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Advances in NDT and materials characterization by eddy currents

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Abstract

New materials and production technologies demand improved non-destructive techniques for inspection and defect evaluation, especially when critical safety applications are involved. In this paper a new non-destructive testing (NDT) system is presented. The innovative system is composed by a new type of eddy currents probe, electronic devices for signal generation, conditioning and conversion, automated mechanized scanning and analysis software. This new probe provides enhanced lift-off immunity and improved sensitivity for defects detection. The IOnic system was developed mostly to be used for the defects detection on aluminum solid state processed alloys as Friction Stir Welding (FSW) and Friction Spot Welding (FSpW), however recent studies revealed IOnic probe good capacities on other applications.

This study evaluates the capacity of the IOnic probe on detecting buried defects under the surface of Graphite and Stainless steel AISI 304 alloys extending the probe application to other materials and defect morphologies. In order to evaluate its performance results, a comparison with results from conventional EC probes is discussed.

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Keywords: Eddy Currents; Non-Destructive Testing; Planar and Differential Probe; Stainless Steel; Graphite

1. Introduction

Non-Destructive Testing (NDT) plays a vital role to achieve reliability and quality at an acceptable cost. Failures of engineering materials, components and structures are well known and can be disastrous [1]. Avoiding the failures cost effectively ensuring safety of use and reliability on a wide range of industrial components are the major industrial NDT objectives.

NDT is facing new challenges for defect detection and quality control of advanced engineering materials such as in multi-material structures [2], non-ferrous alloys for advanced lightweight structures, composites [3] (GLARE), carbon resins composite, Fiber-reinforced Metal Laminates (FML), High Performance Thermoplastic Composites (HPTC) and Metal Matrix Composites (MMC)). In the scope of recent production technologies: Friction Stir Welding (FSW), Friction Surfacing, Friction Stir Processing (FSP) and Single Point Incremental Forming (SPIF), innovative NDT techniques and technologies are required, and must be transfered from research to industry as quickly as possible to solve these challenges [4].

Nowadays, there is a broad range of NDT methods based on different physical principles but the most commonly used are ultra-sonic and eddy currents, X-radiography, magnetic particles and dye penetrant. However, eddy current have seen an enormous increase in the last years. The basic eddy current (EC) probe is a cylindrical coil used to generate and sense the electrical current in the metallic part simultaneously. The modification of the eddy currents due to the presence of a defect, leads to the variation in the coil electrical impedance. NDT instruments register these variations

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allowing the detection and, eventually, characterization of these defects [5].

This study aims to evaluate the capacity of two different EC probes detecting buried defects under the surface of Graphite and Stainless steel AISI 304 alloys and extend the application of the new IOnic probe to other materials and defect morphologies, in order to evaluate its performance, conventional EC probes were used for comparison.

The IOnic probe was developed mostly to be used for defect detection on aluminum solid state processed alloys as Friction Stir Welding (FSW) and Friction Spot Welding (FSpW). However, recent studies [6] revealed IOnic probe has a good potential for other applications.

2. Previous Evaluations

Friction stir welding may exhibit defects of different size and orientations but are usually aligned with the weld direction [7]. Most FSW defects are difficult to detect using conventional NDT methods and instruments since they are characterized by very small and thin cracks with volume close to zero. For defects that are difficult to detect by conventional techniques, industry has employed destructive testing, advanced NDT methods, in-process monitoring, or combinations of these are required by industry, reducing the occurrences of those defects [8].

Previous studies highlighted the capabilities of a custom NDT system including the IOnic probes to detect and characterize FSW joints. Experimental evaluation of this system on FSW joints of AA2024 alloy is discussed [9] [10] and results show that:

- The transversal superficial conductivity profile resembles a Gaussian function centered with the weld joint. The higher conductivity modifications are observed at the joint center;
- Experimental results showed that the IOnic probe is able to identify different FSW root defects by a distinctive perturbation on the output signal and that exists a good proportionality between the defects size and signal perturbation;
- IOnic probes were able to distinguish small local variations of conductivity, caused by typical FSW root micro defects with depth below 60 μm significantly better than the 200 μm detected by conventional EC probes;
- The new probe is less dependent on unwanted interferences such as probe lift-off and material magnetic permeability. Additionally it is less sensitive to small variations of the conductivity changes and electronic issues.

