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Nondestructive testing of advanced materials using sensors with metamaterials

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Abstract. This work presents a method for nondestructive evaluation (NDE) of advanced materials that makes use of the images in near field and the concentration of flux using the phenomenon of spatial resolution. The method allows the detection of flaws as crack, non-adhesion of coating, degradation or presence delamination stresses correlated with the response of electromagnetic sensor.

1. Introduction

Electromagnetic nondestructive evaluation (eNDE) is based on the modification produced by the variation of electrical properties of the examined material due to small inclusions, mechanical /thermal fatigue or of structural components [1]. The term of discontinuity can be defined by the flaw induced in the material during exploitation as well as an imperfection appeared during the technological process. The dimensions and the location of discontinuity, evaluated by noninvasive tests, considered as flaw, are specified in the product standard. The importance of small flaws detection cannot be exaggerated, being known that these can develop due to fatigue or corrosion during exploitation, leading to catastrophic failures. The discontinuities can appear during the fabrication stage and during the coating of metals when the ceramic coatings aims to increase the capacity of high-temperature resistance and protection from thermal oxidation of the substrate. Few coating flaws cannot influence the use of a component, but, per assembly, can decrease the resistance of the finite product. Ceramic materials are optimal for thermal barrier coating (TBC) for their high melting point and possibility to be realized by insular deposition. TBC are essential in aerospace application and mechanical components and systems, for their capabilities of lowering metal surface temperatures. The inspection of equipment from industrial installations represent an efficient way to foreseen and reduce possible risks, but, the use of new materials presenting special properties in extreme environment conditions is nowadays the ideal solution to reach this desideratum. From this reason, the NDE is a domain in continuous developing.

For the material electrical conductive and the flaws possible to appear at the surface or immediately under its surface, one of the NDE possibility is represented by eddy current method.

For the detection of depth cracks with small opening is difficult to apply high frequency electromagnetic methods using "classical" sensors because the standard penetration depth is comparable with crack depth. The detection of surface or subsurface material discontinuities in flat conductive materials is usually performed by electromagnetic method with the sensor scanning the surface to be inspected. For the better localization of discontinuity position, new type sensor with metamaterials (MM) lens is used.

Metamaterials [2], [3] has attracted interest the scientific community, due its possible applications in the optical domain and nondestructive evaluation of materials by construction of performant sensors (perfect lenses, controllable reflection and transmission devices, and electromagnetic absorbers) [4-6]. A generic NDE system is presented below.

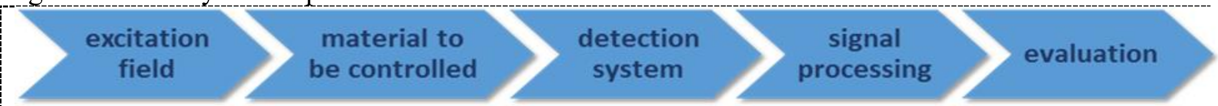


Figure 1. The generic NDE system

The efficient acquisition of data and the displaying of interpretable results of materials properties and their quality has led to development of equipment able to evaluate components/systems without damaging [7].

This paper presents a new type of electromagnetic transducer for detection of micrometric cracks, opened at the surface or immediately subsurface of a material with roughness smaller than the depth of crack.

2. Studied samples; experimental set-up

Let us a steel block, relatively thick, made of advanced materials such as:

a) *steel plates AISI 4340*, low alloy martensitic steel were studied. These present microscopic cracks due to the hydrogen attack. Such steels, when are heat treated to obtain very high strength and hardness, are prone to present microscopic hydrogen cracks due to its high carbon content (0,38-0,43 %) and addition of Mn, Ni, Cr and Mo. The combined high carbon and alloy contents of this steel can lead to the formation of martensite 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. When exposed to rich hydrogen content environments by the manufacturing process or by the service conditions, frequently exhibits what it is called hydrogen induced cracking (HIC). One of the faces of the sample has been polished, with R_a=1μm, determined using Taylor Hobson roughness and precision ultra-surface finish software V5.

