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An alternating current electric flux leakage testing methodology and experimental research for metallic materials

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ABSTRACT

This paper proposes an alternating current electric flux leakage (AC-EFL) testing method, which was verified by a series experiments. The inspection ideal and its feasibility research were detailedly presented on the basis of electric field (E-Field) theory. The inspection principle, which is to evaluate surface defect in AC-carrying metallic components using a coplanar capacitive sensor, was briefly described. Physical experiments with a prototype capacitive probe were also carried out to observe and analyze the detection performance of AC-EFL. Effects of crack size of the conducting specimen, through holes size, flat-bottom holes depth, insulation thickness between the probe and the conducting specimen, and exciting signal frequencies were studied. The proof-of-concept results indicated that the AC-EFL testing method could be used to detect surface defect for metallic specimen, and of complete feasibility and the potential of great practical value as a supplement of conventional NDT methods.

1. Introduction

NDT (nondestructive testing) technology has been widely used for the detections of the defects in metallic materials [1]. As a core component of NDT method, there is a wide range of techniques conventionally used to inspect surface defect in metallic structures. These techniques include alternating current field measurement (ACFM) method [2], magnetostrictive transducer technique [3], eddy current testing (ECT) [4,5], magnetic flux leakage (MFL) method [6,7] and electromagnetic acoustic transducer (EMAT) [8,9], etc. In recent years, there have been several notable advantages in the above-mentioned NDT techniques to detect defects in metallic components, such as capacitive imaging technique [10–12], pulsed eddy current method (PEC) [13–15], far field pulsed eddy current (FPEC) [16] and eddy current induced thermography [17,18].

Nowadays, studies on finding new inspection methods have been a development trend. As well known, a lot of literature to study the electric field (E-Field) distribution inside and outside stationary conductors carrying steady current. This electric field is proportional to the battery electromotive force (emf) and is generated by surface charges along the conductor [19–32].

However, almost no paper reports how to utilize this physical phenomenon for NDT. From the perspective of the E-Field perturbation, it would be a simple and direct way to apply it to develop a new NDT method. On the basis of E-Field disturbance and electric boundary conditions for current-carrying conductor with surface crack, this study is aimed to find out an alternating current electric flux leakage (AC-EFL) inspection methodology and to verify it by experiments.

In this work, firstly the preliminary inspection principle of AC-EFL is schematically explained in Section 2. Then, the detection method of leakage E-Field using a coplanar capacitive probe is described in Section 3. Finally, Section 4 presents experimental verifications of AC-EFL.

2. Preliminary inspection principle of AC-EFL

In recent years, there has been a great interest in the electric field distribution for resistive conductors carrying constant current and a number of problems have been published in the literature, such as coaxial cables [33]; resistive spherical shell [25]; conductor plates [19,26]; resistive toroidal conductor [21,27]; a resistive long straight strip [22]; and a stationary resistive wire carrying a constant current [20].

If there is surface defect within the specimen carrying steady current, as shown in Fig. 1(a), the crack will certainly cause the surface charge redistribution along the conductor, which will generate the E-Field redistribution inside and outside of the conductor, especially in the vicinity near the defect.

However, in this paper, rather than a direct current (DC) driving voltage, a single frequency AC exciting is applied as the

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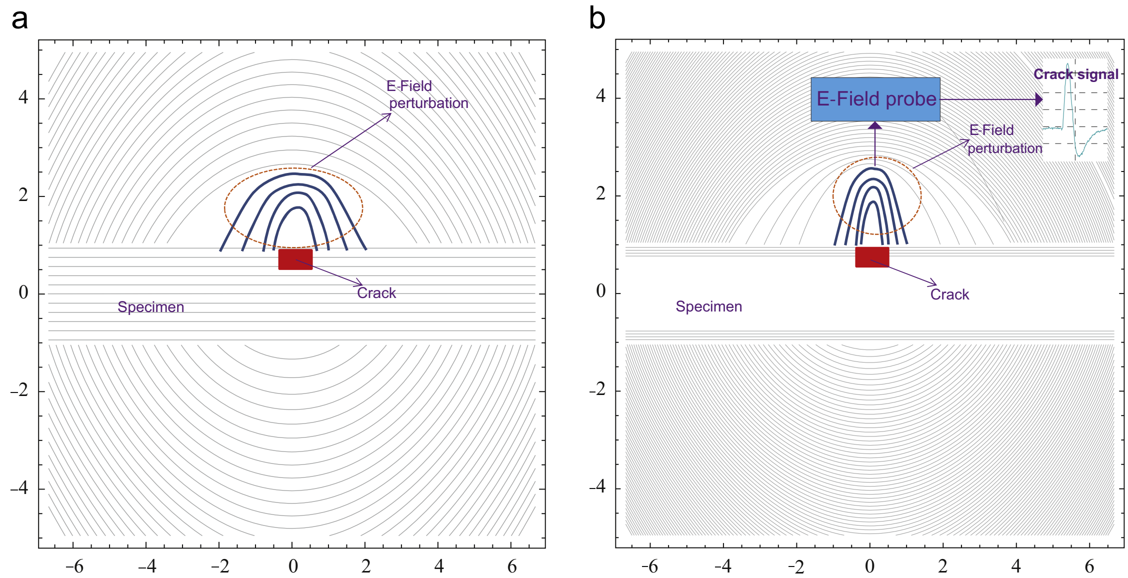