Experiments on Friction Spot Welding (FSpW) with and without Alclad™ and GLARE® composite material [7] revealed that:

- A clear IOnic probe capacity to distinguish welded conditions between Friction Spot Welding (FSpW) aluminum alloys with and without Alclad™ treatment;
- The probe also identifies sub superficial volume and particles alignment defects around the pin location;
- Ability to identify different levels of FSpW quality regions by distinctive perturbations on the output signal, whereas conventional probe cannot distinguish the different FSpW conditions;
- On GLARE® composite material, IOnic probe detects the artificial buried defects up to 2.25 mm significantly better than conventional EC probes.

3. NDT Equipment

The IOnic probe is a planar differential eddy current probe. Unlike the conventional probes, in the innovative IOnic probes, eddy currents are generated and sensed by two individual elements. Eddy currents are generated by an electrical current flow at the central cooper track or a vertical coil, that allows the generation of very confined and extension aligned eddy currents. The sensing element is constituted by two symmetrical wired sensing coils which form a differential magnetic flux sensor. This differential functioning permits high sensitivity measurements of the resulting magnetic field [5].

The presence of defects or other conductivity changes under the probe surface is indicated by the balance change between the two sensing coils and the consequent output voltage increase. That variation is shown to the NDT system operator by an output voltage different than zero.

For this study, a prototype probe was produced using Printed Circuit Board (PCB) technology and a permanent lift-off with a thin 50 μm thickness piece of polymer was used to isolate copper of the coils from the sample surface. Excitation drive is characterized by a 10 mm length, 1 mm width and the sensitive coils for two 10 mm opposite wired 10 turns coils with 50 μm width and 50 μm spaced apart. The prototype probe and its elements are shown in Fig.1.

A previously designed dedicated instrument was used on the experimental procedures to cope with the generation and processing of the IOnic probe signals. Additional details regarding the instruments and the employed digital processing techniques can be found in [11]. Besides these main functions, it also allows controlling scanning devices with up to three axes.

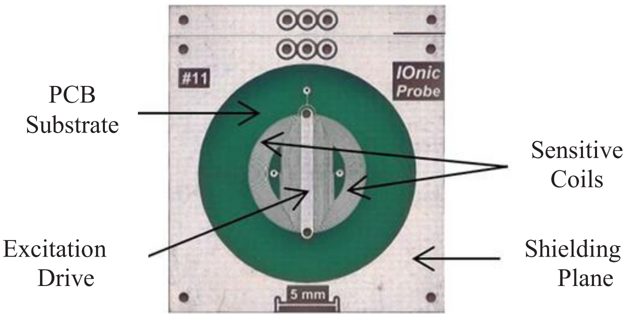

Fig. 1. IOnic probe processed in a printed circuit board substrate.

4. Experimental Procedure

For this study two materials with different electrical characteristics were chosen, stainless steel AISI 304 (ferrous metal) and graphite (non-metal material with electrical conductivity different than zero), whose physical proprieties are described in Table 1.

Table 1. Base Materials Characteristics.

Material	Electrical Conductivity [% IACS]	Relative Permeability [H/m]	Density [Kg/m^3]
AISI 304	2.33	1.008	8000
Graphite	0.22	1	1750

Two 10 mm thickness samples were produced, one of each material with a matrix of drilled holes. The distance between the holes and the inspection surface increased from 100 to 3000 μm. The matrix was divided in three inspection lines, Line 1 (L1), Line 2 (L2) and Line 3 (L3) as shown in the schematics of Fig. 2. On the stainless steel sample, 15 holes 20 mm distant from each other were made. On the graphite sample, the number of holes was reduced to 13 increasing the distance to the edge and reducing the edge effect In this sample Line 2 has defect with depths of 1000, 1300, 1500 and 1800 μm and Line 3 with 1500, 2000, 2500 and 3000 μm. Inspections were performed moving the probes over 100 mm on the top surface with the excitation filament perpendicular to the inspection lines.

For a correct comparison of the IOnic probe capacities all experimental procedures were repeated at the same conditions with two commercial OLYMPUS probes. The selected testing parameters are presented on Table 2.

Table 2. Testing Parameters.

