RECENT TRENDS IN ELECTROMAGNETIC NON-DESTRUCTIVE SENSING

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Summary The paper deals with material electromagnetic non-destructive testing (eNDT) with emphasize on eddy current testing (ECT). Various modifications of ECT sensing are compared and discussed from the desired detected signal characteristics point of view. Except of the optimization of usual probe coils arrangements for the concrete applications, the new magnetic sensors as giant magneto-resistance (GMR) and spin dependent tunneling (SDT) are presented. The advanced ECT sensors are characterized by their sensitivity, frequency range and sensor dimensions.

Keywords: electromagnetic nondestructive testing, eddy current sensing, surface and subsurface defects, detection probes, magnetic sensors, giant magneto-resistance (GMR), spin dependent tunneling (SDT).

1. INTRODUCTION

Non-destructive electromagnetic testing (eNDT) is an effective methodology for diagnostics in many technical and scientific applications. The requirements of new effective eNDT tools are connected with the wide and still increasing demands of high quality and reliability standards in industrial production and also with developments of other technical and scientific areas, e.g. medicine, geology, civil and environmental engineering, etc.

Various NDT techniques form a wide group of rather different tools, which are based on different physical phenomena and they are characterized by different and specific performance and application fields. From the application point of view the eNDT is used in many areas - from the inspection of metallic pipes to the aeronautical maintenance and from the localization of liquids in subsoil to the thoracic imaging for clinical diagnostics.

One of the most popular eNDT methods is the eddy current testing (ECT) and evaluation. The principle of ECT can be briefly described by the following way. Eddy current coil fed by alternating sinusoidal current (AC), of frequencies in the range 50 Hz – 10 MHz, generates primary magnetic field according to the Ampere´s law. This primary magnetic field induces eddy currents in the tested conductive material object according to the Faraday´s law. Then eddy currents generate secondary magnetic field in the opposite direction in agreement with the Lenz´s law. Following from these processes the coil impedance changes in the case of material changes, e.g. in the presence of imperfections - defects in the material object. The impedance change is measured, analyzed and correlated with the defect dimensions. The locus of impedance change formed during the movement of an eddy current probe coil over a test material having defect is called an eddy current signal. Its amplitude provides information about the defect size and its phase angle with respect to lift-off gives information about defect location or depth, Fig.1.

Eddy current density in material is not uniform in

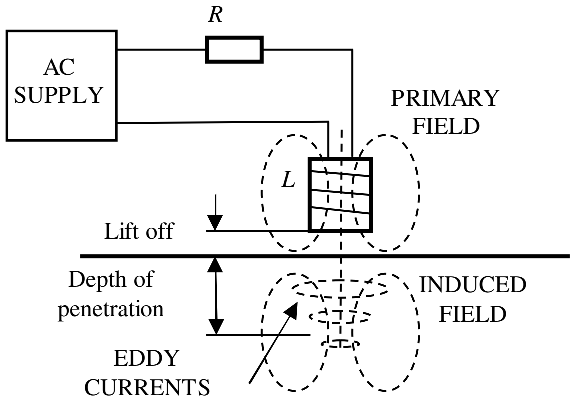

Fig. 1. Eddy current testing arrangement.

the material depth direction. It is greatest on the surface and decreases monotonously with depth (skin effect) according to the relation of standard depth of penetration which decreases with increasing frequency, conductivity and permeability. It means that for measuring thickness of thin surfaces very high frequencies are to be used and on the contrary for detection of sub-surface buried defects and for testing highly conductive (magnetic) thick materials low frequencies are to be employed.

Usually the driving current is kept constant (few hundreds of mA) and the impedance changes occurred due to perturbation of eddy currents at defect regions are to be measured. Since these changes are very small (μΩ), high precision AC bridge is used, Fig. 2. The bridge imbalance is correlated with the defect or material characteristic responsible.

