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Dipole modeling of stress-dependent magnetic flux leakage

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ABSTRACT

Existing magnetic dipole models cannot provide the accurate prediction result of the effect of the stress on the magnetic flux leakage (MFL) induced by defects in ferromagnetic materials. To solve this problem, an improved dipole model is proposed to investigate the stress-dependent MFL in tensioned specimens of Q235 steel. The stress concentration around the defect of a cylindrical through-hole leads to heterogeneous distribution of magnetization along the defect surface. Classic Timoshenko's theory is used to solve the localized compressive stress and tensile stress around the defect. The J-A model is employed to determine the stress-dependent magnetization distribution, which is the key parameter in the magnetic dipole model. The stress-dependent MFL signals predicted by the improved model are well consistent with the results of verification experiments and the peak-to-peak amplitude of the normalized MFL signal demonstrates the parabolic dependency on the applied tensile stress. A stress increment of 100 MPa can increase the amplitude of the MFL signal by 24%, which may cause a significant error in defect sizing. The proposed improved magnetic dipole model can reveal the effect of the stress concentration on the induced MFL signals and it is also applicable to solve the inverse problem for estimating the shapes and sizes of the defects even though the stress is involved.

1. Introduction

Magnetic flux leakage (MFL) testing is an important nondestructive tool to detect the flaws in ferromagnetic pipelines [1,2], wire ropes [3,4], plates [5,6], etc. Many attempts have been made to develop the sensors with novel configurations for detecting special MFL [7,8] and introduce advanced signal processing techniques [9,10] for improving the identification of weak MFL signals submerged in noises. To achieve quantitative evaluation of the defects, the influences of various factors, such as lift-off distance [11] and relative moving speed [12] between the specimen and the sensor, on the flaw-induced MFL signal are commonly investigated. However, the variation in the stress state of the tested components, which is neglected in most cases of MFL applications, may also have a noticeable influence on the MFL detection results.

As emphasized by Kvasnica et al. [13] and Jiles et al. [14], both the elastic strain and plastic strain can result in a noticeable variation in the magnetic hysteresis curve (consequently the permeability) of carbon steels. It is reported that in mild steels at lower field strengths (~400 A/m), the 120 MPa tension perpendicular to the magnetic field reduces the flux density by a factor of about six [15]. Therefore, under the action of an applied magnetic field, both the metal-loss flaws and the stress concentration in the ferromagnetic material can alter the localized magnetization and further change the surface MFL signal. However, it is difficult to differentiate the contributions of the two factors to the detected MFL signal with existing analytical or simulation models.

To improve sizing pit defects on a hydraulic pressure vessel, Mandal et al. [16] experimentally investigated the dependency of MFL signals induced by pits on the stress. It is found that the line pressure stress in in-service oil and gas pipelines can increase the amplitude of the MFL signals by more than 40%. To further evaluate the effect of the stress on the magnetic anisotropy of the steel, the experimental data are fitted with the analytical model of Zatsepin and Schcherbinin. Since the stress parameter was not considered in the Zatsepin and Schcherbinin model (Z-S model), only the fitting value of the linear density of magnetic charges in the mode was used for qualitative discussion [17].

In the Z-S model, a surface defect is simulated as magnetic dipoles so that the radial and axial components of the flux leakage field near the surface can be calculated. Inspired by the Z-S model, several magnetic dipole models are proposed to predict the MFL signal induced by the defects with complex geometry [18] even if the nonlinear magnetic behavior of ferromagnetic materials was involved [19]. However, to the best of our knowledge, analytical magnetic dipole models that can deal with the problem of the stress-induced MFL field at the defect location have not been reported yet.

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The key parameter of magnetic charge density in the magnetic dipole model is related to the magnetization of the material. The magneto-mechanical hysteresis model developed by Jiles and Atherton [20] (referred as J-A model) and Sablik et al. [21] considered the effect of the stress on the magnetization of ferromagnetic materials. Hence, if J-A model is combined with the magnetic dipole model through the stress-dependent magnetization, the new analytical model is expected to reveal the effect of the stress on the MFL signal induced by a defect. For this purpose, an improved magnetic dipole model considering the stress distribution around a cylindrical through-hole on a tensioned dog-bone specimen is presented in this study. Experimental testing is conducted to verify the feasibility of the new analytical model. Finally, the quantitative prediction about the effect of the tensile stress on the defect-induced MFL signals is achieved.

The rest of this paper is organized as follows. In Section 2, the improved analytical magnetic dipole model is presented. The details about the verification experiments, such as the MFL probe based on tunnel magnetoresistance (TMR) device and the tensile test procedure, are given in Section 3. A comparative study between the predicted and measured results of MFL signals is conducted in Section 4. Both the performances and limitations of the improved model are also discussed in Section 4. Finally, the major contributions of this study are concluded in Section 5.