	IOnic	OLYMPUS
NDT Equipment	IOnic dedicated	Nortec 500D
Probe	IOnic #11	MTF905-60 P/500kHz-1MHz
Frequency [kHz]	10, 25, 50, 100, 200, 500, 1000, 1700	
Gain [dB]	35-77	50-90
Lift-off [mm]	0	
Sweep [mm]	100	
Step Resolution [mm]	0.1	
Duration [s]	60	62

An automated handling and positioning device (Fig. 3) was designed and produced to enable probe's accurate and smooth movement [6]. The produced device has a resolution of 0.1 mm and it is controlled by stepper motors. An analysis software developed with LabVIEW [12] allows to process, monitor and register the acquired signals in real-time and to control the XY devices.

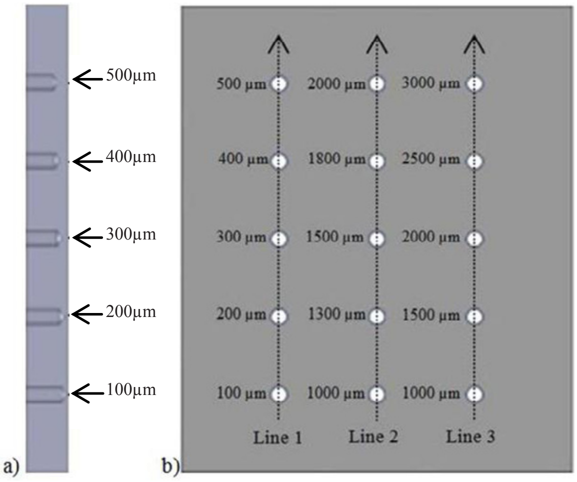

Fig. 2. a) Line 1 cut view and depth representation; b) Stainless Steel IASI 304 hole depth schematic representation of Line 1, Line 2 and Line 3.

Fig. 3. Produced automated handling and positioning device.

5. Results

Both probes, conventional and IOnic, were applied on the defect conditions described above. Data was acquired from the top surface along the inspection lines with the testing parameters described on Table 2.

The inverse positions of the minimum and maximum values of the Im(Z) observed at the IOnic probe graphical representation, are the main feature to detect and identify the defects. Data acquired from commercial probes are presented as the Abs(Z) value and the defects influence is shown as an increase on that same value.

5.1. Stainless Steel AISI 304

For the tests with commercial EC probes on the AISI 304 sample, the results are shown in Fig. 4 where it can be seen that, for frequencies of 10, 25 and 50 kHz (as for all the remaining inspection frequencies) there is no evidences of the defects presence. On the contrary, IOnic probe inspections (Fig. 5) clearly revealed the presence of 100, 200, 300, 400 and 500 µm defects as well as the difference between the holes depth. Near surface defects show bigger variations on the Im(Z) signal than deep buried defects. Higher frequencies showed higher signal amplitude variations. Observing Fig. 6 that compares the results of Line 1defects with IOnic and commercial probes at a frequency of 100 kHz, the difference between both probes capacity to detect the defects its clear.

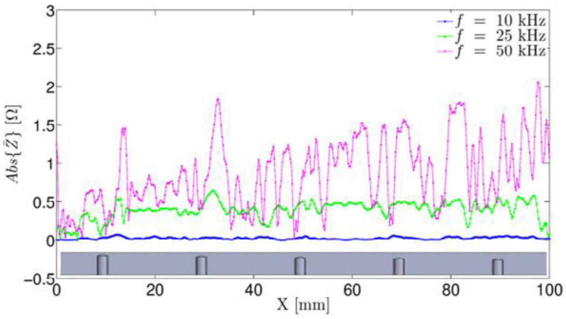

Fig. 4. Results of conventional EC probes inspection along Line 1 in AISI 304 sample (f = 10, 25 and 50 kHz).

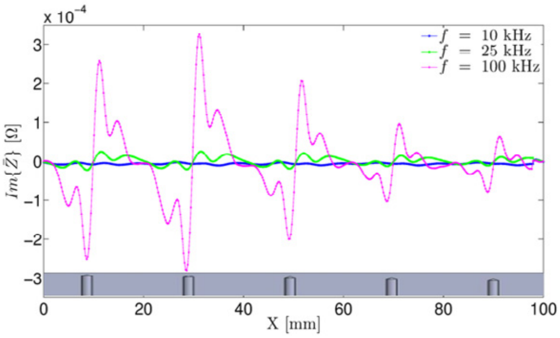

Fig. 5. Results of IOnic probe inspection in Line 1 of AISI 304 sample (f = 10, 25 and 100 kHz).

