

Surface Magnetic Non-Destructive Testing

Evangelos Hristoforou^{1,*}, Konstantinos Kosmas¹ and Eleftherios Kayafas²

¹*School of Mining and Metallurgy Engineering, National Technical University of Athens, Zografou Campus, Athens 15780, Greece, +302107722178, eh@metal.ntua.gr, kkosmas@metal.ntua.gr*

²*School Electrical and Computer Engineering, National Technical University of Athens, Zografou Campus, Athens 15780, Greece, +302107722544*

Abstract- In this paper, we summarize the magnetic and electromagnetic non-destructive testing techniques and devices based on the magnetostrictive delay line principle. Three main techniques are presented. The first is based on surface crack and defect detection on ferromagnetic surfaces by measuring the corresponding magnetic anomaly distribution. The second is the measurement of eddy currents generated around the cracks and defects on a magnetic or non-magnetic metallic surface. The third technique is measuring the surface magnetic permeability of ferromagnetic substances. Finally, the methods of measuring the properties of magnetostrictive ribbons and cylinders used as MDLs, such as magnetoelastic performance and longitudinal sound velocity as well as their uniformity measurements are also discussed

I. Introduction

A number of non-destructive testing (NDT) techniques have been developed in the past by research laboratories and industries working in this field [1,2]. The main target of all these techniques is the determination of cracks and defects on the surface or in the body of a given item. The most widely applicable and important NDT techniques are those referring to metallic surfaces and substances, either being magnetic or non-magnetic.

Among the various NDT techniques, one can distinguish the radiography technique with spatial resolution in the micron region, the ultrasonic mapping which is capable of mapping 3-dimensional defects relatively fast with a sub-mm resolution and the liquid penetrating technique utilizing UV light illumination of fluorescence. Other acoustic techniques have also been developed utilizing electromagnetic acoustic transducers [3] and laser techniques [4].

The magnetic non destructive techniques are also widely used. One of them is the magnetic particle inspection, according to which small magnetic particles, diluted in liquid of well defined viscosity and spread on a magnetized magnetic surface concentrate in the areas of surface defects and cracks, due to the appearance of magnetic field gradients at these areas. The resolution of such method depends on the size of the magnetic particles, which is of the order of 0.1 mm. The magnetic flux leakage technique can be considered as an evolution of the magnetic particle technique, since the magnetic field gradient in the areas of cracks and defects can be detected and monitored by electronic field sensors and correspondingly by a computer [5,6], after a surface magnetization process in 1-4 kA/m. The eddy current technique is based on the contact-less transmission of alternating magnetic field on a metallic surface, causing generation of eddy currents in the vicinity of cracks and defects in a small depth of the material [7,8]. The presence of cracks and defects concentrate eddy currents around them, which can be detected as voltage signals across searching coils, indicating the size of the defect. The measurable depth of cracks and defects is restricted by the depth of magnetic field penetration, which is dependent on the frequency of the alternating magnetic field. Resolution can be of the order of 10 μm .

Our motivation was the development of NDT sensors based on magnetic materials and especially on the magnetostrictive delay line (MDL) technique, which will be hereinafter presented. Detailed analysis of the basic properties, arrangements and applications of the MDL technique can be found in the literature [9].

II. MAD – ECT combination

Towards the detection of small subsurface cracks on magnetic materials we are trying to combine the magnetic anomaly detection (MAD) and the eddy current technique (ECT). According to this principle of operation, the under test magnetic material is biased with dc magnetic field; the most common way of magnetizing the magnetic material is the electromagnetic yoke, allowing the control of the technical magnetization of the under test material as well as the permanent magnet closed circuit.

Having magnetized the specimen at the desired level, an AC magnetic field is transmitted perpendicular to the under test surface at different frequencies. The generated eddy currents at the surface are altered with respect to the cracks and the magnetization, so that the change of the eddy current vector at various depths, controlled by the excitation frequency determine the depth and the size of the cracks. This technique can also be applied for the determination of the depth of small surface cracks. The principle of operation of the method is illustrated in Figure 1. Experimental results indicate better sensitivity as compared to ultrasonic techniques, although having the limitation of the depth of inspection which is limited to a few mm below the surface.