The ECT instrument consists usually of an oscillator (for exciting frequency), constant AC supply, AC (Maxwell) bridge circuit, amplifier and screen (to display the changes in a 2D graph or as a vector). In modern systems there a personal computer with the necessary hardware (plug-in card) and software is used for the measurements,

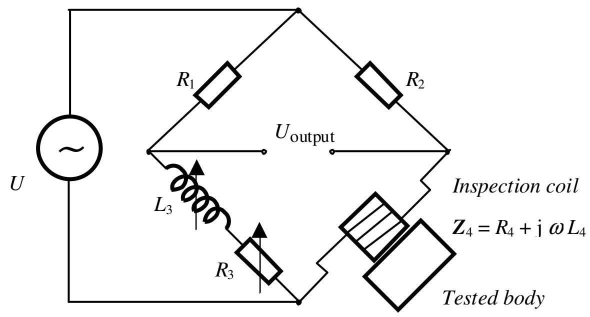

Fig. 2. AC bridge for ECT signal measurement.

adjustment, data storage, analysis and management. The ECT is the mostly used technique for detecting fatigue cracks and corrosion in conductive materials. The cost of using technology is low and it is possible to monitor subsurface defects and defects under insulating coatings without touching the surface specimen. One of the most important parts of ECT device is the sensing part called probe which is created obviously by probe coils or other sensors.

Because safety-critical systems depend on early detection of fatigue cracks to avoid major failures, there is an increasing need for eddy current probes that can reliably detect very small defects. Also there are increasing demands for probes that can detect deeply buried defects to avoid disassembling structures. There are also many other applications where ECT is successfully used, e.g. material thickness measurements, coating thickness measurements and conductivity measurements for the material identification, heat damage detection, case depth determination or heat treatment monitoring. According to the application areas the measuring set-up is designed a realized.

2. EDDY CURRENT PROBES CONFIGURATIONS

As it was mentioned above the appropriate selection of probe coil is very important in ECT in order to get the right (desired) information from it. The most common probes used in ECT are surface or pancake probes (with the axis normal to the surface) which are chosen for inspection of plates and bolt-holes either as a single element or an array, in both absolute and differential modes. The encircling probes are used for inspection of rods, bars and tubes with outside access and the Bobbin probes for pre- and in- service inspection of heat exchanger, steam generator, condenser and others with inside access, Fig. 3, [1]. These three types can also operate in the send-receive mode with the separate coils for sending and receiving of signal and also in absolute or differential mode.

The absolute EC probe consists of a single sensing coil for signal excitation and reception. It is determined for detection of cracks as well as gradual

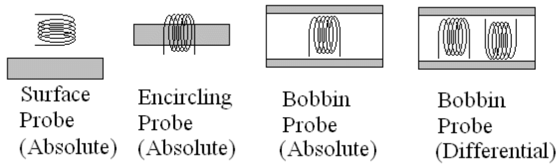

Fig. 3. Configurations of ECT Probes.

variations. But absolute probes are also sensitive to lift-off, probe tilt, temperature changes, etc. Differential probes have two sensing coils wound in opposite direction and investigating two different regions of the material. These probes are good for high sensitivity detection of small defects and they are more immune to changes in temperature and probe wobble.

There are many factors which influence eddy current response from a probe. Successful assessment of flaws relies on holding the others constant, or somehow eliminating their effect on the results. The main factors are material conductivity, permeability, frequency, geometry and the lift-off.

As for the material conductivity is seen the greater the conductivity the greater the flow of eddy currents on the surface. From the conductivity measurements we can get the information about the material composition, heat treatment and work hardening, etc.

For the non-ferrous metals the permeability is the same as of the "free space", the relative permeability is equal to one, and for the ferrous metals it has values several hundreds or more. Permeability is varying strongly within the metal part due to localized stresses, heating effects, etc.

Frequency greatly affected the eddy current response but it can be controlled without problems. Geometrical features such as curvature, edges, grooves, etc. affect the eddy current response. The used techniques must recognize this, e.g. in testing an edge for cracks the probe will normally be moved along parallel to the edge so that small changes may be easily seen. Where the material thickness is less than the effective depth of penetration this will also affect the eddy current response.

As for the proximity or lift-off the closer a probe coil is to the surface the greater will be the effect on that coil. It means that the lift-off signal arises as the probe is moved on and off the surface and the sensitivity will be reduced as the coil product spacing increases.