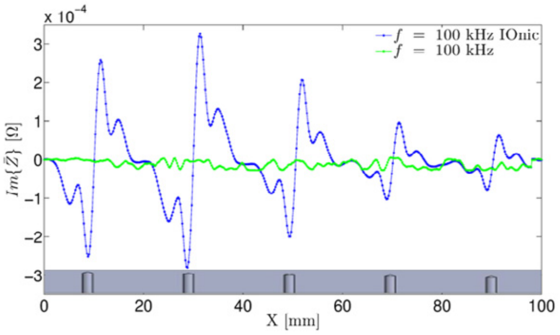

Fig. 6. Comparison of the inspections results for the IOnic and the conventional probes in Line 1 of AISI 304 sample (f = 100 kHz).

5.2. Graphite

The results on the Graphite sample with the commercial probes revealed the defects presence at Line 1, up to 500 µm and that the Abs(Z) amplitude decreases approximately linearly with the defects depth increment as shown in Fig. 7. On the other hand, the IOnic probe exhibit evidences of all the produced defects, existing in Line 1 (100-500 µm), Line 2 (1000-1800 µm) and Line 3 (1500-3000 µm) (Fig. 8,

Fig. 9, Fig. 10). In this case higher frequencies produced better results. The IOnic probe also allowed differentiating the depth of the defects. A comparison of the IOnic and commercial probes results can be observed in Fig. 11.

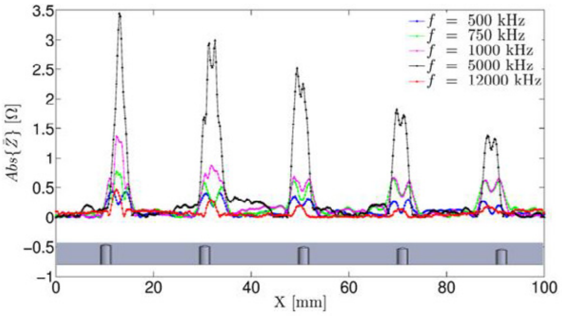

Fig. 7. Results of conventional EC probes inspection along Line 1 in Graphite sample (f = 500, 750, 1000, 5000 and 12000 kHz).

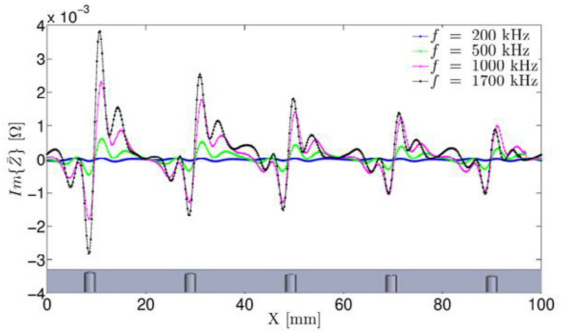

Fig. 8. Results of IOnic probe inspection in Line 1 of Graphite sample (f = 200,500, 1000 and 1700 kHz).

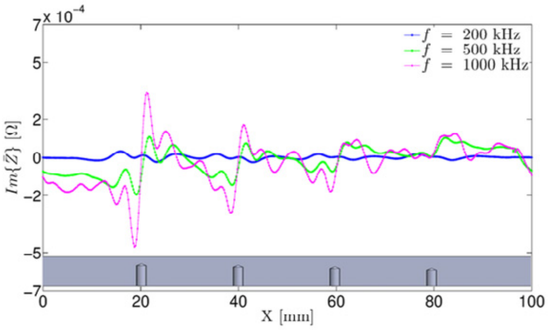

Fig. 9. Results of IOnic probe inspection in Line 2 of Graphite sample (f = 200,500 and 1000 kHz).

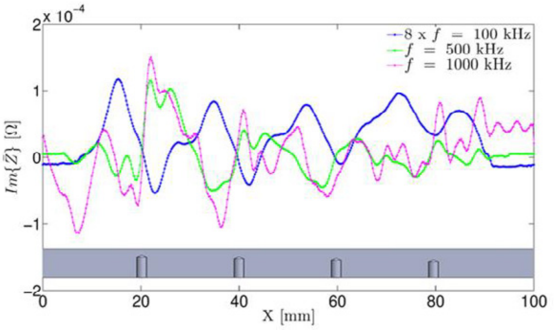

Fig. 10. Results of IOnic probe inspection in Line 3 of Graphite sample (f = 100,500 and 1000 kHz).

