing method and examples of discontinuities detected using this method.

The magnetic flux induces the variable magnetic field, which in turn, generates eddy currents. The flow of eddy currents is disturbed, e.g. by material discontinuities. Eddy currents induce the magnetic field which overlaps with the magnetic field excited by the coil. The eddy-current testing method is safe for the work environment and testing personnel; it is used in the aviation, metallurgical and machine-building industries as well as for tests of heat exchangers. The method can be automated easily and used in difficult conditions. The disadvantages of the method include resolution or discontinuity imaging quality [6].

In the LFIS method, electric and magnetic properties are identified within the range of several Hz to several MHz. Electric and electromagnetic impedance (analysed using various methods utilising eddy currents induced in a given material) depend on the chemical composition of the material, the type and quality of microstructure, operating loads triggered by internal stresses and material temperature [7]. The LFIS method is applied, among other things, to monitor the production in the automotive industry. The method is used to determine the electric and magnetic properties of tested materials including electric conductivity (specific conductance) σ, electric susceptibility ε and magnetic permeability μ [7]. The above-named

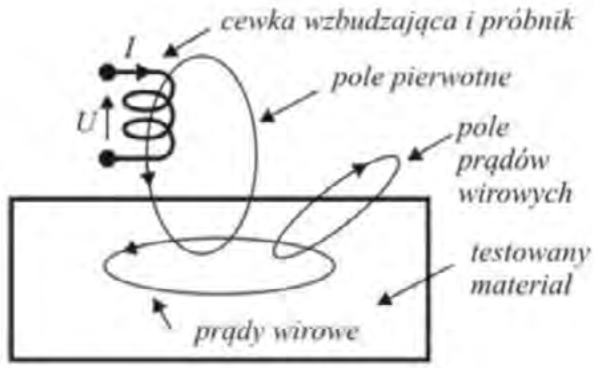

Fig. 6. Idea of eddy-current inspection [6]

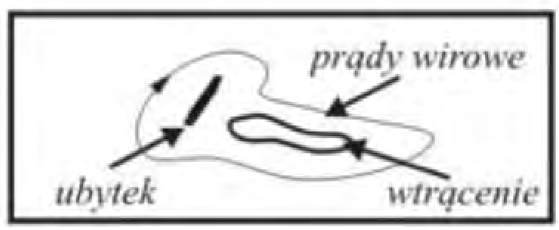

Fig. 7. Discontinuities (losses) and inclusions [6]

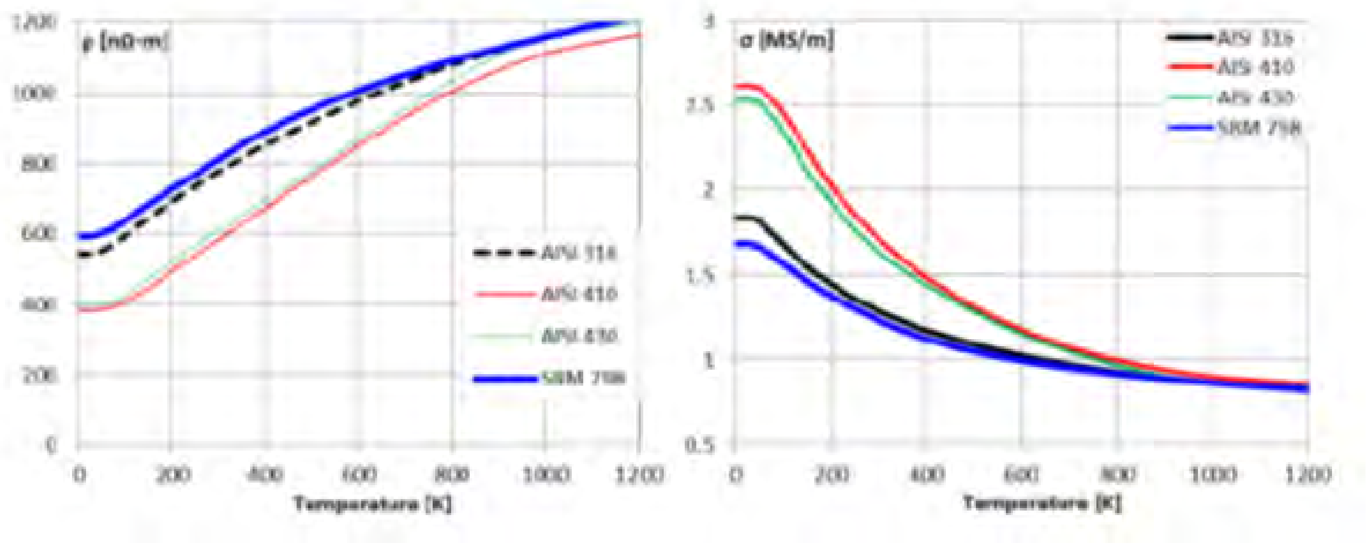

Fig. 8. Effect of temperature and microstructure on electric properties (resistivity and conductivity) [7] (Temperature)

parameters define the effect of a material being tested on the external electromagnetic field, which is generated in the measurement coil and induces eddy currents in the material. Stresses and structural degradation increase the inhomogeneity and anisotropy of materials. The correlation of microstructural parameters and electromagnetic properties is responsible for changes of parameters of electric conductivity σ, electric susceptibility ε and magnetic permeability μ. Electromagnetic properties, among other things, depend on a testing signal and the temperature of a given material (see Figure 8).

