INVITED PAPER

Advances in Electromagnetic NDE and its Applications to the steel and allied industries

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Introduction

Increasing demands in the performance requirements from industrial components and structures has put the onus on Nondestructive Evaluation (NDE) techniques and processes to improve the capability, reliability and productivity in the detection and characterization of flaws and other material properties which can impact its structural integrity. Electromagnetic NDE techniques have been very widely used in the industry for surface & near-surface flaws at all stages; raw material, manufacturing / fabrication, maintenance, in-service and remaining life estimates. Over the decades, there have been a number of advancements in all adjacent disciplines thus giving rise to large number of advancements in the area of electromagnetic NDE. The large range of materials used in today's industry, the complex shape of components for greater efficiency, the ability to process dat a at fast rates, the capability to miniaturize sensors & create arrays, desire to automate the inspection process and the need to expand the application space for the electromagnetic NDE techniques have also brought along with it a set of challenges which need effective solutions. Apart from the technique advancements such as the use of multifrequency, remote field and pulsed eddy current for newer and challenging inspections, the use of the higher end of the electromagnetic spectrum such as microwave and terahertz are being extensively explored today.

This paper describes the state-of-the-art in the area of electromagnetic NDE in general including newer techniques, advanced sensors, effective utilization of modelling and simulation, improved reliability through signal processing and pattern recognition. Applications to the steel and allied industries in specific with suitable examples from the real world which are being practised or attempted are listed. This will help to build the confidence and enhance its utilization to larger areas in the industry.

Eddy Current Techniques

Eddy current testing (ECT) has its origins with Michael Faraday's discovery ofelectromagnetic induction in 1831. In 1879 Hughes recorded changes in theproperties of a coil when placed in contact with metals of different conductivity andpermeability, but it was not until the Second World War that these effects were put topractical use for testing materials. Much work was done in the 1950's and 60's,particularly in the aircraft and nuclear industries, and eddy current testing is now anaccurate, widely used and well-understood inspection technique.

Starting from the Conventional ECT which essentially uses a single frequency measurement which is the simplest form of the technique, there have been advances in the past two decades as the demands from the industry increased. Multifrequency ECT is an important advancement, and it can be applied to realize multi-parameter detection and interference elimination effectively.An essentia l element in the eddy current testing methodology is the use of multiple testing frequencies. A truevolumetric inspection requires complete penetration of the tube wall from various perspectives. Since primefrequency is set to approximately thirty seven percent standard depth of penetration of the tube wall, additionalfrequencies are required to gain an accurate and detailed perspective of the defect. In fact, the need foradditional frequencies is absolutely necessary to characterize particular defects such as under-deposit corrosionand microbiologically influenced corrosion. In such cases a minimum of three frequencies are required to performoptimum testing. The frequencies will vary from low, midrange to high depending on the material under test. Afourth frequency can also be used to identify tube supports and tubesheets.

Pulsed or transient eddy current (PEC) is a novel non-destructive evaluation (NDE) technique that has potential for inspection both the surface and internal structure of a component. Importantly, PEC can provide quantitative measurements of various entities such as surface deformations, cracks, delamination, corrosion, etc that are essential in performing any form of structural health monitoring. As a consequence, PEC has immense potential for a variety of applications, albeit limited by the condition that component be conductive.

Flexible Eddy Current Array Probe Technology

Eddy Current array technology can be an extremely useful tool for increasing productivity and detection capabilities for surface and sub-surface defects. Typical surface inspection technique s such as Dye Penetrant methods, require chemicals and development time, whereas an eddy current technique can be done cleanly and nearly instantly with no chemical clean up afterwards. New probe technology makes flexible arrays easier and cheaper to use, and eddy current systems and software easier to apply to new testing requirements, and simple enough for entry level technicians to learn and operate. The outcome is better, more uniform test with a digital record. And since the eddy current arrays are tunable to a particular defect type or size, the Probability of Detection (POD) increases dramatically for the defects of interest compared to manual single channel eddy current inspection, while decreasing the likelihood of false defect calls.

