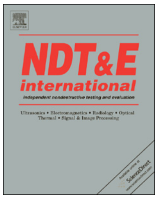
NDT&E International 74 (2015) 24–32

Contents lists available at ScienceDirect

NDT&E International

journal homepage: www.elsevier.com/locate/ndteint



Design of eddy current-based dielectric constant meter for defect detection in glass fiber reinforced plastics

Koichi Mizukami*, Yoshihiro Mizutani, Akira Todoroki, Yoshiro Suzuki

Tokyo Institute of Technology, Department of Mechanical Sciences and Engineering, 2-12-1-I1-70, Ookayama, Meguro-ku, Tokyo 152-8552, Japan

ARTICLE INFO

Article history:
Received 30 January 2015
Received in revised form
24 March 2015
Accepted 24 April 2015
Available online 12 May 2015

Keywords:
Composite materials
FRP (fiber reinforced) plastic
Dielectric
Eddy currents
Theoretical modeling

ABSTRACT

This paper presents the design of an eddy current testing probe for inspection of non-conductive glass fiber reinforced plastics. Because the magnetic field contains information pertaining to the permittivity of materials under test, eddy current testing offers the possibility of flaw detection in non-conductive materials through detection of the difference in permittivity between the intact part and the defective part of each material. We analytically investigated the design of a probe suitable for dielectric constant measurements. Experimental studies proved that the proposed probe can detect slit defects and flat-bottomed holes located 2 mm away from the surface of the glass fiber reinforced plastic samples.

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1. Introduction

Glass fiber reinforced plastics (GFRPs) are low-cost structural materials with high specific strength and stiffness, and are used in many applications, including aircraft, wind power generator blades, small boats and tanks. Defects occur in GFRPs both during the manufacturing process and in service. One GFRP manufacturing method, resin transfer molding (RTM), is increasingly commonly used to mold GFRP products because it offers low equipment costs and excellent moldability of complex shapes and large parts [1]. In RTM, a dry fiber reinforcement called a preform is placed in the mold cavity and a low viscosity resin is then pumped into the mold under pressure until the cavity is filled. In particular, when a large composite structure is molded, non-uniform resin flow can easily occur and dry spots are formed [2]. Because these dry spots can cause strength degradation, they must be detected by nondestructive testing (NDT). When GFRP structures are in service, the common forms of damage that occurs in these structures are fiber breakage and matrix cracking [3]. These forms of damage also lead to deterioration of the material's strength and must be detected before they exceed a critical level. The surfaces of GFRP structures in service are often given an approximately 0.5 mm thick polyester gel coating to improve weather resistance. Flaws in GFRPs under these gel coatings can be invisible and flaw detection is thus a challenging task.

Many NDT techniques have been developed for GFRP inspection, including ultrasonic, thermography and radiography testing. In addition to these techniques, studies of electromagnetic wave-based methods such as microwave and terahertz imaging have been reported in recent years [4–6]. Although these techniques are useful in many applications, they have certain limitations. Ultrasonic testing requires the use of couplant to enable ultrasound to propagate into the material under test, which increases the time cost of the inspection process [7]. In thermography testing, defect detectability depends on the heating conditions and the surface characteristics of the material under test. For example, non-uniform heating and surface emissivity variation make defect detection more difficult [8]. In radiography testing, the inherent radiation hazards are sometimes problematic. Microwave testing and terahertz imaging require expensive test equipment. Testing methods based on capacitance measurements have also been investigated with the aim of overcoming some of the limitations described above. Yin and Hutchins used co-planar capacitive electrodes to detect the local dielectric properties of GFRPs [9]. Detection of local changes in the dielectric properties in damaged regions has been shown to be effective for inspection of GFRPs with a simple apparatus.