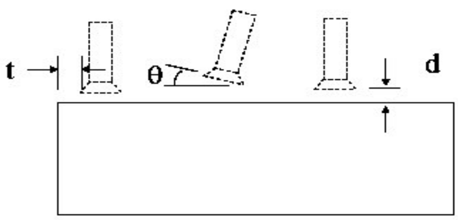

Fig. 4. Positions of ECT probes above tested object.

Fig. 4 shows various positions of the probe above the tested object according to changes of liftoff, tilt and geometry of edge effects.

3. ADVANCES OF EDDY CURRENT PROBES

Eddy current testing probes usually combine an excitation coil that induces eddy currents in a specimen and a detection element that identifies the perturbation of the currents by cracks or other defects. In order to detect deeper defects in material object it is necessary to propose the advanced coils configuration and following data processing, as it was realized and published e.g. in the papers[2], [3].

The optimization and creation of a new probe modification is connected with the used ECT technique. The new coils probe development used in the remote field eddy current testing (RFECT) devoted to the inspection of pipes have been described e.g. in the paper [4]. But except of coils and their various arrangements the ECT detection elements can be also superconducting quantum interference (SQUID) detectors, or solid-state magnetic sensors, such as Hall effect, fluxgate or magneto-resistance (AMR or GMR) and spin-dependent-tunneling (SDT) sensors.

The use of low-field solid-state magnetic sensors represents a significant advance over more traditional inductive probes in use today, [5]. Two key attributes will open opportunities for increased use of eddy current probes: sensor constant sensitivity over a wide range of frequencies and development of smaller sensors.

Probes that detect eddy current fields using inductive coils have less sensitivity at low frequencies. Unfortunately, this is where the device would have to operate to detect deep flaws. Small sensing coils which are required to detect small defects, also have low sensitivity. In contrast, small, high-sensitivity thin film sensors can locally measure a magnetic field over an area comparable to the size of the sensor itself /tens of micrometers/. Limitation of conventional eddy current probes is the difficulty of detecting small cracks originating at the edges of a specimen. This defect is the most common type encountered in practice. An example is the cracks that appear around the fastener or rivet holes in aircraft multilayer structures. Most inductive coil probes are sensitive to both the edge and the cracks initiating from or near the edge. The edge creates a large signal that obscures the small signal from the crack. GMR and SDT magnetic sensors can be oriented to eliminate the edge signal. With this orientation the presence of the edge enhances the signal from the crack.

To achieve high resolution for detecting small surface and near-surface defects it is necessary to reduce the dimensions of the excitation coil. The minimum length of a detectable crack is roughly equal to the mean radius of the coil. There have been developed and tested probes incorporating small, flat, pancake coils or planar excitation coils deposited on the sensor substrate.

Recent development of thin film magnetic technology has resulted in films exhibiting a large change in resistance with magnetic field, [5]. This phenomenon is called giant magneto-resistance to distinguish it from conventional anisotropic magneto-resistance (AMR). Whereas AMR resistors exhibit a change of resistance of up to 3%, various GMR materials achieve about a 10% - 20% change in resistance.

GMR films have two or more soft magnetic layers of iron, nickel and cobalt alloys separated by a nonmagnetic conductive layer such as copper. Because of spin-dependent scattering of conduction electrons, the resistance has maximum value when the magnetic moments of the layers are anti-parallel and minimum when they are parallel, [5].

SDT structures are a recent addition to the materials exhibiting a large change in resistance. In these structures an insulating layer separates two magnetic layers. Quantum tunneling through the insulator allows conduction. The angle between the magnetization vectors in the two magnetic layers modulates the magnitude of the tunneling current between the two layers. There were observed changes of resistance of 10% to 40% in SDT structures. The field required for maximum change in resistance depends on the composition of the magnetic layers and the method of achieving anti-parallel alignment. Values of the saturation field range from 100 to 10000 A/m. At the low end, this offers the possibility of extremely sensitive magnetic sensors.

Within the frame of sensors progress there have been adapted SDT materials to create highly sensitive magnetic field sensors for use in low-field applications that presently require fluxgate magnetometers. These sensors are very small, require little power, and are easily combined with other electronics. The insulating tunnelling layer provides high-resistance sensors suitable for battery operation. There can be fabricated extremely small SDT devices (several tens of micrometer on a side) with high resistance using photolithography, allowing dense packing of magnetic sensors in small areas.