The capabilities of Eddy Current hardware and software have improved dramatically. Digital systems can manipulate data as it is being collected to enhance the Probability ofDetection (POD) of target defects in ever increasing difficult test criteria. Data can be stored and used for reference for future tests. The gains in capabilities in hardware and software has made in possible to use

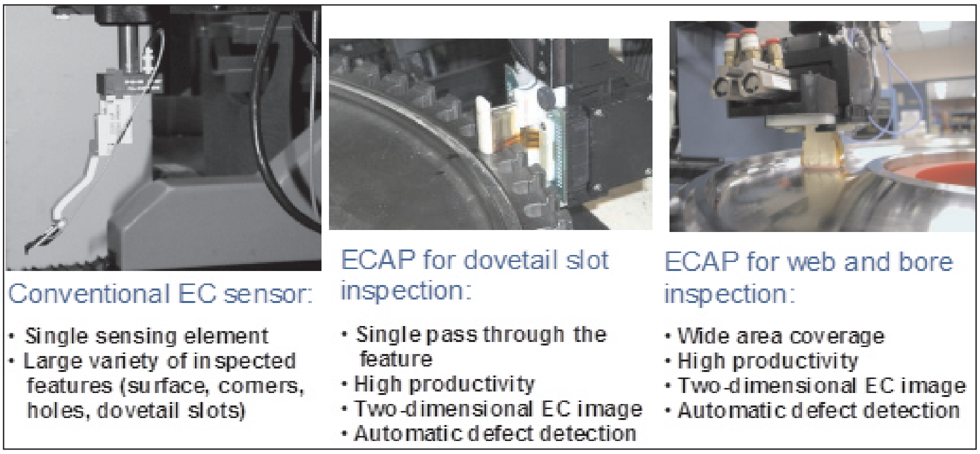
Eddy Current technology in new and powerful ways. One new way to apply Eddy Current technology is in using arrays to cover large areas, where in the past a single Eddy Current coil would be mechanically manipulated over a large or complex geometric shape. Arrays can be developed custom-fitted to complex shapes or span large areas to make testing faster and with higher POD. The use of Eddy Current arrays can make many of these tests better, faster and more repeatable.

Current array technology increases productivity and detection capabilities for surface inspection. The inspection of large surfaces has always been problematic due to the low

Probability of Detection (POD), for the defects of interest, if the inspection is done manually or by the complexity and cost associated with scanner and fixture. Inspection times can be long and therefore costly, or present a bottleneck in a production environment. Visual surface techniques like dye penetrant, fluorescent penetrant or magnetic particle require development time, can mean production of chemical wastes, and provide data that can only be recorded by photograph. In many cases the repeatability of the test is highly operator dependent. Eddy Current array techniques can be done cleanly and nearly instantly without the need of complex scanner or chemical clean up afterwards. The outcome is a better, more uniform test with a digital record. Since the resolution of Eddy Current arrays is a design parameter (application specific) a known surface coverage with a known sensitivity and resolution results in a dramatically increased Probability of Detection (POD) for the defects of interest compared to manual single channel Eddy Current inspection.

Arrays have been made from conventional coils and are therefore subject to the same limitations of single channel coils. Cost to manufacture can be significant. If a standardsingle channel pencil main cost is the manufacture of the coil itself, than a multi coil probe will have incrementally greater cost of manufacture, which limits the range of applications where this technology can be economically used. Often test problems include a requirement to follow a varying surface profile such, as an airfoil surface. Arrays can be made flexible; but because each individual probe themselves are not, there is always a limit past which coils will be less effective, or the wire will start to fail.

Advances in electronics manufacturing, especially in the sector of flexible printed circuit boards, have been used to develop a new type of Eddy Current probe. These are often referred to as film coils or etch coils. These coils are manufactured using a GE patented process in a similar fashion to electronic PCBs. The result is a very thin and flexible coil that can work as a conventional Eddy Current coil. The design possibilities are endless. Coils can be designed to work in every operating mode (absolute, differential, transmit-receive…) and size. They can be made as single coil or as arrays. There are many advantages to film coils but probably the most important ones are for arrays. Existing array probe technology can results in probes to costly for a particular application. Using film technology will make arrays easier and therefore less expensive to manufacture. The reduced coil-to-coil variations realized with etch coils, as opposed to conventionally wound coils permits a far more uniform test with equal sensitivity across all coils. Flexible probes, the inspection of parts with sharp corners and radii, field replacement of coils, and compact design are other key features that this technology allows.