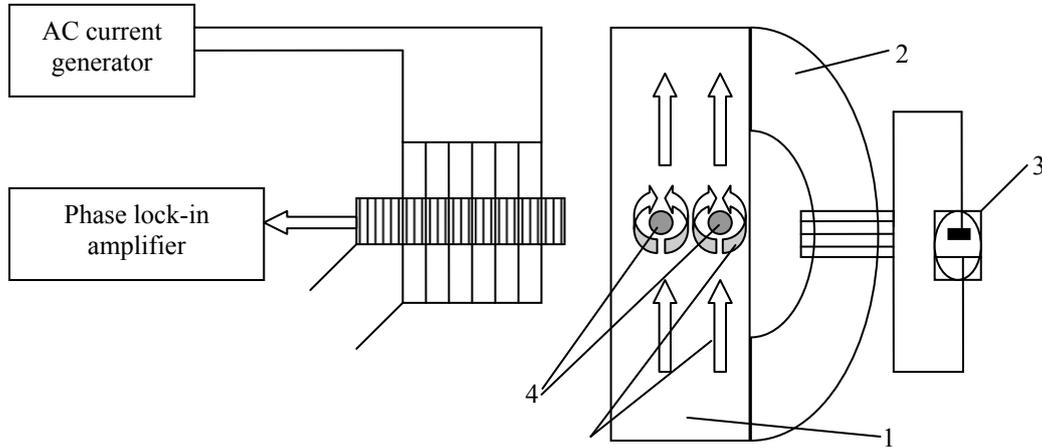


Figure 1: The principle of operation of the MAD-ECT technique. (1) Under test specimen; (2) Magnetizing soft magnetic material; (3) Magnetization coil and generator; (4) Subsurface crack; (5) Magnetization far and close to the crack; (6) Eddy current excitation coil; (7) Eddy current sensing means.

II. Magnetostrictive Delay Lines in Magnetic Anomaly Based Defect Detection

Our first trial for involving the MDL technique on magnetic non-destructive testing was the realization of a dc field dependence of the MDL output, having a range and sensitivity of the order of $50 \mu\text{T}$ and 5 nT respectively, due to the achievement of soft magnetic and magnetoelastic response after careful magnetic field annealing at 350°C and 250 A/m for $\frac{1}{2}$ hour in inert atmosphere, as well as due to the negligible presence of Barkhausen noise caused by the MDL operation in high frequency pulsed fields, with amplitudes well above the anisotropy field barrier. Such dependence, as illustrated in Figure 2, offers the possibility to test the existence of cracks on the surface of a ferromagnetic material. A single point field sensor was initially developed as shown in Figure 3. The details of the structure of this sensor can be found in [10]. Despite the relatively good sensitivity of the sensor, its use requires an X-Y translator for point by point mapping reasons. Therefore its practical application would be comparable to a Hall, or MI, or GMI element, while the last may exhibit better performance.

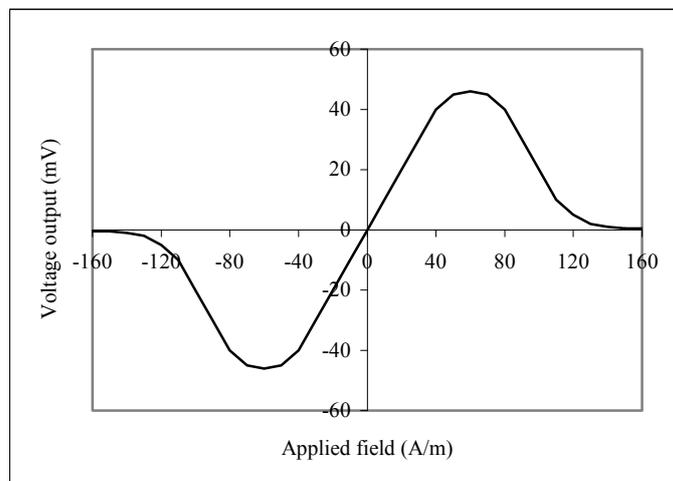


Figure 2. Magnetic anomaly detection using the MDL technique. (a) A typical MDL voltage output dependence on biasing field; (b) Detecting cracks by using the simplest coil-coil MDL arrangement; (c) Serializing the cracks by using a long search MDL coil.

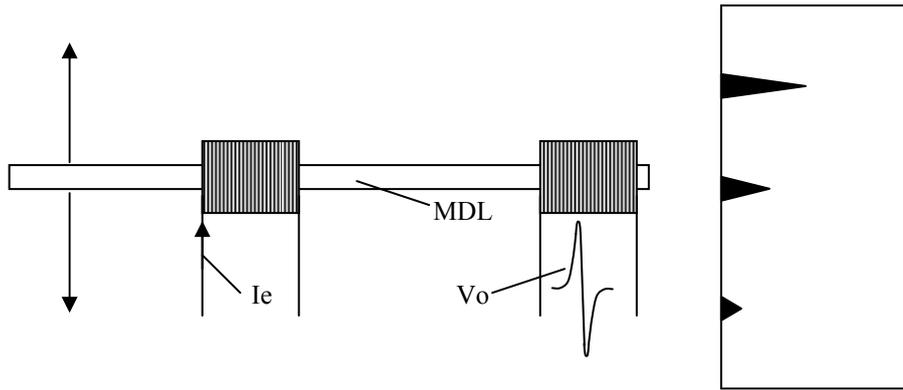


Figure 3. Detecting cracks by using the simplest coil-coil MDL arrangement; (c) Serializing the cracks by using a long search MDL coil.

