Evaluation of thin discontinuities in planar conducting materials using the diffraction of electromagnetic field

A Savin\textsuperscript{1}, F Novy\textsuperscript{2}, S Fintova\textsuperscript{3,4} and R Steigmann\textsuperscript{1,5}
\textsuperscript{1}National Institute of R&D for Technical Physics, Iasi, Romania
\textsuperscript{2}Zilina University, Faculty of Mechanical Engineering, Zilina, Slovak Republic
\textsuperscript{3}Institute of Physics of Materials AS CR v.v.i., Brno, Czech Republic
\textsuperscript{4}Materials Research Centre, Brno University of Technology, Brno, Czech Republic
\textsuperscript{5}Alexandru Ioan Cuza University, Faculty of Physics, Iasi, Romania

E-mail: asavin@phys-iasi.ro

Abstract. The current stage of nondestructive evaluation techniques imposes the development of new electromagnetic (EM) methods that are based on high spatial resolution and increased sensitivity. In order to achieve high performance, the work frequencies must be either radiofrequencies or microwaves. At these frequencies, at the dielectric/conductor interface, plasmon polaritons can appear, propagating between conductive regions as evanescent waves. In order to use the evanescent wave that can appear even if the slits width is much smaller that the wavelength of incident EM wave, a sensor with metamaterial (MM) is used. The study of the EM field diffraction against the edge of long thin discontinuity placed under the inspected surface of a conductive plate has been performed using the geometrical optics principles. This type of sensor having the reception coils shielded by a conductive screen with a circular aperture placed in the front of reception coil of emission reception sensor has been developed and “transported” information for obtaining of magnified image of the conductive structures inspected. This work presents a sensor, using MM conical Swiss roll type that allows the propagation of evanescent waves and the electromagnetic images are magnified. The test method can be successfully applied in a variety of applications of maxim importance such as defect/damage detection in materials used in automotive and aviation technologies. Applying this testing method, spatial resolution can be improved.

1. Introduction

In literature exists a great number of paper that treats the diffraction EM field on ideal crack shape material discontinuities \cite{1, 2}. In all studies, the calculations are based on theory of diffraction \cite{3} and are developed in the hypothesis that the discontinuities have infinitely small width, is long, representing a perfect barrier for the eddy current circulation; the displacement currents are neglected. Scattered electromagnetic (EM) field from planar conductor materials consist in change direction of propagation, amplitude and phase or polarization state. The diffraction of EM field is also a process of scattering and on nondestructive testing (NDT) these results obtained contain information’s versatile about material properties. Understanding how EM waves interact with macroscopic bodies that can contain some discontinuities placed under the inspected surface of conductive plate has been performed using the geometrical optics principles \cite{4}. From point of view of NDT electromagnetic method in the case of ideal cracks we are interested only on two parameters, crack’s depth in the case of surface breaking cracks and crack’s depth under subsurface for subsurface cracks.
This paper presents a sensor; using metamaterials (MM) that allows the propagation of evanescent waves and electromagnetic images are magnified. The test method can be successfully applied in a variety of applications of maximum importance such as defect/damage detection in materials used in automotive and aviation technologies. Applying this testing method, spatial resolution can be improved.

2. Electromagnetic field diffraction on ideal cracks

The current stage of NDT imposes the development of new EM method that is based on the high spatial resolution and increased sensitivity. In order to achieve high performance, the work frequencies must be either RF or microwave that assures good detection sensitivity for a minimum 3/1 signal to noise ratio as well as a good spatial resolution. A crack opened at surface with width and depth in the range of 50 µm is admitted as eddy current method sensitivity limit, the detection being made with SQUID [5].

If the tested material has the electrical conductivity \( \sigma \) and magnetic permeability \( \mu \), the incident field is generated by a one-turn rectangular coil, having 20x60 mm, using a Cu wire with 1.2 mm diameter, and fed with an alternating current. A plane EM TMz polarized wave acts over the plane of conducting materials. The dependency by distance of the Hx component of magnetic field generated by the rectangular coil at the interface air-plane materials is presented in figure 1.

