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Multi-source effect in magnetizing-based eddy current testing sensor for surface crack in ferromagnetic materials

Zhiyang Deng [a,*], Yihua Kang [a,*], Jikai Zhang [a], Kai Song [b]

[a] State Key Lab of Digital Manufacturing Equipment & Technology, Huazhong University of Science and Technology, 1037 Luoyu Road, 430074, Wuhan, China

[b] Key Laboratory of Nondestructive Test (Ministry of Education), Nanchang Hangkong University, 696 Fenghenan Road, 330063, Nanchang, China

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ABSTRACT

The mechanism of widely applied magnetizing-based eddy current testing (MB-ECT) sensor for ferromagnetic materials is simply emphasized by "the magnetization eliminates the non-uniformity of the permeability and increases the penetration depth", resulting in rough application for non-destructive testing (NDT). Hence, the neglected permeability distortion around the surface crack is pointed out and analyzed at different magnetization states. In this paper, the multi-source effect of MB-ECT method is analyzed using the equivalent source method. The disturbed magnetic field source is actually composed of the primary magnetic leakage field, secondary disturbed magnetic field caused by the crack itself and the permeability distortion around the crack. Furthermore, the influence of the magnetizing current and the probe lift-off are investigated by finite element analysis (FEA). The simulation result shows "concave" feature as a consequence of the permeability distortion. A series of experiments are designed to analyze the dominant signal components under different conditions. The magnetizing current selection in MB-ECT method corresponds to a unique shape while plotting the signal amplitude as a function of the magnetizing current and lift-off of the probe. This study reveals the multi-source effect in the mechanism of MB-ECT sensors and provides the basic theory or analysis principles for the precision crack evaluation.

1. Introduction

The practical electromagnetic nondestructive testing methods, such as the magnetic flux leakage (MFL) method, the eddy current testing (ECT) method and the pulse eddy current method (PEC) et.al. analyze the distribution of electromagnetic field caused by abnormal electromagnetic properties. Traditional ECT has been widely used for non-contact discontinuities evaluation and thickness measurement of conducting layers [1–3]. It is also combined with other NDT methods to achieve superior performance [4–6]. The advantages and promising result yielded by ECT method bring tons of attentions focused on derived topics such as the novel ECT sensors or array probes [7–10], numerical models [11–14], inverse problems [15], scanning velocity [16,17], signal processing [18] and its relevant practical engineering applications [19,20].

Compared with non-ferromagnetic materials, the magnetic permeability of ferromagnetic material plays an important role in ECT, which varies with the position inside the specimen and worsens the signal to noise ratio (SNR). It is widely acknowledged that a DC magnetization method, by which the magnetization is partially or totally oriented into one direction, needs to be cooperated with the traditional ECT method to ensure the testing reliably. Many practical application devices also have verified that this MB-ECT method does perform well [19–23]. Hence, researchers turn to some related advanced detection probe for more practical solutions [24,25]. Innospection Ltd provides leading magnetic eddy current (MEC) detectors for fast scanning which own advantages of easier realization, higher sensitivity, lower cost and higher speed for various damages in ferromagnetic pipes [26,27]. The MB-ECT method uses a combination of DC magnetic field with an eddy current field, of which the mechanism is always interpreted as the increasing penetration depth for inner surface crack. However, in the previous work, the generating principle and theory regarding the mechanism of permeability-measuring magnetic flux leakage testing (P-MFL) are elaborated. The magnetic field distortion caused by the crack results in the permeability distortion of the surface layer and it is measured by differential pick-up coils [28].

The mechanism of signal source for the surface crack is more complicated than that of the inner surface crack. Not only is the

* Corresponding authors.
E-mail addresses: yihuakang@hust.edu.cn (Y. Kang), dzy@hust.edu.cn (Z. Deng)
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eddy current in surface layer (generated by the AC excitation field) directly disturbed by the crack (permeability and conductivity), but also it is affected by the changes in local permeability. In ferromagnetic materials, the permeability is a function of magnetization and serves as the dominant factor inside the material. One of the most significant phenomena is that the permeability decreases as the magnetization becomes stronger, owing to the non-linear magnetic property. In the application of the saturated MB-ECT method for the inspection of the spent fuel elements from fast reactors or duplex stainless steel, the ferromagnetic material is simplified and treated as non-magnetic material [29]. Some scholars take the influence of DC magnetic field into account in eddy current effect, however, they seldom pay attention to the permeability distortion around the crack or regard the permeability change as a uniform change when the magnetization changes [30–32]. D. L. Atherton et al. use magnetically-saturated regions in remote field eddy current tools and reduce the relative permeability of the material under strong magnetization from 70 to 5 in FEA method, but the real magnetic properties lack necessary consideration [33]. Some studies give the analytical solution in eddy current testing of material with depth varying permeability [34,35]. Besides, the sensitive differential permeability is considered to evaluate the stress concentration situation and degree of fatigue damage of a ferromagnetic component [36,37]. When the pipe is being magnetized, the surface crack causes an interruption to the internal magnetic field, resulting in partial magnetic field distortion and significant permeability distortion on both sides of the crack. This local permeability distortion area acts as a new discontinuity according to its definition and brings the disturbing field. Therefore, it should arouse more attention how the permeability is distributed and what the effect of this change to testing signals is.