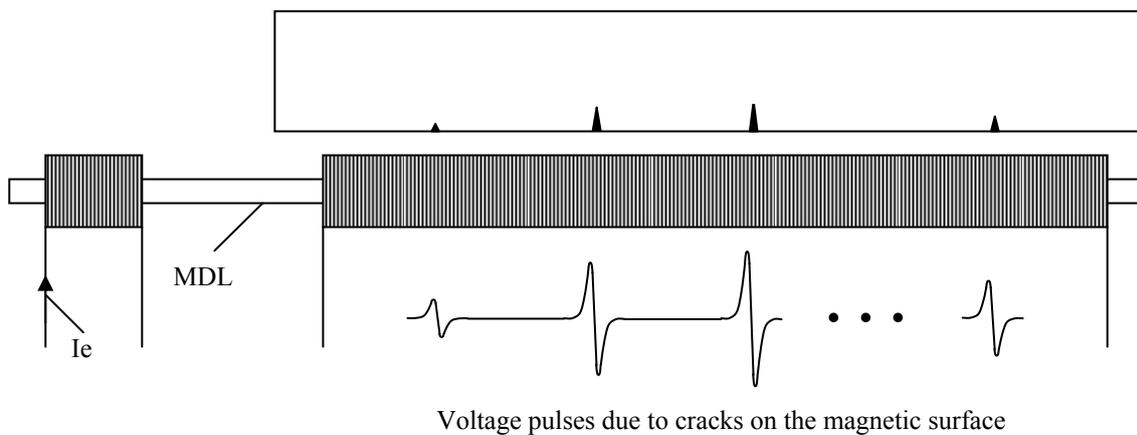


Figure 4. Serializing the cracks by using a long search MDL coil.

Having as target the decrease of time of scanning a ferromagnetic surface, we have developed the sensor shown in Figure 4. A long magnetostrictive element, preferably in the shape of wire, is used as the magnetostrictive delay line (MDL). A short coil, set around the MDL at the one end of it, is used to transmit the pulsed current I_e . A one-layer long search coil is wound around the MDL to detect any fluctuation of magnetic flux. Transmitting pulsed current through the short coil results in a micro-strain and an elastic pulse propagating along the MDL. Provided that the ambient field around the MDL is uniform and the MDL element is magneto-elastically uniform, the search coil can detect only two small voltage peaks, corresponding to the ends of the long search coil. Approaching the sensing arrangement to a metallic surface without cracks, the MDL operation is not disturbed significantly, resulting again into two voltage peaks, larger than before, corresponding to the ends of the long search coil. Approaching the sensor to a magnetic surface crack, the magnetic leakage of the crack breaks the magnetoelastic symmetry of the MDL, this resulting in the generation of an elastic pulse at the vicinity of the MDL above the crack and correspondingly on a pulsed voltage output, with time delay and amplitude corresponding to the position and size of the crack respectively. This magnetic NDT sensor offers the possibility of short inspection time due to the multiplexing or serialization of the crack measurements of an axis to a single voltage output response. Unfortunately, the sensitivity and the spatial resolution of such an arrangement are limited to 0.3 mm and 30 mm respectively.

In order to improve the above described sensor, we have developed the device depicted in Figure 5. According to it, a conducting cylinder is used as the substrate for a thin magnetostrictive tube. Passing pulsed current through the conductor, the magnetostrictive thin tube is excited circumferentially, thus resulting in a circumferential microstrain along the whole length of the tube. Provided that the material has undergone proper tailoring to obtain magnetoelastic uniformity, the propagating micro-strains, in the absence of magnetic anomalies along its length, are only those originated at the ends of the magnetostrictive tube. In the presence of magnetic anomalies like field spikes due to cracks on a magnetic surface, the magneto-elastic symmetry breaks down, resulting in discrete elastic pulses propagating along the material. Details of such a sensor can be found in [11].