Eddy current testing (ET) is a well-established NDT method for defect detection in electrically conductive materials such as metals. In ET, eddy currents are induced in the conductive material under test by the driver coil in accordance with Faraday's law. Defects in the material cause local changes in eddy current path and the distorted magnetic field produced by the eddy currents cause changes in the output signal of the pickup coil that is used as a magnetic sensor. ET offers the advantages of short-time and

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* Corresponding author. Tel./fax: +81 3 5734 3178.
E-mail address: kmizukam@ginza.mes.titech.ac.jp (K. Mizukami).

http://dx.doi.org/10.1016/j.ndteint.2015.04.005
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non-contact inspection [10]. In addition, the costs of test equipment for ET are relatively low. Although ET is conventionally only applied to electrically conductive materials, ET also has the potential for use in non-conductive material inspection as the magnetic field is dependent on the material's dielectric constant because of the presence of the displacement current. Heuer proved experimentally that ET can measure the dielectric constants of non-conducting materials at high frequency [11]. Heuer investigated the ET output signals from several non-conductive materials while varying the drive frequency, and showed that dielectric constant causes distinct changes in the signal at frequencies above approximately 9 MHz [11]. Gaebler et al. carried out high frequency ET of curing resin and PMMA with artificial hole defects [12]. The experiments of Gaebler also indicate that sample permittivity is a part of ET response. Thus, ET has potential to be a fast and non-contact method for testing of non-conductive materials that overcomes the limitations of the existing NDT methods. However, configuration of ET probe specialized for permittivity measurement has not yet been studied.

In this paper, the design of the test probe for dielectric constant measurement for GFRP defect detection applications is studied. First, an analytical solution for the electromagnetic field during ET of an anisotropic non-conductive material was derived to investigate the output signal's dependence on the dielectric constant of the material under test. Second, the probe was designed such that the pickup coil has a large fractional change in output voltage with dielectric constant. We studied the influence of probe's dimensions and the arrangement of the driver and the pickup coil on the detectability of change in the material's permittivity. Third, a test probe was fabricated on the basis of the proposed probe design and was used for experimental detection of defects in GFRPs. In the experiments, a GFRP specimen containing a slit and specimens with flat-bottomed holes were tested to verify the potential of ET for non-conductive GFRPs.

2. Derivation of analytical solutions to ET problems

Analytical solutions for the electromagnetic field in ET of a non-conductive anisotropic medium are derived using the formulation of Dodd and Deeds [13,14]. Dodd and Deeds derived analytical solutions for the vector potential in ET of an electrically conductive isotropic material. In this study, the vector potential in ET of a non-conductive material is derived by assuming that the conductivity of the tested material $\sigma = 0$ in the Dodd and Deeds formulation, and this formulation is extended to the case of a material with anisotropic permittivity. Fig. 1 shows the analytical model used to derive analytical solutions for the vector potential. In the analytical model, the driver coil and the pickup coil are placed above the material in (r, θ, z) cylindrical coordinates. The driver coil has n turns and a rectangular cross section (inner radius: r_1, outer radius: r_2, lift off: l_1, height: l_2–l_1). The pickup coil is a wire loop with radius r_p at $z = l_p$. The distance between the central axis of the driver coil and that of the pickup coil is L. It is assumed that the material under test is a semi-infinite plate that occupies the region where $z < 0$, and the material has conductivity σ_{xy} in the in-plane direction, conductivity σ_z in the z direction, relative permittivity ε_{xy} in the in-plane direction and relative permittivity ε_z in the z direction. This assumption of anisotropy is valid for a woven GFRP and a chopped strand mat GFRP, in which the material properties are considered to be approximately isotropic in the in-plane direction.

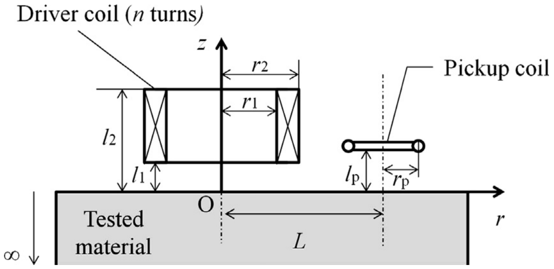

Fig. 1. Analytical model for derivation of analytical solutions for vector potential.