![Figure 1. The dependency of Hx by distance.](image)

It is observed that on a relatively small distance, compared with the length of crack (~1 mm) take in consideration, the field can be considered practically constant. At a distance over 25 mm the EM wave, can be considered a plane wave TMz polarized. In this region, the reception device of the EM sensor with MM lens is placed. According to [6], at TMz excitation, presence of the crack with very small comparatively with \( \lambda \) (where \( \lambda \) is the free space wavelength of the incidence EM waves) the evanescent modes appear. The crack, filled with air can be considered a single slit into planar conducting materials.

The amplitude of evanescent modes exponentially decrease with distance z. In order to manipulate these modes, a sensor with MM lens can be used, operating at the frequency at which relative magnetic permeability of the medium is maximum.

Electromagnetic sensor with MM has been made in this case using Conical Swiss Rolls (CSR), the operation frequency depending both by the constitutive parameters of MM as well as by the polarization of incident EM field TMz. On the basis of theoretical aspects developed, using a sensor with MM developed by us [8-10] as shown in [6] the evanescent modes can be manipulated, the lens realized with two CSR for which an optimal working frequency was chosen so that the \( \mu_{\text{eff}} \) will be a maximum. The detection principle is similar with the one of near-field EM scanning microscopy [11]. The reception coil functions as an antenna, converting localized energy into an electromotive force. The focal distance of the lens using MM is \( f \approx l \), where \( l \) is the height of a CSR.
Figure 2. Sensor with metamaterial lens: (a) Schematic representation (b) Design of device for testing.

The functioning of the entire detection system can be described using Fourier optics [12], [4]. For an object placed in the plane $z = 0$ described by the function $f_0(x,y)$, at passing through an aperture, in the case of Fresnel diffraction (the aperture is closely to the object), the image obtained at the distance $z$ from the object will be $f_z(x,y)$ and can be calculated using the algorithm presented in figure 3.

$$f_0(x,y) \rightarrow \text{2D Fourier Transform} \rightarrow F_{(u,v)} \rightarrow \exp \left[ -\frac{j2\pi^2}{k}(u^2 + v^2) \right] \rightarrow F_z(u,v) \rightarrow \text{Inverse 2D Fourier Transform} \rightarrow f_z(x,y)$$

Figure 3. The image modification by an aperture due to Fresnel diffraction.

Between the Fourier variables and spatial ones must be the relations:

$$du = \frac{2a}{Ndx_0}; \quad dv = \frac{2a}{Mdy_0}$$

where $N$ and $M$ constitute the number of measurement points along $x$ and $y$ direction; $dx_0$ and $dy_0$ are the scanning step along $x$ and respective $y$ directions.

Using the Fourier optics method [4], the image $I(x',y')$ an object $O(x,y)$ is given by [13]

$$I(x',y') = \frac{1}{\lambda^2d_2d_z} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \exp \left[ \frac{i}{2d_z} k \left( (x-x_1)^2 + (y-y_1)^2 \right) \right] P(x,y) \exp \left[ \frac{i}{2f} k \left( (x_1^2 + y_1^2) \right) \right] \times$$

$$\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} O(x,y) \exp \left[ \frac{i}{2d_1} k \left( (x-x_1)^2 + (y-y_1)^2 \right) \right] dx_1 dy_1$$

where $P(x,y)$ is the pupil function defined as

$$P(x,y) = \begin{cases} 1 & x^2 + y^2 \leq d_1^2 \\ 0 & \text{otherwise} \end{cases}$$

$d_1 = R + l$ is the distance from the object to the center of the lens, $d_2 = l$ is the distance from the center of the lens to the detecting coil and $K = 2\pi / \lambda$ is the wave number.