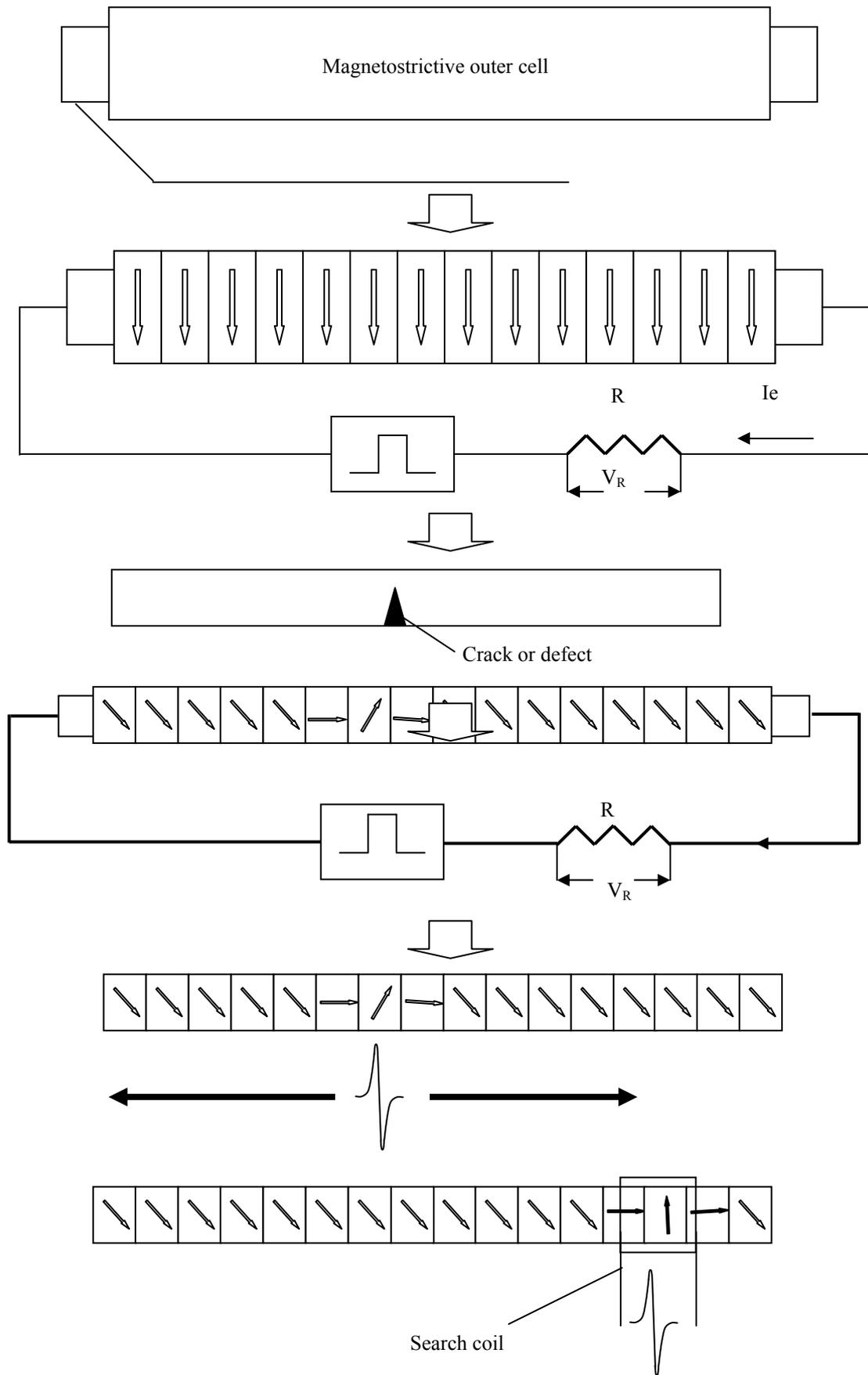


Figure 5. A cylindrical MDL film deposited on conducting Cu or Al for generating transverse elastic waves, able to detect and serialize surface cracks and defects.

We performed tests for this sensor on artificially developed line and hole cracks. Line cracks had either constant width of 1 mm and varying depth of 0.1 mm to 1 mm in steps of 0.1 mm, or constant depth of 1 mm and varying width of 0.1 mm to 1 mm in steps of 0.1 mm. Artificial holes had a given depth of 1 mm and diameter from 0.1 mm to 1 mm in steps of 0.1 mm. The response of the sensor is shown in Figures 6, 7 and 8, illustrating acceptable behavior down to 0.1 mm region of measurements, with a spatial resolution of 1 mm.

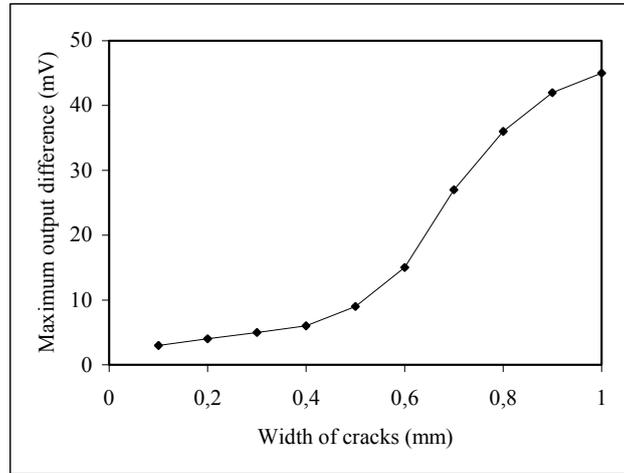


Figure 6. Response of the MDL used for magnetic anomaly detection on a ferromagnetic steel plate. Measurement of the width of line artificial cracks with a given depth equal to 1 mm.