The differential equation for the vector potential A in cylindrical coordinate when a sinusoidal current density with amplitude i_0 and frequency ω is applied to the driver coil is written as [15–17],

$$\nabla^2 \overrightarrow{A} = -\mu_0 \begin{pmatrix} 0 \\ i_0 \\ 0 \end{pmatrix} + \left(j\omega\mu_0 \begin{pmatrix} \sigma_{xy} & 0 & 0 \\ 0 & \sigma_{xy} & 0 \\ 0 & 0 & \sigma_z \end{pmatrix} - \omega^2 \mu_0 \varepsilon_0 \begin{pmatrix} \varepsilon_{xy} & 0 & 0 \\ 0 & \varepsilon_{xy} & 0 \\ 0 & 0 & \varepsilon_z \end{pmatrix} \right) \overrightarrow{A}. \tag{1}$$

where, μ_0 and ε_0 are the magnetic permeability and the permittivity of a vacuum, respectively, and $j = \sqrt{-1}$. Note that the vector potential A in Eq. (1) is expressed in complex form [13,14]. Because axial symmetry is valid for this problem, there is only a θ component of the drive current [13] and therefore of A. The θ component of Eq. (1) gives,

$$\frac{\partial^2 A_\theta}{\partial r^2} + \frac{1}{r}\frac{\partial A_\theta}{\partial r} + \frac{\partial^2 A_\theta}{\partial z^2} - \frac{A_\theta}{r^2} = -\mu_0 i_0 + \left(j\omega\mu_0\sigma_{xy} - \omega^2\mu_0\varepsilon_0\varepsilon_{xy}\right)A_\theta. \tag{2}$$

The contributions of the conductivity and the permittivity to the vector potential are determined by the ratio of the terms in brackets in Eq. (2). Because $\omega\varepsilon_0\varepsilon_{xy}/\sigma_{xy} >> 1$ ($\varepsilon_0 = 8.85 \times 10^{-12}$ F/m, $\varepsilon_{xy} = 3 \sim 5$, $\sigma_{xy} \cong 1 \times 10^{-13}$ S/m) is valid for testing of GFRPs at frequencies above 10 MHz, the first term in the brackets can then be negligible and Eq. (2) can be written as follows.

$$\frac{\partial^2 A_\theta}{\partial r^2} + \frac{1}{r}\frac{\partial A_\theta}{\partial r} + \frac{\partial^2 A_\theta}{\partial z^2} - \frac{A_\theta}{r^2} = -\mu_0 i_0 - \omega^2\mu_0\varepsilon_0\varepsilon_{xy}A_\theta. \tag{3}$$

The regions of interest in Fig. 1 in this study are $l_1 \le z \le l_2$ and $z \le 0$. The vector potentials in the regions where $l_1 \le z \le l_2$ and $z \le 0$ are required to calculate the output voltage of the pickup coil and the displacement current in the material under test, respectively.

Solutions to Eq. (3) can be given by separation of the variables as Dodd and Deeds derived. Solutions for the regions where $l_1 \le z \le l_2$ and $z \le 0$ are written as follows [13].

$$A_\theta(r,z)\big|_{l_1 \le z \le l_2} = \frac{\mu_0 i_0}{2}\int_0^\infty \frac{1}{\alpha\alpha_0^2} I(r_2,r_1) J_1(\alpha r)(F+G)d\alpha, \tag{4}$$

$$A_\theta(r,z)\big|_{z \le 0} = \mu_0 i_0 \int_0^\infty \frac{1}{\alpha\alpha_0} I(r_2,r_1) J_1(\alpha r) \frac{e^{\alpha_1 z}}{\alpha_0+\alpha_1}\left(e^{-\alpha_0 l_1} - e^{-\alpha_0 l_2}\right)d\alpha. \tag{5}$$

where J_1 is a first-order Bessel function,

$$\alpha_0 = (\alpha^2 - \omega^2\mu_0\varepsilon_0)^{1/2}, \tag{6}$$

$$\alpha_1 = (\alpha^2 - \omega^2\mu_0\varepsilon_0\varepsilon_{xy})^{1/2}, \tag{7}$$

$$I(r_2,r_1) = \int_{\alpha r_1}^{\alpha r_2} xJ_1(x)dx, \tag{8}$$

$$F = 2 - e^{-\alpha_0(l_2-z)} - e^{-\alpha_0(z-l_1)}, \tag{9}$$

$$G = \frac{\alpha_0-\alpha_1}{\alpha_0+\alpha_1} e^{-\alpha_0 z}(e^{-\alpha_0 l_1} - e^{-\alpha_0 l_2}). \tag{10}$$

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