3. Eddy current procedure of detection

We analysed the block which present an opened crack at surface with $5 \mu m$ width, $20 \mu m$ depth and $1 mm$ length. The electrical conductivity of the material is $\sigma = 10^7 S/m$ and the relative magnetic permeability $\mu_r = 20$. In electromagnetic testing, the frequency is chosen so that $h \approx 3\delta$ where $h$ is
the depth of the flaw and \( \delta = \sqrt{\frac{1}{\pi f \sigma \mu}} \) represents the standard penetration depth, 
\( \mu = \mu_0 = \mu_s \cdot 4\pi \cdot 10^{-7} \text{H/m} \). Using CIVA version 9.2 software [14], a ferromagnetic steel block having a crack with \( L=1\text{mm}, l=5\mu\text{m} \) and \( h=20\mu\text{m} \) has been modeled. For this the crack is discretized in \( N_x \times N_y \times N_z = 20 \times 5 \times 10 = 1000 \) cells, according to axis presented in figure 1. Figure 4 shows the answer of the absolute eddy current sensor at scanning with 10\( \mu \text{m} \) step over a crack, respectively line scan and impedance plane.

![Figure 4. The answer of the eddy current transducer at scanning with 10\( \mu \text{m} \) step over a crack with \( L=1\text{mm}, l=5\mu\text{m} \) and \( h=20\mu\text{m} \): a) absolute transducer – line scan; b) absolute transducer – impedance plane.](image)

The answer of a classical eddy current sensor shows that the limit of detection is conditioned by noises, the signal to noise ratio can be improved using sensors with better spatial resolution. The circular aperture serves for the diffraction of evanescent waves that can occur on slits. This ensure paraxial incident beam.

4. Studied sample and experimental set-up

Using the sensor with MM lens a two type of planar conducting materials has been evaluated: ferromagnetic AISI 4340 steel (low alloy martensitic steel) which present cracks with micrometric features created by the hydrogen attack and ceramic zirconia top-coating on stainless steels, to differentiate evaluation areas with good/inferior quality.

4.1. Ferromagnetic AISI 4340 steel

Let us consider a ferromagnetic steel block, relatively thick, having maxim roughness 0.1. Such steels when heat treated to very high strength and hardness, are prone to present microscopic hydrogen cracks due to due to its high carbon content (0.38–0.43 %) and addition of Mn, Ni, Cr and Mo. Steel plates of AISI 4340, low alloy martensitic steel was used to introduce HIC which were obtained by exposing the samples to a rich \( \text{H}_2\text{S} \) environments, for different times at room temperature without external loads, for 96 h at room temperature and without external loads, following the test conditions of the NACE TM 0284 standard [15]. The combined high carbon and alloy contents of this steel may lead to the formation of a martensitic microstructure when it is cooled too fast from high temperature to below the transformation temperature. The carbon content is sufficiently high to form hard martensite that may be brittle. The samples were analysed by optical microscopy ZEISS Axio Imager after conventional metallographic polishing with diamond paste down to 1 \( \mu \text{m} \). HIC counting was carried out with the aid of two dedicated software’s for image processing AxioVision 7.4 and Image Pro 6.2. For steel sample with HIC planar dimension is 38x35\( \mu \text{m} \). Surface view of sample with HIC not reaching their edge. The scanning is carried out by passing perpendicularly over the length of HIC. The dimensions of A-A section is 100 x 40 \( \mu \text{m} \).

4.2. Ceramic zirconia top-coating

Ceramic zirconia top-coating on stainless steels are most commonly used as materials for thermal
This work is focused on the properties of Yttria stabilized zirconia (YSZ) as part of TBC. Most present day YSZ is normally used for the TBC [16] due to its outstanding mechanical properties depending on the yttrium content. Stainless steels are very often used as support for TBC, the most widely used is AISI 316L. The AISI 316L steel is low carbon version of AISI 316 (≤0.03 %C), which may be susceptible to intergranular corrosion in certain corrosive media after it is welded or otherwise heated at temperatures between 430°C and 860°C. TBC is a system which consists of a ceramic coating of low thermal conductivity such as zirconia deposited on metallic support using either plasma spraying or electron beam physical vapor deposition processes, with or without Thermally Grown Oxide (TGO), deposited on a metal support [11-13]. Laminar structures of YSZ TBC layers deposited on stainless steels are typically porous and the pore size and character depends on the process parameters.