The detection of discontinuities in heat exchanger tubes is one of the applications of the method. In such a case, it is difficult to detect external discontinuities in areas of tubes covered by plates. Tubes being several metres in length are fixed on steel plates. The multi-frequency eddy-current testing method uses signals of various frequencies. Low-frequency signals provide information about discontinuities located deeper, whereas high-frequency signals enable the verification of surface and subsurface layer quality. A greater number of signals enables the more precise identification of discontinuities. Figure 9 presents the correlation of amplitude S and frequency f, taking into account the location of transducer x, y [6].

Magnetic flux leakage method (MFL)

The magnetic flux leakage method (MFL) is used in the testing of ferromagnetic materials and consists in the appropriate saturation of a given material area with the magnetic field. The area adjacent to a discontinuity is characterised by increased resistance in the direction of magnetic field induction. If its value is sufficiently high, the magnetic field propagates around material discontinuities. The leakage of the magnetic field is measured using magnetic sensors located near the surface. The MFL method is used in tests of steel structures such

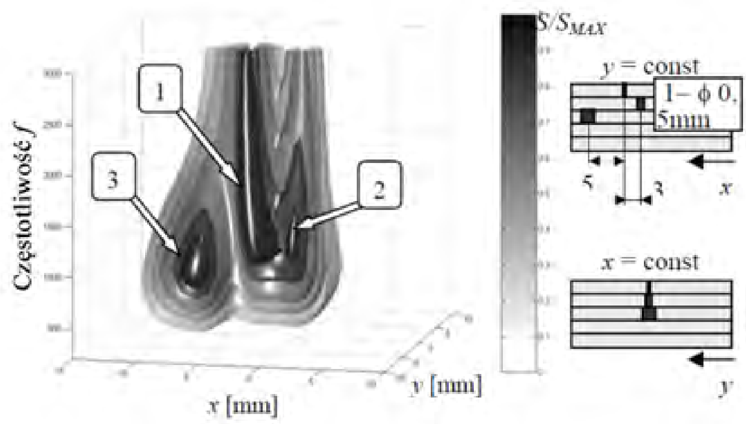

Fig. 9. Exemplary 3D spectrogram S (x, y, f) obtained in relation to a discontinuity characterised by complex structure [6]

as ground-based storage containers [8]. The magnetic flux leakage method is useful in testing very large areas, identifying the location of discontinuities and determining losses of material (see Figure 10).

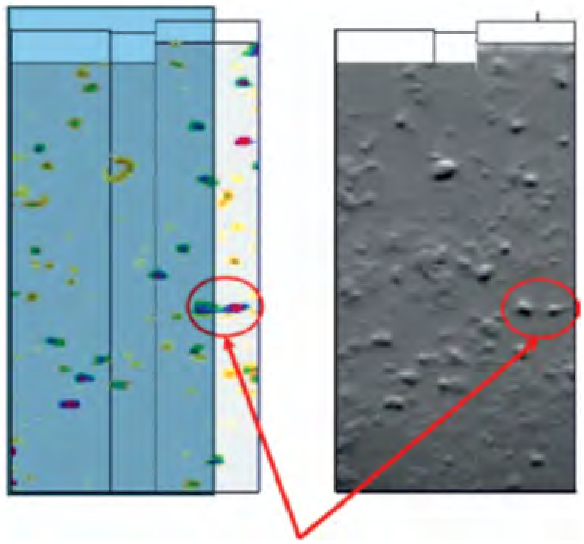

Fig. 10. Result of the MFL mapping of the container bottom [8]

Tests often involve the use of scanners with sensors placed perpendicular to the direction of movement. The yoke system consists of two magnets, bridge and two pole pieces (see Figure 11).

The height of the sensors controls the gain of the MFL signal. For testing personnel, the method is significantly simpler in terms of interpretation. Outside the amplitude signal it is possible to identify the location of signals "generated" by welds or discontinuities. The number of sensors affects measurement accuracy. Before tests, measurement equipment must be

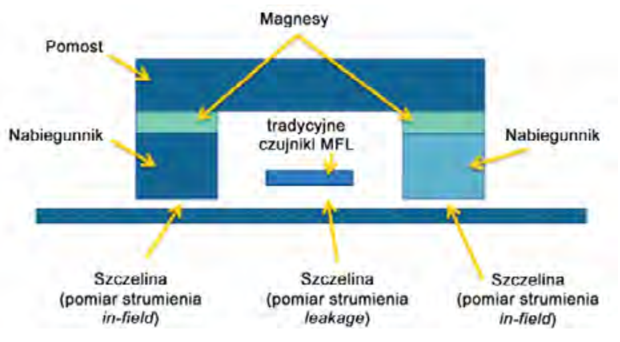

Fig. 11. Elements of the magnetic yoke and the position of MFL sensors in relation to one another and to the material [8]

subjected to calibration. The interpretation of signals can be encumbered with an error triggered by the geometry of surface or its condition or by the thickness of coating.

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