2. Magnetic dipole model considering the stress effect

2.1. Magneto-mechanical hysteresis J-A model

When a ferromagnetic material is subjected to the action of elastic stress (σ) in an applied magnetic field (H), the magnetization (M) of the material is dominated by an effective field, H_e, which can be expressed as

$$H_e = H + \alpha M + H_\sigma^e, \tag{1}$$

where α quantifies the amount of domain coupling; H_σ^e represents the equivalent magnetic field induced by the elastic stress. In the thermodynamic or anhysteretic state, when the direction of magnetization (M) is parallel to the applied stress (σ), the term of H_σ^e can be expressed as [20, 21]

$$H_\sigma^e = \frac{3\sigma}{2\mu_0}\frac{\partial\lambda}{\partial M}. \tag{2}$$

The reported experimental results show that the dependency of the bulk magnetostriction (λ) on the magnetization (M) varies with the tensile stress [20–22]. The exact partial differential of $\partial\lambda/\partial M$ should be determined with the measured magnetostriction curve. An empirical model can be used to simulate the relationship between the magnetostriction and magnetization, and the expression that ignores the higher-order term is,

$$\lambda(\sigma, M) \approx \gamma_0 + (\gamma_{11} + \gamma_{12}\sigma)M^2. \tag{3}$$

where γ_0, γ_{11}, and γ_{12} are stress-dependent coefficients and can be determined through fitting the measured magnetostriction curve to Eq. (3). By substituting Eq. (3) into Eq. (2), the stress-induced effective field can be rewritten as:

$$H_\sigma^e = \frac{3\sigma(\gamma_{11} + \gamma_{12}\sigma)M}{\mu_0}. \tag{4}$$

Hence, the total effective field H_e can be simplified as follows,

$$H_e = H + \tilde{\alpha}M, \tag{5}$$

where $\tilde{\alpha} = \alpha + \frac{3\sigma(\gamma_{11}+\gamma_{12}\sigma)}{\mu_0}$. The anhysteretic magnetization curve, M_{an}, is used to illustrate the change of the net magnetization of each pseudo domain caused by the reversible domain moment (m) rotation. The anhysteretic magnetization curve M_{an} can be expressed by a modified Langevin equation as [20–22]

$$M_{an} = M_s\left[\coth\left(\frac{H_e}{a}\right) - \frac{a}{H_e}\right], \tag{6}$$

where M_s is the saturation magnetization and $a = k_B T/(\mu_0 m)$. In the hysteresis part of the J-A model, domain wall translation is included as an irreversible contribution to the magnetization. The irreversible contribution to the magnetization arises along with the domain wall motion, which is impeded by the presence of pinning sites. Energy dissipation occurs as the domain walls are pinned and unpinned in the increasing field. According to the energy conservation principle, the magnetization energy increment can be derived from the following equation [23]

$$\mu_0\int M\mathrm{d}H_e = \mu_0\int M_{an}\mathrm{d}H_e - \mu_0 k\int\frac{M_{irr}}{\mathrm{d}H_e}\mathrm{d}H_e, \tag{7}$$

where M_{irr} and μ_0 are respectively the irreversible magnetization and the vacuum permeability; k is the pinning coefficient, which is not constrained to be constant and may vary with M or H. The adjustment of k can be modified as $k\left[1 - \beta\left(\frac{M}{M_S}\right)^2\right]$, where β determines the adjustment amount [24].

The first term on the right-hand side of Eq. (7) represents the energy increment obtained from lossless M_{an}, and the second term denotes the energy dissipation caused by the irreversible contribution. Differentiating both sides of Eq. (7) with respect to H_e gives,

$$M = M_{an} - k\delta\frac{\mathrm{d}M_{irr}}{\mathrm{d}H_e}, \tag{8}$$

where δ is $+1$ when $\mathrm{d}H/\mathrm{d}t > 0$ and -1 when $\mathrm{d}H/\mathrm{d}t < 0$. The component of the reversible magnetization (M_{rev}) caused by domain wall bowing reduces the difference between the irreversible magnetization (M_{irr}) and the anhysteretic magnetization (M_{an}) at a given field strength. The component of M_{rev} can be estimated as,

$$M_{rev} = c(M_{an} - M_{irr}), \tag{9}$$

where c is the ratio of the initial magnetic susceptibility to the initial anhysteretic susceptibility. The total hysteresis magnetization (M) should meet the following formula:

$$M = M_{rev} + M_{irr}, \tag{10}$$

Based on Eqs. (8)–(10), the hysteresis magnetization can be given in the differential form [23],

$$\frac{\mathrm{d}M}{\mathrm{d}H} = \frac{(1-c)(M_{an} - M) + ck\delta\frac{\mathrm{d}M_{an}}{\mathrm{d}H}}{k\delta - \tilde{\alpha}(M_{an} - M)}. \tag{11}$$

The solution of hysteresis magnetization under different stresses can be obtained from Eq. (11) with the implicit function solver and Newton-Raphson method.

2.2. Magnetic dipole model for MFL prediction

A dipole model is extended based on the previous studies [25,26] to investigate the MFL field induced by a cylindrical through-hole defect in a tensioned ferromagnetic plate. Stress concentration occurs around the defect and results in localized magnetization variations according to Eq. (11) of J-A model.

The cylindrical through-hole defect is simulated to locate in the center of the plate with a thickness of b. The radius (R) of the defect is assumed to be much smaller than the width (W) of the plate. As shown in Fig. 1, both the external applied magnetic field ($\mathbf{H_0}$) and the tensile stress ($\boldsymbol{\sigma_0}$) are aligned in the positive direction of the y-axis. The top surfaces of