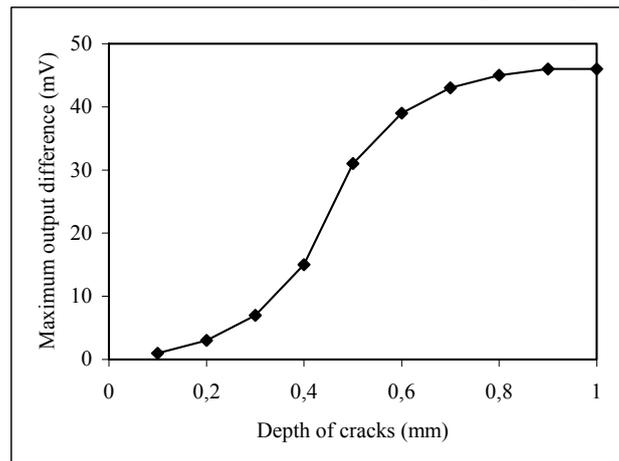


Figure 7. Response of the MDL used for magnetic anomaly detection on a ferromagnetic steel plate. Measurement of the depth of line artificial cracks with a given width equal to 1 mm.

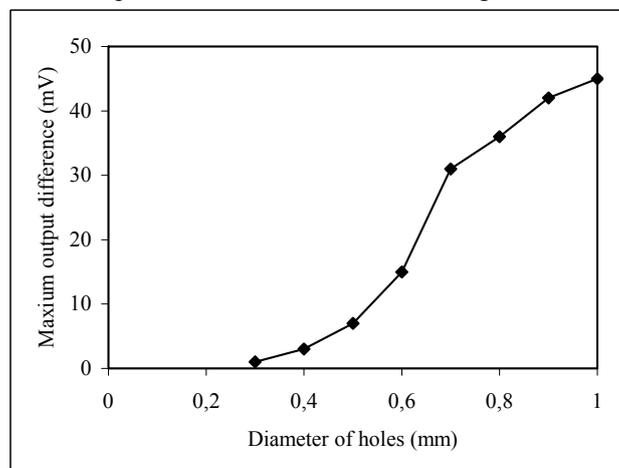


Figure 8. Response of the MDL used for magnetic anomaly detection on a ferromagnetic steel plate. Measurement of the diameter of holes artificial defects with a given depth of 1 mm.

III. Magnetostrictive Delay Lines in Eddy Current Based Defect Detection

Having as motivation the realization of a sensor able to perform fast scanning on non magnetic surfaces, the sensor demonstrated in Figure 9 has been developed. A long MDL and a pair of pulsed current conductors are set parallel to the under test surface. The transmitted pulsed current induces pulsed magnetic field orthogonal to the MDL, resulting in no propagating elastic pulse. A search coil is wound around the one end of the MDL to detect any fluctuation of magnetic flux. Approaching the sensing arrangement to a metallic surface with no cracks or defects, the generated eddy currents are uniformly distributed on the metallic surface. Thus, no elastic strain is generated into the MDL. Assuming that the under test specimen has a defect, the pulsed eddy current density around this defect is increased, inducing a pulsed field component along the length of the MDL at positions determined by the shape and size of the defect. Hence, a travelling elastic wave is generated in the MDL, which can be detected as a pulsed voltage by the receiving coil. The size of the pulsed voltage output defines the magnitude of the eddy current, which is related to the size of the crack, while its time delay determines the position of the crack [12].

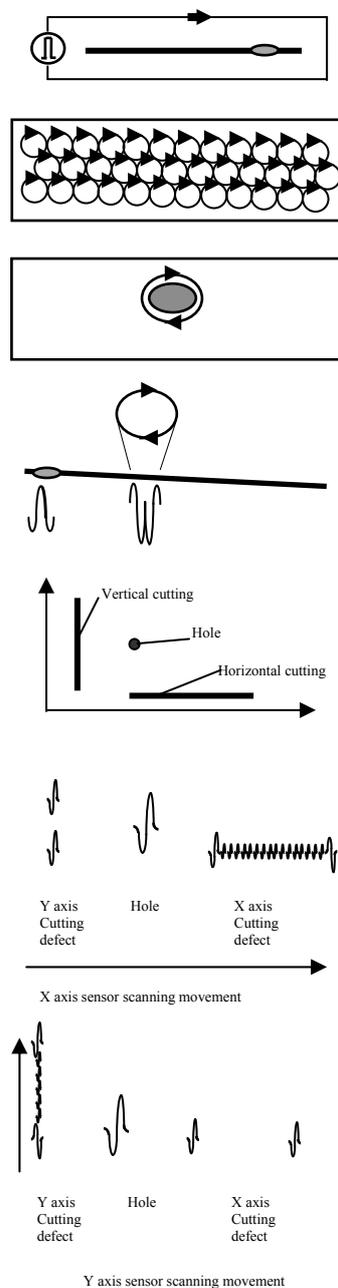


Figure 9. Measuring surface cracks and defects in magnetic and non-magnetic metallic surfaces. Transmitting pulsed current parallel to the MDL generates no elastic pulse in the MDL. For the case of a uniform metallic surface the generated eddy currents due to the pulsed transmitted current, cancel each other and therefore no elastic pulse is generated. In the presence of a crack, local eddy current density increases, resulting in an elastic pulse, detectable by the search coil.