HIC were obtained for the samples according to the test conditions of the NACE TM 0284 standard [8], without external loads.

b) *steel plates AISI 316L*, coated with ZrO_2 and ZrO_2 and 20 % Y_2O_3. The optimization of the substrate surface topography preferably is based on more complete characterization in order to achieve a reasonable balance between the level of induced delamination stresses and the mechanical bonding, minimization of the defect size. Yttria Stabilized Zirconia (YSZ) ceramics are considered Thermal Barrier Coating (TBC) materials due to their thermal conductivity (~2.0 $m^{-1}.K^{-1}$ at 1100 °C), refractory, chemical inertness, and compatible thermal expansion coefficient (10.1 × 10^{-6} K^{-1} at 873 K) with metallic support. 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 steel is low carbon version of AISI 316 (0.018 %C), which may be susceptible to intergranular corrosion (IGC) in certain corrosive media after it is welded or otherwise heated at temperatures between 430 and 860 °C.

In order to detect flaws as cracks, non-adhesion of coating, etc. high frequency electromagnetic methods must be used, so that the standard penetration depth shall be comparable dimensions of flaws. For detection the possible discontinuities is use an electromagnetic sensor with MM lens, absolute send-receiver-type [9].

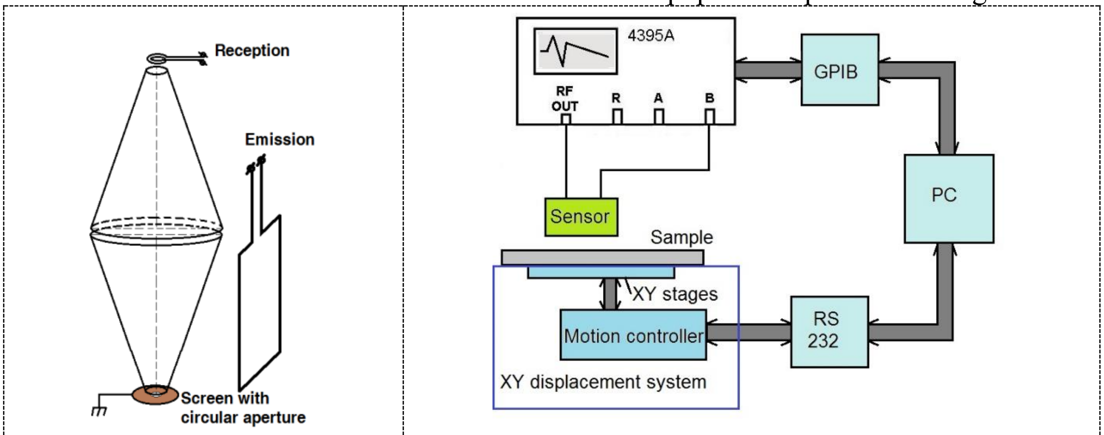
In electromagnetic NDE [10, 11], the frequency is chosen so that h≈3δ where, h is the depth of the flaw and $\delta = \sqrt{\frac{1}{\pi f \sigma \mu}}$ represents the standard penetration depth, $\mu = \mu_r \mu_0 = \mu_r \cdot 4\pi \cdot 10^{-7}$ H/m.

The sensor with MM lens [12, 13] used in electromagnetic nondestructive evaluation (eNDE) [10, 11] is an absolute receiver-type sensor. The lens is made using two conical Swiss rolls (CSR) [7] having a large basis face to face and is focusing the electromagnetic field and also the evanescent waves (Figure 2a). A CSR consists of a number of spiral wound layers of an insulated conductor on a conical mandrel.