Inductive sensors are the most commonly used sensors ineddy current (EC) nondestructive testing (NDT). Howevertheir performances are limited by their sensitivity decreasewith frequency and size. In this context, magnetic sensorswith high sensitivity have been investigated for some yearsto improve the performances of the EC probes. Anisotropicmagneto-resistance (AMR), giant magneto-resistance(GMR), fluxgate and squid sensors have been used in NDT. Application of othermagnetic sensor to nondestructive testing: the giantmagneto-impedance (GMI) sensor.GMI sensors offer promising performances for developingEC probes because they combine extremely highsensitivity, fast response and small size. Moreover thesesensors show excellent temperature stability and a widelinear range. These features make this kind of sensorsattractive for a large range of industrial applications. An EC probe based on GMI sensor has been developedand evaluated for the detection of embedded flaws in a304 L stainless steel mock up. Results have shown the good performances of this kindof magnetic sensors to detect small fields at low frequencies and confirms that high sensitivity EC testing can beachieved by using the GMI as a sensor [4].

Signal and Image Processing

The analysis and interpretation of pulsed eddy current inspection data is not a straightforward task. PEC data are a classic case of spectral or time-frequency signals. Depth information, be it in the form of material loss or interlayer gaps, etc, is acquired across the entire time period of the measured signal. The primary goal is to detect any potential material loss, ascertain the cause of loss - corrosion, interlayer gaps, cracks, etc and finally quantify the material loss. In the case of multiple such indications, further computation is required to extricate essential information. Poor signal-to-noise levels of broadband signals render this task difficult. Moreover pulsed eddy current signals are extremely sensitive to data acquisition parameters such as lift-off, conductivity, thick ness of the specimen, etc. The ultimate aim is to invert the pulsed eddy current response to produce a complete three-dimensional map of the actual structure of a component. To this end, time-frequency distributions are an appropriate tool to unravel the intricacies of pulsed eddy current responses. This study is aimed at understanding the capabilities of different time-frequency domain signal processing methods on PEC signals for corrosion inspection. Most time-based techniques utilize a reference signal to eliminate undesirable noise effects and then extract indications of any kind of material loss. This is an empirical means of detecting and measuring material loss and uses pre-determined information to eliminate effects such as lift-off, inter-layer gaps, etc. In most cases, this analysis does not provide exact information of the actual depth of the material loss. The use of suitable time-frequency decomposition can overcome this shortcoming. Many time-frequency analyses such as the Wigner-Ville, Short-term Fourier Transform have been used to this end. However the wavelet decomposition along with its multi-resolution capability provides analysts more alternatives with respect to signal analysis. Study of the use of various wavelet decompositions for the analysis of pulsed-eddy current signals has proved useful. Experiments have been performed on aluminum panels with flat bottom holes, specimens with varying thickness & lift-off. This simulates typical conditions of material loss by corrosion damage. The advantages and limitations of these signal-processing methods are discussed vis-à-vis accuracy of reconstruction of the internal geometry of the component under test. These tests are conducted with various wavelets on different runs of the inspection with varying noise levels.

Applications

Carburizing has long been used in industry to improve surface hardness and fatigue resistance ofsteel parts while maintaining the toughness of the core. Proper control of surface carbon content is amajor factor in performing a successful carburizing process and providing essential mechanicalproperties for the part. Traditionally, this has been done using costly chemical analyzing methods. The eddy current method has been recently used to determine physical and metallurgical propertiesof steel parts. Determination of surface carbon content in carburized steels is a new application fornon-destructive eddy current method, which has been studied. The relationbetween the surface carbon content and two parameters; impedance and phase angle has beenestablished. The study shows a good relationship between the carbon percent and phase angle canbe established [1]

In industrial sheet metal forming processes several factors influence the quality of the producedparts. These are the human factor, method - especially the tooling, equipment like the press and itssettings, raw material and environment. The variations of these parameters, althoughthey are inside the specified tolerances can cause defects in the manufactured part or product. The mechanical properties can change fast and become evident only whendefects in the finished parts are detected.Eddy current measurement systems are well known in quality assurance and commonly used todetect defects in materials. In using a multifrequency eddy current system, a fingerprint of theinspected sample can be obtained. Combining the eddy current values with modern data miningalgorithms allows measuring the mechanical properties of conductive materials like steel oraluminum. The examined material is DC06 a cold rolled mild steel, with a thickness of 0.8mm anda zinc coating on both sides. According to the specifications, the mechanical properties of thismaterial can vary in a wide range.The measurement system was developed to acquire the material properties of sheet metal inline inproduction. The accuracy of the system is high enough so that the measured data can be used toadjust the press settings and to generate a database for future sensitivity analysis. The material properties are not constant along one coil. Although their variations lie within thespecifications they can have a significant influence on the deep drawing process. The achievedaccuracy of the measurement system is sufficient to use the acquired data to sort out inappropriatematerial or to adapt the press settings, e.g. die cushion pressure, blank holder force or lubrication.Scrap production can be reduced and the press operator will be unburdened.When the system is installed in the press shop, it can also be used to generate a database forsensitivity analysis in the tool shop for draw die development and as input data for stochasticsimulations to reduce simulation time.