Fig. 1. The diagrammatic sketch of E-Field distribution for current-carrying specimen with surface defect: (a) when the conductor is driven by DC voltage; (b) when the conductor is driven by AC voltage.

driving voltage between the specimen terminals. There are two reasons for this consideration: firstly, there is a tendency for an AC to concentrate near the outer part or "skin" of a conductor and the E-Field of the material surface is much stronger than that when carrying DC. The corresponding leakage E-Field in the vicinity of the defect is much greater too, which can enhance the possibility of realizing AC-EFL using E-Field sensors. Secondly, the AC exciting voltage is more convenient for signal processing and filtering to improve signal to noise ratio (SNR), which can also increase the probability to verify AC-EFL proposed in this paper.

If proper non-contact E-Field probes can be utilized to inspect the disturbed E-Field when the probe scans over the surface defect in the resistive metallic material carrying AC, they will be forming a new non-contact NDT method namely AC-EFL testing, just like the E-Field is leaking out from conductor to air when the E-Field in the specimen encounters the defect, as shown in Fig. 1(b). A coplanar capacitor sensor is selected for AC-EFL testing in this work.

Another reason of the possibility for AC-EFL is relative to the boundary conditions for the electric field $\boldsymbol{E}$, as schematically illustrated in Fig. 2. It is well known that, at an interface between two media 1 and 2 (with $\hat{\boldsymbol{n}}$ being the unit vector normal to the interface at every point), the tangential component of $\boldsymbol{E}$ is continuous, $E_{t1} = E_{t2}$ or $\hat{\boldsymbol{n}} \times (\boldsymbol{E_1} - \boldsymbol{E_2}) = 0$. On the other hand, the normal component may be discontinuous according to $\hat{\boldsymbol{n}} \bullet (\varepsilon_2 \boldsymbol{E_2} - \varepsilon_1 \boldsymbol{E_1}) = \sigma$, where ε_j is the dielectric constant of the medium j, and σ is the density of surface charges at the interface.

When the E-Field in the specimen encounters a defect, E-Field lines will be refracted from the conductor into air due to boundary conditions, leading to obvious E-Field mutation near the crack and thereby creating leakage electric fields, as displayed in Fig. 2. Owing to the skin effect, only the surface defect can be detected, which is experimentally proved in Section 5.4.

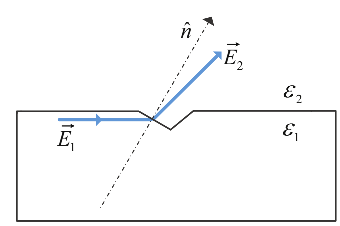

Fig. 2. The boundary conditions for the electric field intensity.

3. Fundamental of the coplanar capacitor technique

The active coplanar capacitive (the probe rather than the specimen actively generate the E-Field) approach has been widely used in a wide range of industrial applications due to its robustness, low cost and high level of performance [10–12,34]. The general technique is to inspect changes in the local electrical characteristics near the probe using active coplanar electrodes. The principle of the coplanar capacitive sensing is on the basis of the interaction between a specimen and the fringing electric field. The transition from a parallel-plate capacitor to a planar sensor with the consideration of the fringe effect is schematically shown in Fig. 3. A fringing field between the coplanar electrodes will be produced when an AC exciting voltage is applied to it. The presence of a metallic specimen within the sensitive volume of the resultant fringing E-Field will affect the field distribution shapes. Any change (such as the presence of a defect) can cause a field distortion, leading to a change in stored charge at the sensing electrode. Such a probe scans across a surface to pick up the resultant E-Field and to generate a map of changes in electrical properties in the sensing area, realizing the whole detection process.

But in this paper, the coplanar capacitor probe dose not produce any E-Fields, on the contrary, it is utilized to passively inspect the leakage E-Field generated by the AC-carrying specimen with surface defect, as shown in Fig. 4.

A schematic diagram of the AC-EFL testing approach is shown in Fig. 4. The power signal generator connecting the specimen produces the surface charge distribution along the conductor, which generates an E-Field inside and outside the specimen. Any property change in the sample (such as the presence of a defect) within the volume covered will affect the surface charge distribution and influence the resultant E-Field pattern. When a coplanar probe scans over the defect, the resultant perturbed E-Field will