The geometrical parameters of CSR are 20 mm base diameter, 3.2 mm top diameter, 20° aperture angle, 55 mm height and 3 turns made from 18 μm thickness copper foil adhesiveless laminated with 12 μm thickness polyimide foil (LONGLITE™200 produced by Rogers Corporation), in order to decrease the losses at high frequencies. The operation frequencies depending both by the constitutive parameters of MM as well as by the polarization of the incident electromagnetic field (TE_z or TM_z). The focal distance of this lens is *f=l*, where *l* represents the height of the CSR. The frequency dependence of the effective magnetic permeability of the CSR was determined measuring the S parameters (S_{11} and S_{21}) and applying the effective medium method using a 4395A Network/Spectrum/Impedance Analyzer coupled with an Agilent 87511A S Parameters Test kit. CSRs are tuned at 105 MHz frequency [9].

MM lenses are lenses that, at working frequency, have either $\varepsilon_{eff} = -1$ and then electric evanescent modes can be manipulated, either $\mu_{eff} = -1$ and then the lens can focus magnetic evanescent modes [15]. As shown in [14] the sensor with MM lens functioning in the range of frequencies such that μ_{eff} are a maxim value. For a resonance frequency of 105 MHz, the relative magnetic permeability is 24. The incident field is generated by a one-turn rectangular coil, having 35 × 70 mm, using a Cu wire with 1 mm diameter. In focal plan of the MM lens is placed one turn circular coil with 1mm diameter and 0.1mm wire. During the measurement, the sensor is maintained in fix position, the relative displacement sensor – object to be controlled is made with a XY motorized stage Newmark, which assures the displacement in plan with ±10 μm precision, at the scanning of area with established steps in both directions. Once the level of noise was estimated, the optimal signal processing method is started. The scanning, measurements, acquisition and the processing of data were commanded by a PC using programs developed in Matlab 2014b.

The scheme to connection of sensor with MM lens with equipment is presented in figure 2b.



(a) (b)

Figure 2. Scheme of : Sensor with MM lens (a); connection of sensor with MM lens with equipment (b)

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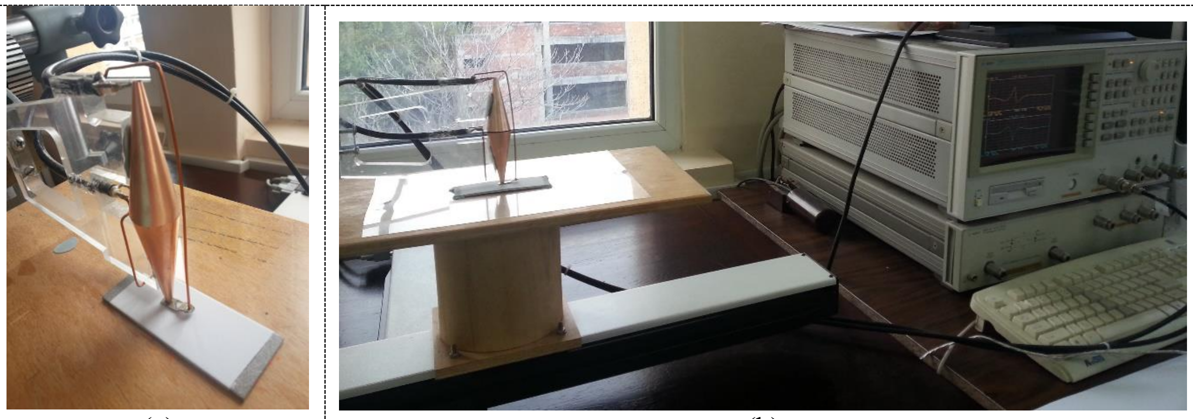
During the scanning of the selected region of sample the presence of discontinuities disturb the propagation field and the sensor detect the signal. The image delivered by the sensor is amplified.

The method presents the advantage of giving in one representation both the information about amplitude and phase obtained from the sensor.

The sensor is connected to Network/Spectrum/Impedance Analyzer 4395A Agilent coupled through IEEE 488 interface switch to a PC which also commands the displacement system. The physical realization of this is presented in Figure 3a and the connection with equipment in Figure 3b.