The AISI 316L used as support is austenitic stainless steel, having good corrosion resistance, (composition in wt. % according to EN 1.4404). After mechanical processes we obtain specimens with dimensions 20x80 mm² and 2 mm height. Electrical conductivity is 1.3513 × 10⁶ S·m⁻¹, thermal expansion coefficient 17.2 × 10⁻⁶ K⁻¹ at 473 K, but may be susceptible to intergranular corrosion in certain corrosive media after it is welded or otherwise heated at high temperatures. Deposition of ceramic coatings was done using plasma torch F 400 with commercial atmospheric equipment APS 100 produced by Swiss Company Plasma-Technik AG. The transformation t→m during a cooling process is accompanied by a volume increase (approximately 4 %) and shear distortion, sufficient to cause failure. At nanoscale level, the main method of tetragonal phase stabilization is the introducing in zirconia lattice of the stabilization component such as Ce or Y. A crack growth approach has been connected for TBC with delamination and spallation. Monolithic coatings of various thickness consisting of zirconia doped with 20 % ytrria and sandwich zirconia doped with 20 % ytrria and pure ytrria coatings were deposited on AISI 316L. The coating material is produced by Metco as powder Metco™ 202NS and Metco 6035A-1 used for plasma spraying, having excellent resistance to oxidation and corrosion at temperature till 1000 °C and can create excellent thermal barrier coatings. Pure ytrrium oxide is a highly stable compound with a high melting point and is very inert chemically and exhibits excellent electrical insulation (volume resistivity and dielectric breakdown strength).

5. Experimental results
Parallelepiped samples from AISI 4340 steel attacked with hydrogen were taken into study. One of the faces has been polished, with Rₐ=1μm, determined using Taylor Hobson Roughness Tester and precision ultra-surface finish software V5. The cracks appeared due to hydrogen attack are invisible with naked eye. In order to visualize and characterize the cracks, a microscope BX51 Olympus USA, functioning in reflection regime, with magnification 200X. The cracks were identified and marked as direction. The samples were placed on the displacing system, the electromagnetic transducer described above being positioned so that the small side of the rectangular emission coils shall be approximately perpendicular on the direction of the crack. The samples were scanned on 100x40µm² with 1 µm scanning step.

In figures 5a,b are presented the microscopic image of two cracks identified and in figures 5c, d the amplitude of electromotive force induced in the reception coil of the electromagnetic transducer at the scanning of the corresponding zone from the sample. In order to reduce the noise, the amplitude represented in each measurement point is the arithmetic average of three measurements. The measurement frequency has been 484MHz. The analysis of the data from figure 5c and d shows that the electromagnetic images of the cracks, optical identified, are in good concordance with the microscopy images, fact that recommend the proposed method for the detection of cracks with very small widths and depths.
The ceramic zirconia top-coating is nonconductive and nonmagnetic and therefore behaves like an air gap between the electromagnetic sensor and the conductive substrate and only creates a probe lift off effect. The substrate AISI 316L stainless steel is nonmagnetic with magnetic permeability equal to 1, allowing electromagnetic test. Due to the porous structure of ZrO₂, comparatively with AISI 316L substrate, to obtain relevant information about the influence of yttria concentration over the adherence at support, Secondary Electrons (SE) images, as well as Backscattered Electrons (BSE) images (Figure 6) were taken.

Using a procedure for image processing was determined that pores created about 3 up-to 12% of the analyzed layers. Pores are distributed random and nonhomogeneous. In figure 6 b are presented the histograms of voids data. It can be observed that with the doping with yttria, the voids are larger, however their number decreases. The presence of pores in material can be observed, being indifferent by the deposition methods, their difference being given only by the dimensions and density of distribution [17].

Transversal line profiles have been taken into consideration for the specimen. For the this case, in the cumulative spectrum shown in figure 7 low image, the presence of Fe, Ni and Cr can be observed as belonging to 316L substrate, as well Zr and O belonging to the deposited layer. The images show a possible formation of new oxides in both exposed specimens with yttria, however is observed at interface between the steel and layer of zirconia that a greater oxidation occurs in, more scattered within the zirconia doped with yttria. Nondestructive identification of the last type of oxidation is of interest in this paper. The sensor with MM lens has allowed the identification and estimation of the zones where the nanoparticles have created shear distortions, possible to degenerate.
in the damage of the coatings. The samples were placed on the displacing system, with emission coil perpendicular on the surface and on scanning direction (figure 2a). The sample were scanned on 10x10mm2 with 200µm scanning step. In figure 8 is presented the amplitude of the voltage induced in the reception coil of the electromagnetic sensor at the scanning of the corresponding zone from the sample.