Figure 10. Operation of the device demonstrated in Figure 9, for vertical and horizontal artificial cracks. The serialization of the elastic pulses due to the eddy currents caused by the cracks or defects is possible.

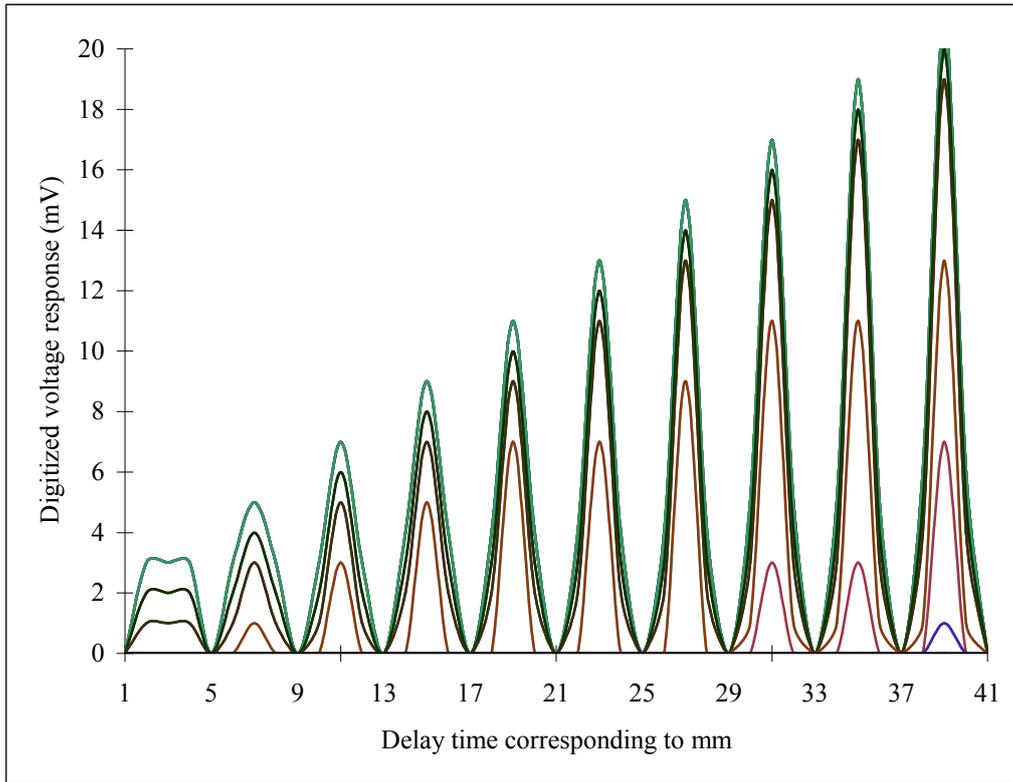


Figure 11. Response of the MDL device of Figure 9 for artificial cracks on a ferromagnetic steel plate. Measurement of the width of line artificial cracks with a given depth equal to 1 mm.