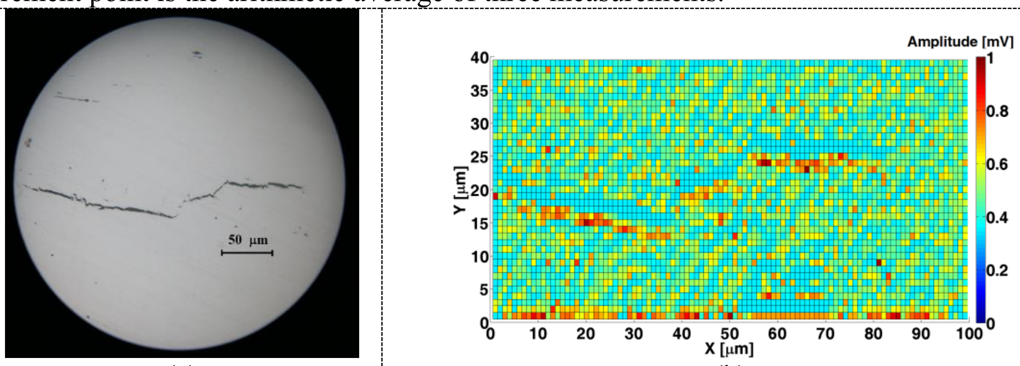
(a) (b)

Figure 3. Electromagnetic sensor with MM lens: physical realization (a); experimental set-up (b)

3. Results

3.1. *The samples AISI 4340 steel* attacked with hydrogen are one of the faces polished, with R_a=1μm, determined using Taylor Hobson rugosimeter and precision ultra-surface finish software V5. Presence of the cracks appears due to hydrogen attack and these are invisible with naked eyes. Using a microscope BX51 Olympus USA, functioning in reflection regime, with magnification 200X this cracks is identified and marked as direction. This sample was scanned on 100x40μm^2 with 1 μm scanning step.

In Figure 4a is presented the microscopic image of crack identified and in Figure 4b the amplitude of electromotive force induced in the reception coil of the electromagnetic transducer at the scanning of the corresponding zone from the sample. For the measurements, the amplitude represented in each measurement point is the arithmetic average of three measurements.



(a) (b)

Figure 4. Comparison between optical images (200X magnification) (a) and electromagnetic images (b) for the crack

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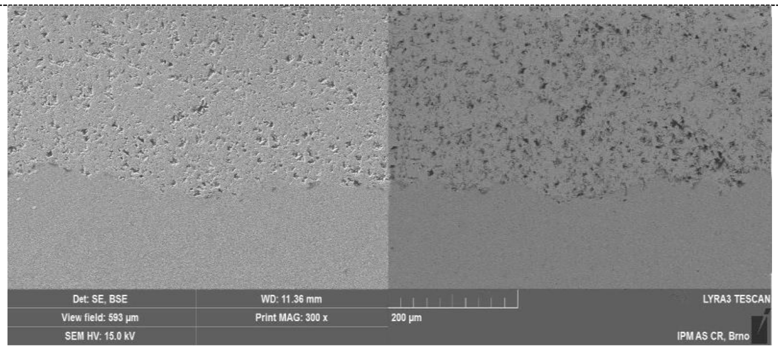
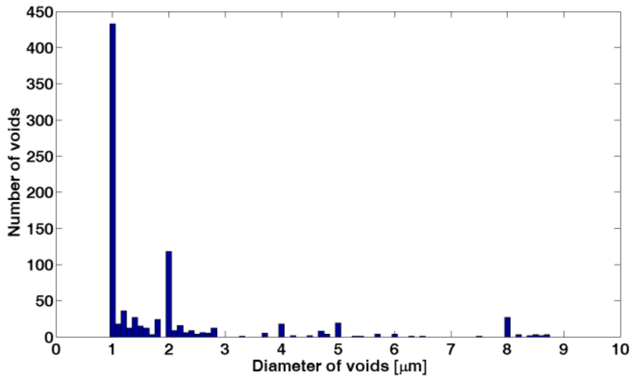
3.2. *Steel plates AISI 316L* - for the characterizing the sample, the SEM method has been used, so SEM images (Figure 5a) emphasize that the 316L steels substrate is compact, with some inclusions and/or pores between it and the ZrO_2 layer.