More importantly, both the conductivity and permeability of the material to be tested act as the internal factors. However, another signal source MFL due to the magnetic refraction plays an important role in outer space of the specimen where the detection probe always stands in. In terms of MFL, many corresponding theories and studies provide guidance for the actual detection, such as the signal mechanism [38–42], probe lift-off [43–47], some novel sensors [48] and the magnetization of workpiece [49]. The static and singular MFL acts as a disturbance source relative to the moving probe, which will be bound to contribute to the MB-ECT signal and is worthy of attention. In fact, the effect of MFL to MB-ECT signal depends on not only the magnetization state but also the probe lift-off. Some studies focus on the limit of the MFL probe lift-off [42,45] or the best range of lift-off values [46], also the increase of the lift-off by various signal enhancing methods [43,47,44]. Meanwhile, some other works indicate that the probe lift-off affects the impedance of the ECT coil and some efforts are made to reduce the lift-off effects [50–52]. According to the principle of electromagnetic induction, the probe lift-off is of great significance to the final signal components because each disturbance field exists in a certain spatial range. In this sense, different MB-ECT signals will arise from equivalent defect, and even the same MB-ECT signals are likely to appear at different magnetization or different lift-off due to the multi-source effect. Only by clarifying the signal mechanism can we make an effective crack evaluation or analyze the inversion problem of MB-ECT method.

Summarily, the basic theories or whole physical mechanisms of MB-ECT and presentation are still waiting for further discovery and revealing. In this paper, the multi-source effect in present MB-ECT sensors is analyzed using the equivalent source method for the first time. Actually, it is composed of the primary magnetic leakage field, disturbed magnetic field caused by the crack itself and the permeability distortion around the crack. The paper is organized as follows, Section 2 presents the mechanism of permeability distortion around a surface crack, and the disturbed magnetic field in MB-ECT is analyzed. In Section 3, the FEA model is built and the multi-source effect of MB-ECT sensor is analyzed by simulations. Furthermore, as the major determinants of testing signal, the magnetizing field and the probe lift-off are analyzed in detail. Afterwards, Section 4 elaborates on the experimental study by a set of comprehensive tests on a slotted steel plate, meanwhile and particularly, the detection capability under large lift-off is verified. Additionally, the multi-source effect of MB-ECT method and its dominant signal source are discussed in detail. In Section 6, derived conclusions are given. The experimental results show good correlation with the simulations and clarifying the mechanism of MB-ECT is of great significance to precision evaluation of cracks and related applications.

2. Mechanism

2.1. Magnetic permeability distortion around a crack

In isotropic ferromagnetic material, the relationship between $\boldsymbol{B}$ and $\boldsymbol{H}$ exhibits both non-linearity and hysteresis: $\boldsymbol{B}$ is not a single-valued function of $\boldsymbol{H}$, but also depends on the history of the material [53]. The magnetic induction $\boldsymbol{B}$ is related to $\boldsymbol{H}$ by the relationship

$$\boldsymbol{B}=\mu_0(\boldsymbol{H}+\boldsymbol{M})=\mu_0(1+\chi_m)\boldsymbol{H} \tag{2.1}$$

Where μ_0 is the permeability in vacuum, $\boldsymbol{M}$ is the magnetization of the material, $\boldsymbol{H}$ is the magnetic field strength, χ_m is the magnetic susceptibility and $(1+\chi_m)$ is the relative permeability of the material.

From the microscopic aspects, the magnetization results from both the domain wall motion and domain rotation. An acceptable division is described as "wall motion is the main process up to about the "knee" of the magnetization curve. From there to saturation, rotation predominates; In this region work must be done against the anisotropy forces, and a rather large increase in $\boldsymbol{H}$ (Magnetic field strength) is required to produce a relatively small increase in M (magnetization)." According to the inclusion theory of domain-wall pinning [54], the crack in the material is equivalent to a resistance which forms pinning to the domain walls, but the magnetization vector in the domain must be turned to the direction of the external magnetic field. Domain wall motion and domain rotation are impeded by interaction of the moving wall with the spike domains normally attached to cracks rather than by interaction with the cracks themselves. The magnetization at the edge of the crack cannot be offset by the magnetization within the adjacent magnetic domain, so that the reverse barrier is formed on both sides of the crack, which impedes, resulting in magnetic charge buildup near the edge of the crack. Finally, the magnetic field is changed around the crack and its near area, resulting in the non-uniform permeability distribution. From the macroscopic aspects, the magnetic field lines inside the material are parallel to the external magnetic field when there are no cracks. Thus, the magnetic flux directly travels through the interface without any deflection, However, when a crack lies on the surface, some refractive magnetic field lines near one side of the crack finally enter into the vicinity of the crack (the other side), forming the flux leakage. The magnetic leakage field strength decreases sharply as the lift-off increases. On the other hand, the existing surface crack makes the other part of the magnetic field lines tend to twist abruptly to below-crack side. Then the pattern of the field tends to be channeled through the material, which seems like water disturbed by a stone in river, as shown in Fig. 1(a).

The magnetic field distortion caused by the crack changes the magnetic induction around the crack in the material, and it can be described as $\boldsymbol{B}_{dst}$. In this case, few magnetic lines of force squeeze