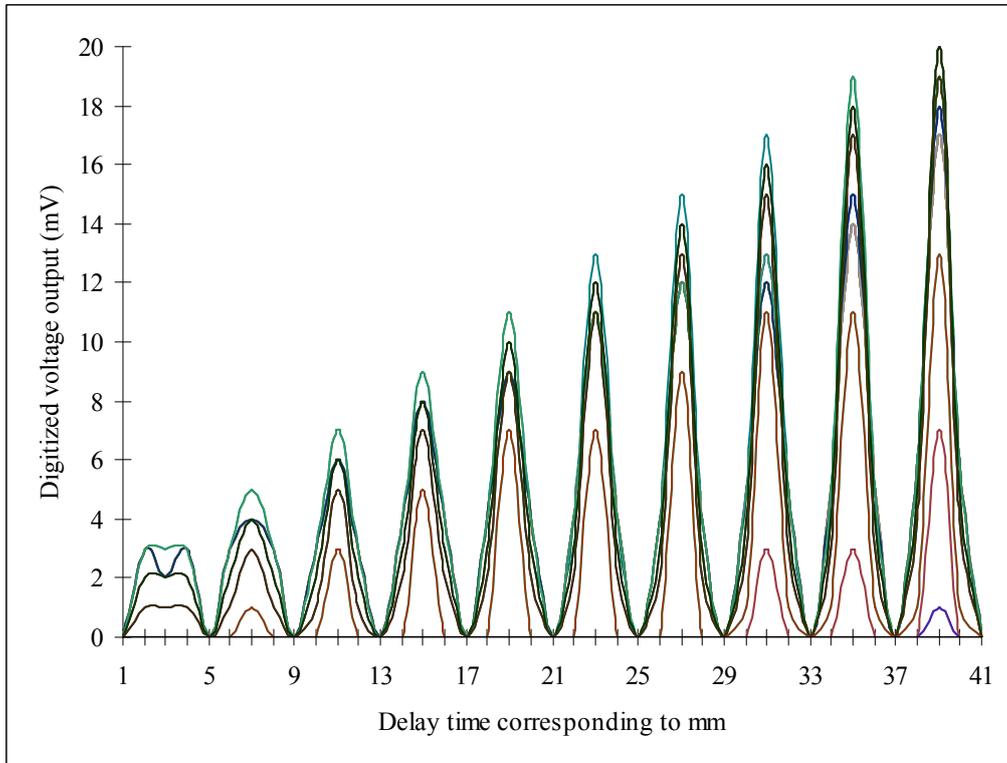


Figure 12. Response of the MDL device of Figure 9 for artificial cracks on a ferromagnetic steel plate. Measurement of the depth of line artificial cracks with a given width equal to 1 mm.

The operation of the sensor is illustrated in Figure 10. Having a number of such defects along the MDL axis, results in the generation of discrete elastic strains in the MDL, at the defect-MDL intersection points which are correspondingly detected by means of a train of pulsed voltages at the receiving coil. Moving the MDL along the under test specimen, results in mapping those defects. If a defect is parallel to the MDL axis, only the defect boundaries contribute to the generation of elastic strains. Thus, mapping in two orthogonal axes and consequently superimposing the sets of voltage outputs, can result in mapping the surface defects of the under test surface. Using a 20 mm by 15 mm Al metallic matrix, having pre-prepared vertical and horizontal cuttings, in the same way as for the magnetic anomaly NDT sensor, the experimental results are illustrated in Figures 11 and 12. Width and depth of cracks starts from 0.1 mm to 1 mm, with a step of 0.1 mm. A continuous translation of the MDL device has been performed for the realization of the experiment.

IV. Magnetostrictive Delay Lines in Permeability Measurements

Having as motivation to measure the surface magnetic permeability as well as its distribution uniformity along the under test surface, we have developed a new NDT method based on an old sensing principle [13]. The method is based on the magnetostrictive delay line technique. According to this technique, a special balanced structure of MDL excitation conductors is used to detect the amplitude and the change of magnetic permeability on a ferromagnetic surface. Such magnetic permeability uniformity function determines the quality of the surface under inspection.

The method is based on the arrangement of Figure 13. According to this set-up, a balanced structure of MDL using a pair of pulsed current excitation conductors is employed, allowing the MDL to be free of stresses under any circumstances. When a pulsed current I_c is transmitted in the same direction in the two conductors, in the absence of any other magnetic element in the neighborhood, there is no magnetic flux in the delay line and consequently zero pulsed voltage output is detected. In the presence of the reference ferromagnetic element, the amount of flux inside the MDL is maximized and the pulsed voltage output amplitude V_o is maximized. When an under test ferromagnetic element is positioned close to the MDL, as illustrated in Figure 13, the magnetic flux unbalance in the MDL decreases. The amount of decrease depends on the magnetic permeability of the under test sample. Consequently, the amplitude of the MDL pulsed voltage output decreases. The amount of the unbalanced flux inside the MDL depends on the magnetic permeability of the approaching under test magnetic sample as well as on the distance between the MDL balanced structure and the magnetic element. Maintaining the distance between the device and the under test surface unchanged, scanning of the ferromagnetic surface results in the determination of the magnetic permeability of the magnetic surface. The uniformity of the magnetic permeability determines the quality of the tested surface. In all measurements the amplitude of the pulsed voltage output V_o is the system output.

Various ferromagnetic samples of different permeability have been used to evaluate and calibrate the device. These samples were ferromagnetic steels used after different heat treatment and cold drawing. Their permeability has been determined by using minor loop ac magnetometry. The dependence of the voltage output V_o on the permeability of a ferromagnetic steel under test, is illustrated in Figure 14. In all these measurements the reference standard was a Metglas ribbon of relative permeability equal to 70000. The distance between the device and the under test specimen has been maintained equal to 0.2 mm. Taking into account that the distance between the device and the under test specimen is of critical importance, we performed measurements of voltage output dependence on the device – under test surface distance. From these results it became apparent that the device response does not change significantly for distances lower than 0.4 mm.