(a)



(b)

Figure 5. The SEM images (a)and voids counting (b) for specimen with 0.2 mm thick monolithic coating ZrO_2 with addition of 20 % Y_2O_3

In particular, the results obtained [16] show that for the specimens, with 0.2 mm thick monolithic coating of ZrO_2 with addition of 20 % Y_2O_3, the 316L substrate is compact, some little inclusions and/or pores between the support and the ZrO_2 layer. 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. EDX analysis shows the interface between the steel and the zirconia layer, a higher degree of oxidation takes place, more scattered within the zirconia doped with yttria. Nondestructive identification of the last type of oxidation is of interest in this paper. For this type of specimen the ceramic top-coating (nonconductive and nonmagnetic) become a material which create a probe lift-off. The response of the sensor depends only on coating thickness and the existence or lack of adhesion. On the other hand, the residual stresses in the TBC affected its performance. The amplitude of the signals received by the sensor is presented in Figure 6.

Examining Figure 6, it can be observed that the values of electromotive force induced in the reception coil of sensor are usually affected by several parameters, as lift-off, inspection frequency, material composition, and the presence of inhomogeneity on or near the object surface. Monolithic coating zirconia, with addition of 20% yttria having different thickness does not presents non adherence zones. The amplitude of the voltage induced in the reception coil has relatively constant value, excepting the regions where the variations appear due probable to oxide agglomerates. The surface of metallic substrate was blasted to create perfectly clean and rough enough surface for good adhesion of deposited ceramic coating.

The eNDE is non-invasive method, interpretation of results requires considerable knowledge of the electromagnetic properties of the samples as well as the technique itself.

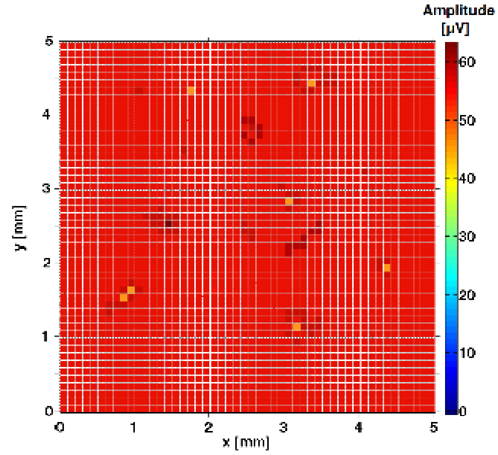


Figure 6. The amplitude of the voltage induced in the reception coil of the sensor at the scanning of the sample.

New types of materials or of materials already studied in special environmental conditions need other adaptable methods for characterization and evaluation. The challenge for the development of new types of electromagnetic sensors consists in the obtaining of good detection sensitivity for a minimum 3/1 signal to noise ratio (signal strength relative to background noise) as well as good spatial resolution. The signal to noise ratio has been determined measuring the signal in the reception coil over the tested samples and in free space. The analysis of the results show the possibility to apply this method to determine the eventual dislocations of coating layer from the substrate layer and can be improved further to complete the existent methods (infrared thermography, ultrasounds, etc).

4. Conclusions

In order to detect the intensification of evanescent waves, a sensor with MM lens is used at normal incidence, in the near field. Using plane electromagnetic waves, TMz polarized; evanescent wave can appear in cracks, or which are diffracted by the crack's edges. Using this type of sensor, the evanescent waves can be manipulated and the electromagnetic images of the detected cracks are obtained. These images are in good concordance with the images obtained by optical microscopy.

New nanocomposites, with nanometer - sized second phase particles dispersed in ceramic matrix and/or at grain boundaries have shown an ability to withstand thermal cycling at temperatures significantly higher than simple layer YSZ-coatings. They also have significant better strength and creep resistance than other coatings. Hence the evaluation of the surface structure and possible delamination at the interface of deposited layers for this type of zirconia coating on stainless steel is important.

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 localized small-sized discontinuities and the resulting MM sensor indication.

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