Regular high-strength carbon steel pipe is the most often used pipe type for nowadays on-shore andoff-shore pipelines. However, for many tasks special pipe types or modifications are employed. Thesepipe types are designed to give higher resistance to corrosion, like cladded pipe or pipe with thickcoating, to give better mechanical flexibility, like flexible pipe or to allow for the transport under highertemperature like heat-insulated pipe.As the inspection method strongly depends on the type of pipe and the type of degradationmechanism, regular inspection methods are usually not applicable. This is the case for internal as wellas external pipe inspection. It has been found that eddy current technologies are indeed a veryversatile method to design tailor-made inspection instruments. In general the correct design and careful production of eddy current sensors is the key in obtainingvaluable measurement. Many parameter like coil size, wire gauge, number of turns, measurementfrequency and source gain are important parameters to be determined. In particular there are manyeddy current coil types each suited for a specific inspection task. It requires a certain level ofexperience to determine the right configuration [3].

During the fabrication of subassemblies that contain bearings (that are either self contained in that subassembly or are captured in a race) it is important to verify that the full compliment of bearings that were meant to be installed in that subassembly are, in fact, present. To fulfill this requirement, an Eddy Current based inspection system that has the capability to verify that a given number of bearings have been installed in virtually any type of bearing subassembly has been developed.

Summary

This paper reviews the state-of-the-art methods of eddy current testing which is one of the most widely used non-destructive forms of testing. Eddy current testing permits crack detection and measurements that are beyond the scope of other techniques such as non-conductive coating thickness, alloy composition and hardness in a large variety of materials.

Eddy current sensors are insensitive to dirt, dust, humidity, oil or dielectric material in the measuring gap and have been proven reliable in a wide range of temperatures. Coil probes are the most widely used type of sensors, and standard coils can be used in a wide range of applications.Although eddy current testing has been developed for several decades, research into developing new probes, techniques and instrumentation is currently being conducted by manufacturers and research groups around the world in order to satisfy the increasingly higher quality standards required in almost every industry. These days, scientists are trying to develop new coil probes and research the use of other magnetometers such as superconducting quantum interference devices (SQUIDs), Hall-effect and magnetoresistive sensors that also provide very interesting responses.

Electromagnetic modelling and simulation is a powerful tool for the technologist to explore the capabilities of the technique and help in optimizing the probes and the process very efficiently.Eddy current testing is a versatile technique that makes possible the hot eddy current testing of semi-finished products such as wires, bars and tubes at temperatures of up to 1,200 °C and at production speeds of up to 150 m/s. Early detection of these defects in production lines can save large sums of money in the metal industry.

In conclusion, eddy current techniques can provide the industry with reliable quality control systems. The adjacent developments in technology continues to provide the necessary impetus for eddy current techniques to grow further in all aspects be it instrumentation, probes or data analysis and will lead to even more applications of these techniques.

References

1. D. Mercier, J. Lesage, X. Decoopman, D. Chicot. Eddy currents and hardness testing forevaluation of steel decarburizing ;NDT&E International 2006; 39: 652-660

2. Jörg HEINGÄRTNER, Marcel BORN, Pavel HORA, Online Acquisition of mechanical properties of sheet metal for the prediction of product quality by eddy current ; Institute of Virtual Manufacturing, ETH Zurich; Zurich, Switzerland

3. K. Reber and A. Bönisch; Inspection of unusual pipe types with eddy current technologies, Innospection Germany GmbH and UK

4. F. Vachera, , F. Alvesb, C. Gilles-Pascauda; Eddy current nondestructive testing with giantmagneto-impedance sensor, NDT& E International, 40 (2007) 439-442.