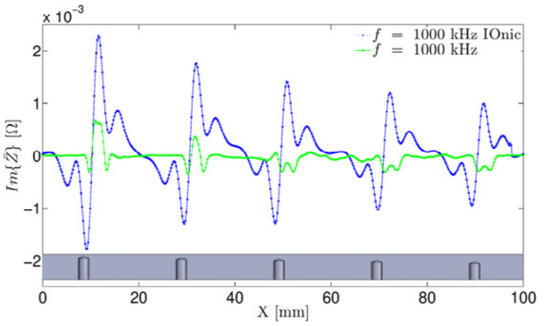

Fig. 11. Comparison of the inspections results for the IOnic and the conventional probes along Line 1 of the AISI 304 sample (f = 100 kHz).

6. Conclusions

In this work, the IOnic eddy current probe NDT system was experimentally evaluated on deep buried defects detection on Stainless Steel AISI 304 and Graphite. For results validation, comparison with conventional EC probes was made. The following conclusions can be retained:

- The IOnic probe can clearly distinguish defects up to 500 µm depth on Stainless Steel AISI 304 alloy, while the conventional EC probes were not able to detect none of the produced defects;
- The IOnic probe also identifies the presence of all the produced defects on Graphite between 100 and 3000 µm depth, greater than the best result of 500 µm obtained with the conventional probes;
- The results for the IOnic probe showed a very good proportionality between the signals amplitude and defect properties on both the inspected materials.

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References

[1] European Federation for Non-Destructive Testing (EFNDT), "Overall NDT Quality System," June 2008.

[2] P.M.G.P. Moreira, T. Santos, S.M.O. Tavares, V. Richter-Trummer, P. Vilaça and P.M.S.T. de Castro, "Mechanical and metallurgical characterization of friction stir welding joints of AA6061-T6 with AA6082-T6," *Materials and Design,* vol. 30, pp. 180-187, 2009.

[3] D. C. Sorin V. Teles, "Closed disbond detection in marine glass-epoxy/balsa," *NDT&E International,* vol. 41, pp. 129-136, 2008.

[4] Z. Liu, David S. Forsyth, Jerzy P. Komorowski and Koichi Ha, "State of the Art in NDE Data Fusion Techniques," *IEEE Transactions on Instrumantation and Measurement,* vol. 56, pp. 2435-2451, December 2007.

[5] L. S. Rosado, T. G. Santos, P. M. Ramos, P. Vilaça and M. Piedade, "A differential planar eddy currents probe :Fundamentals ,modeling and experimental evaluation," *NDT&E International,* vol. 51, pp. 85-93, 2012.

[6] G. Almeida, *Simulação Numérica e Avaliação Experimental do Desempenho de Sondas Inovadoras de Correntes Induzidas em Diferentes Materiais e Defeitos,* Tese de Mestrado, FCT, UNL, Lisboa, 2012.

[7] T.G. Santos, P. Vilaça, L. Quintino, J. dos Santos and R. M. Miranda, "Application of Eddy Current Techniques to Inspect Friction Spot Welds in Aluminium Alloy AA2024 and a Composite Material," *Weld World,* vol. 55, pp. 9-10, 2011.

[8] D. Lammlein, N. Trepal, M. Posada and A. Floyd, "Defect Significance and Detection in Aluminum Friction Stir Welds: A Literature Search," Naval Surface Warfare Center, Carderock Division, West Bethesda, MD 20817-5700, November 2011.

[9] T. Santos, P. Vilaça, J. d. Santos and L. Quintino, "A New NDT System for Micro Imperfections Detection: Application to FSW and FSpW," *Weld World,* vol. 53 (Especial Issue), 2009.

[10] L. S. Rosado, T. G. Santos, M. Piedade, P. M. Ramos and P. Vilaça, "Advanced technique for non-destructive testing of friction stir welding of metals," *Measurement,* vol. 43, 2010.

[11] L. S. Rosado, M. Piedade, P. M. Ramos, T. G. Santos and P. Vilaça, "A Reconfigurable Digital Signal Processing System for Eddy Currents Non-Destructive Testing". In: *Proceedings of the IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*, Austin, EUA, May 2010.

[12] LabVIEW, "National Instruments," [Online]. Available: http://www.ni.com/labview/pt/.