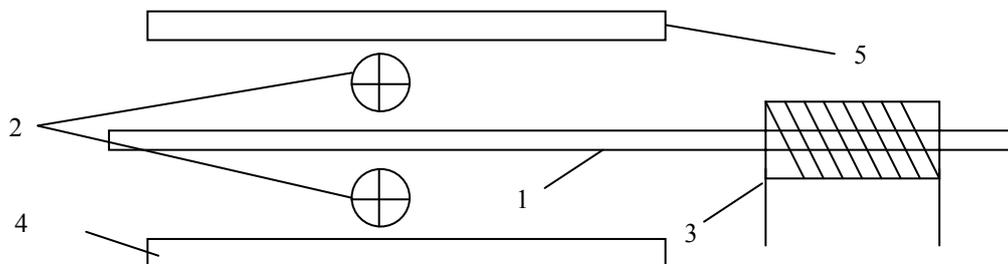


Figure 13. The MDL device Measuring the relative magnetic permeability on a ferromagnetic steel plate; (1) MDL, (2) pulsed current conductors, (3) search coil, (4) reference plate, (5) under measurement surface.

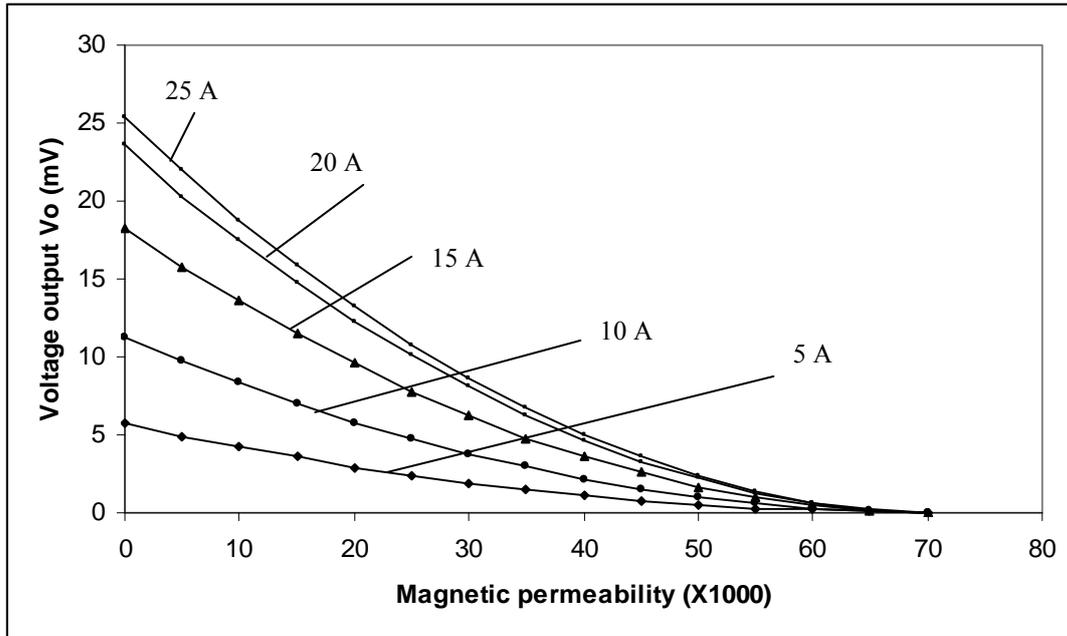


Figure 14. A typical MDL response for different relative magnetic permeability of a ferromagnetic steel plate.

V. Discussion

The above presented devices used for magnetic non-destructive testing have got advantages and disadvantages. Among advantages, the most important property is the ability of some of the devices of multiplexing or serializing the information of the position and size of a crack or defect below the MDL in one single reading. In particular, the device depicted in Figure 5 can be used for magnetic anomaly inspection of ferromagnetic surfaces, with a spatial resolution of 1 mm, while the device demonstrated in Figure 9 can be used for non magnetic metallic surface crack testing. The major disadvantages of the presented techniques or devices are the relatively poor sensitivity in comparison to some other techniques, the restricted spatial resolution, as well as the ability to perform only surface measurements. Of course, the surface measurements can also be correlated with the subsurface structure of the material. This is especially valid for the device presented in Figure 13, able to perform surface permeability measurements. Applications of the above presented devices can be continuous monitoring of the stress distribution and corrosion on magnetic and non magnetic surfaces like bridges and tunnels.

Finally, it is worth mentioning that the MDL technique can also be used for non destructive testing of magnetostrictive materials in the shape of an acoustic waveguide, like ribbons and wires. In this case the under test material is the MDL itself. The magnetoelastic uniformity tests can be performed using the arrangement illustrated in Figure 4. The description of such a device and method is depicted in [14]. Furthermore, measurements of the longitudinal sound velocity and its uniformity can also be obtained by measuring the delay time between two distinct positions of the excitation and search MDL coils, as described in [15]. Recently, a new method for measuring M-H, λ -H and their uniformity using the MDL technique, has also been presented [16], thus allowing more detailed studies of the MDL itself.

Acknowledgments

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