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Logarithmic analysis of eddy current thermography based on longitudinal heat conduction for subsurface defect evaluation

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HIGHLIGHTS

- Longitudinal heat conduction induced by eddy current is investigated.
- Logarithmic analysis is used to detect and evaluate the subsurface defects in metal.
- Separation time is defined as the characteristic feature to measure the defect's depth.

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ABSTRACT

Longitudinal heat conduction from surface to inside of solid material could be used to evaluate the subsurface defects. Considering that the skin depth of high frequency eddy current in metal is quite small, this paper proposed logarithmic analysis of eddy current thermography (ECT) to quantify the depth of subsurface defects. The proposed method was verified through numerical and experimental studies. In numerical study, ferromagnetic material and non-ferromagnetic material were both considered. Results showed that the temperature–time curve in the logarithm domain could be used to detect subsurface defects. Separation time was defined as the characteristic feature to measure the defect's depth based on their linear relationships. The thermograms reconstructed by logarithm of temperature can improve defect detectability.

1. Introduction

Infrared thermography is a non-destructive evaluation (NDE) method with an increasing span of applications [1–4]. In the active scheme, an external thermal stimulation is brought to the part to be inspected and analysis of the thermal response to this stimulus is recorded by an infrared detector to provide information about the internal structure of the part (such as thermal properties and presence of defects). Eddy current thermography (ECT) is an emerging IR thermography specifically for conductive material, which combines the advantages of eddy current testing and IR thermography, such as non-contact, fast and high resolution [5,6]. Many researchers have proposed various ECT methods, such as thermal-inductive [7], electromagnetic–thermal [8], tone burst eddy current thermography (TBET) [9], eddy current pulsed thermography (ECPT) [10–12], induction thermography [13], eddy current lock-in thermography (ECLT) [14], eddy current pulsed phase thermography [5] and eddy current step heating thermography [15]. Among these works, ECPT is widely and in-depth researched by Tian's group and several signal processing methods were used to improve the defect detectability [16–18]. What is more, a new ECT based technique is proposed for defect detection in ferromagnetic specimens using a low frequency alternating magnetic field induced heating [19]. However, the contemporary research has a great missdistance with quantitatively evaluation. In order to bridge this gap, some researchers are focusing on the temperature decay response after the pulsed inductive heating. For example, the subsurface defect of steel was evaluated based on the heat conduction using induction thermography [20]. Eddy current pulsed phase thermography (ECPPT) technique and related features in the frequency domain were proposed for subsurface defect evaluation [5,21]. In this work, logarithmic analysis of eddy current pulsed thermography was proposed. The quantitative analysis using separation time has been investigated through numerical studies and experimental studies. The thermograms constructed by logarithm of temperature are utilized to improve defect detectability.

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2. Methodology

Fig. 1(a) shows the diagram of logarithmic analysis of eddy current thermography. The excitation signal generated by excitation module is a short period of high frequency current, which is driven to the excitation coil above the conductive material. Then, the electric current in the coil will induce eddy currents and generate the resistive heat in the conductive material (in skin depth). EC heating will conduct from surface to inside of conductive material. Consequently, the temperature distribution on the surface of material is captured by an IR camera and the sequences of infrared images are transmitted to a PC. The physical meanings including induction heating and eddy current field distribution of eddy current thermography for specimen with surface defects have been introduced in previous works [22]. For subsurface defect which is beyond the skin depth, the heat conduction should be analyzed. This is the emphasis in this work, as shown in following.

The skin depth of eddy current in metal depends on the frequency of excitation signal, electric conductivity and magnetic permeability of material [23], which can be calculated by:

$$\delta = 1/\sqrt{f\sigma\pi\mu} \tag{1}$$

where f is excitation frequency, σ is the electrical conductivity, and μ is the permeability of the material under inspection. Due to the variance on electric conductivity and permeability, there are different heating modes for materials, such as surface heating, near-surface heating, and volumetric heating [11,24]. If the material under test is ferromagnetic metals with high permeability, the skin depth is much small (about 0.04 mm at 100 kHz and 0.03 mm at 200 kHz) [20]. In this case of surface heating, the skin depth can be neglected. If the material under test is aluminium alloy, the skin depth is small (about 0.3 mm at 100 kHz). In this case of near-surface heating, the skin depth cannot be neglected. If the material under test is carbon fibre reinforcement plastic (CFRP) with small conductivity, the skin depth is much great. In this case of volumetric heating, the skin depth has a big influence. In the first place, we consider the ferromagnetic material as the material under test. For an infinitely thick, semi-infinite ferromagnetic solid with a front surface that is instantaneously heated by a spatially uniform pulse, the surface temperature after heating is given by [25–28]:

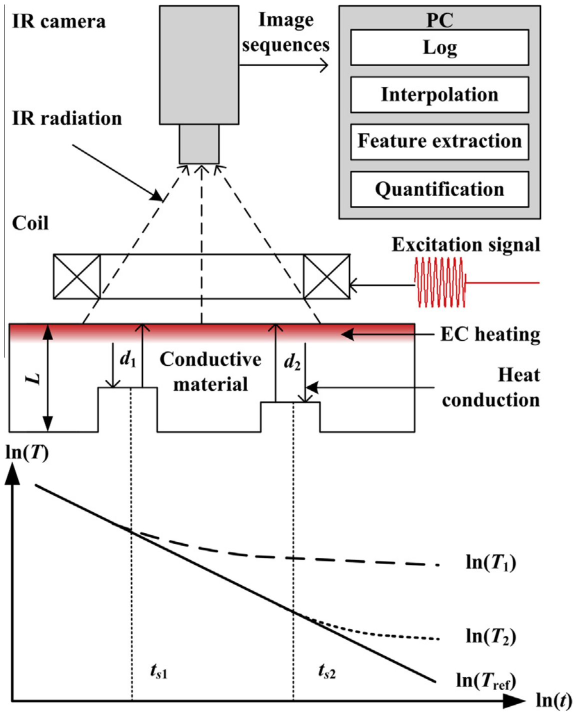

Fig. 1. Principle of logarithmic analysis of ECT. $\ln(T_1)$, $\ln(T_2)$ and $\ln(T_{\mathrm{ref}})$ are logarithmic curves of temperature responses for defect 1, defect 2 and defect-free area.

$$\Delta T = \frac{Q}{e\sqrt{\pi t}} \tag{2}$$

where Q is heat applied on the surface and e is thermal effusivity of material, which is defined as:

$$e = \sqrt{k\rho c} \tag{3}$$

where k is thermal conductivity, ρ is mass density and c is specific heat of the material. Taking the natural logarithm of both sides of Eq. (1), it becomes:

$$\ln(T) = \ln\left(\frac{Q}{e\sqrt{\pi}}\right) - \frac{1}{2}\ln(t) \tag{4}$$

Clearly, the relationship between $\ln(T)$ and $\ln(t)$ presented by Eq. (4) is linear with the slope -0.5. In actual environments, the thickness of material is finite and the skin effect of eddy current has little influence. Thus, the measured $\ln(T)$–$\mathrm{n}(t)$ curve for defect-free area is approximately linear, which is shown as solid line at the bottom of Fig. 1 and called as the reference signal ($\ln(T_{\mathrm{ref}})$). Given two subsurface defects (depth is d_1 and d_2, respectively) in conductive material, heat flow will be reflected when it arrives at the interface between material and defects. Therefore, temperature response of defects ($\ln(T_1)$ and $\ln(T_2)$) will separate from the reference signal ($\ln(T_{\mathrm{ref}})$), which are shown as dot lines at the bottom of Fig. 1. Therefore, logarithmic curves of temperature response can be utilized to detect the defects. Here, we define the time when $\ln(T_1)$ and $\ln(T_2)$ separate from $\ln(T_{\mathrm{ref}})$ as separation time (t_s). Then, it is concluded that the separation time for defect 1 (t_{s1}) is smaller than that of defect 2 (t_{s1}), because the depth of defect 1 (d_1) is smaller than that of defect 2 (d_2). Therefore, separation time can be used as the characteristic feature to evaluate the defects' depths. In this work, separation time is extracted after the interpolation of logarithmic curves of temperature responses.

3. Numerical studies

Numerical studies were conducted using COMSOL Multiphysics 3.5a. As shown in Fig. 2, the 3D Finite Element Modelling (FEM) consists of specimen, coil and subsurface defect (air's parameters). Table 1 shows the material parameters which were used in the simulations. According to coordinate system, the specimen size was constant as $150 \times 60 \times 10\ \mathrm{mm}^3$. Subsurface defects were constructed by six rectangular blocks with the same length × width ($60 \times 6\ \mathrm{mm}^2$) but different depths. As shown in Fig. 2, d indicates depth, V indicates width. Depths for six defects were set as 1, 1.5, 2, 2.5, 3 and 4 mm, respectively. Accordingly, their size-to-depth ratio ($\upsilon = V/d$) were respectively 6, 4, 3, 2.4, 2, and 1.5. Six defects were numbered as defects 1 to 6 in sequence. The coil was placed above the defect-free side. The lift-off distance between coil and sample was 1 mm. The excitation frequency and current were set as 256 kHz and 380 A. The heating period was set as 0.1 s and the recorded time (pulse time) after inductive heating was set as 2.5 s. Then, the temperature response (T–t) in the time domain on the surface (defect-free side) of the specimen was recorded and transformed to logarithmic curves ($\ln(T)$–$\ln(t)$) then analysed.

Firstly, the specimen material is set as steel. Fig. 3(a) and (b) shows the thermograms for defect 1 with 1 mm in depth at 0.2 s and 2 s, respectively. Fig. 4 shows the logarithmic curves after normalization [29] for six defects and defect-free area. Clearly, curves