The main components of an eddy current probe for non-destructive testing are pancake-type coil and an AC bridge of GMR or SDT sensors. Arrangement of coil and GMR sensor for eddy current detection of defects in conductors is shown in the Fig. 5, [5]. When measuring the sensing axis, it must be kept the GMR probe coplanar with the surface of specimen. The excitation field on the coil axis, being perpendicular to the sensing axis of the GMR, has no effect on the sensor. In this way, the detected field, which is the result of the perturbation of the eddy current flow paths caused by the crack, is separated from the excitation field.

Eddy current induced in the surface of a defect-free specimen are circular because of the circular symmetry of the field produced by the coil.

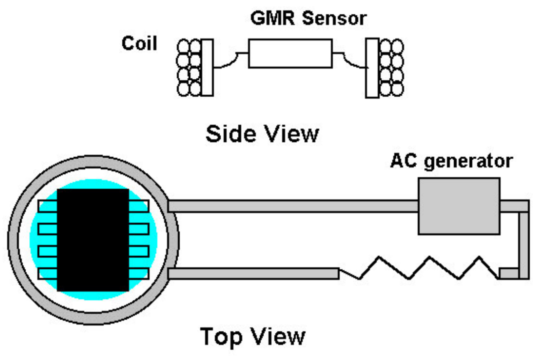

Fig. 5. Setup of ECT with GMR sensor.

The tangential component of the field created by the eddy currents is zero at the location of the sensor. In presence of defects, the eddy currents are no longer symmetrical and the probe provides a measure of the perturbed eddy currents caused by underlying flaws. The size of the coil is related to the resolution necessary to detect the defects. For large defects and for deep defects, large coils surrounding the sensors are required. Small coils located close to the specimen are necessary to resolve small defects.

Eddy currents shield the interior of the conducting material with the skin depth related to the conductivity and the frequency. By changing the frequency it is possible to probe differing depths of the material. GMR and SDT sensors with their wide frequency response, from DC to the MHz range, are well suited to this application. The small size of the sensing element increases the resolution of defect location while the detector is raster-scanned over the surface. More rapid scans can be preformed using an array of detectors, [6].

Within the recent development there were built the optimized EC probe prototypes to detect and map different types of defects encountered in practice. They are evaluated probe performance on calibrated slots of different lengths, widths, and heights machined into the top surface, bottom surface, or edges of specimen. The results are combined with the results obtained on a specimen that contained real cracks artificially grown around a hole. Finally, they demonstrated magnetic profile imaging by scanning a given object using a high-resolution probe, [6].

EC probes were tested on surface cracks longer than the excitation coil diameter. Quality of the maps produced when scanning this type of defect depend on the relative orientation of the sensitive axis of the SDT or GMR sensing elements with respect to the crack orientation. Short surface cracks can also be reliably detected using small excitation coils. The unidirectional sensitivity of GMR and SDT sensors enables the detection of cracks at and perpendicular to the edge of a specimen. This discrimination is possible because the sensitive axis of the sensor can be oriented parallel to the edge. Consequently, the output signal of the sensor is caused only by the crack.

SDT sensors are particularly attractive for nondestructive evaluation, low-frequency applications, such as the detection of deeply buried flaws. In contrast, inductive probes have poor sensitivity at low frequencies because they are sensitive to the time derivative of the magnetic field rather than to the magnitude of the magnetic field created by the flaw. To detect deep cracks, it is necessary to use large diameter excitation coils to increase the penetration of the eddy currents in the material under test.

4. CONCLUSION

The main characteristics of ECT probes were described and compared in the paper. According to the various requirements on the detected signals and to the used ECT techniques the applications of usual and selected advanced probe devices were discussed and mutually compared. As for the last ECT sensing trends the emphasis was put mainly on the solid state GMR and SDT sensors and their properties such as the constant sensitivity in a wide frequency range, their small size and the possibility of low magnetic fields measurement. The examples of the wide utilization of these types of ECT sensors were presented mainly for the practical cases where the ECT coil probes applications have some limitations.

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