![Figure 7. EDXS of specimen with sandwich coating 0.25 mm ZrO2 + 20 %Y2O3 and 0.005 mm Y2O3.](image1)
![Figure 8. The amplitude of the voltage induced in the reception coil of the EM sensor at the scanning of the specimen sandwich coating 0.25 mm ZrO2 with addition of 20 %Y2O3 and 0.005 mm Y2O3.](image2)

6. Conclusions
Simulations effectuated using the software CIVA have shown that the classical eddy current transducers, even of small dimensions and using high permeability ferrite core cannot detect cracks with micrometric features. The factor that limits this detection is evidently the noise. Using plane electromagnetic waves, TMz polarized as excitation, in the region of the cracks appear evanescent waves in cracks, or which are diffracted by the crack’s edges. Using a MM lens, CSR type, the evanescent waves can be manipulated and the EM images of the detected cracks are in very good concordance with the images obtained by optical microscopy.

From the zone inspected, the results allow the characterization of the surface microstructure and possible spallation/delamination at the interfaces of deposited layers. Also small roughness can be emphasized. The results of the NDT method have been confirmed by optical methods.

Further tests on a larger number of specimens with different coating aspects of the surface / number of layers are needed to establish the accuracy of the results and also the correlation between the located very small defect in size and the results of MM sensor response.

Acknowledgments
This paper is partially supported by Romanian Ministry of Research and Innovation under project PN-II-PCCA-2013-4-0656 and Nucleus Program PN 16-37 01 01 and Bilateral Cooperation with JINR Dubna under protocol no. 4414-4-2015/2017.
7. References
[1] Kahn A H, Spal R and Feldman A 1977 J. Appl. Phys. 48 4454
[2] Sommerfeld A1964 Optics: Lectures on Theoretical Physics IV (New York: Academic Press)
[3] James G L 1986 Geometrical theory of diffraction for electromagnetic waves 4 (Herts: IET)
[4] Born M and Wolf E 2002 Principles of Optics 7th ed.(Cambridge: University Press)
[5] Muck M, Korn M, Welzel C, Grawunder S and Scholz F 2005 IEEE T Appl Supercon 15 (2) 733
[6] Grimberg R and Tian G Y 2012, Proc. R. Soc. A 468 2146
[7] Grimberg R, Savin A, Steigmann R, Serghiac B and Bruma A 2011 Insight 53 3 132
[8] Grimberg R, Savin A and Steigmann R 2012 NDT & E Int 46 70
[9] Grimberg R and Savin A 2011 Electromagnetic transducer for evaluation of the structure and integrity of composite materials with polymer matrix reinforced with carbon fibers (Patent no. RO126245-A0)
[10] Savin A, Steigmann R and Bruma A 2014 Sensors 14 11786
[11] Savin A, Steigmann R, Bruma A and Šturm R 2015 Sensors 15 15903
[12] Goodman J W 2005 Introduction to Fourier optics. (Greenwood Village: Roberts and Company Publishers)
[13] Engheta N and Ziolkowski R W 2006 Electromagnetic Metamaterials: Physics and Engineering Explorations. (NY:Wiley)
[14] CIVA 9.2 - EXTENDE – User Manual.
[15] NACE TM0284-2011 Standard Test Method - Evaluation of Pipeline and Pressure Vessel Steels for Resistance to Hydrogen-Induced Cracking. National Association of Corrosion Engineers. (2011)
[16] Schulz U 2000 J Am Ceram Soc 83 904
[17] Faktorova D, Novy F, Fintova S, Savin A, Steigmann R, Iftimie N, Turchenko V and Craus M L 2016 Stud Appl Electromag 41 254