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Physica C 372–376 (2002) 174–177

PHYSICA C

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Crack detection for the graphite slab using the high- T_c SQUID in unshielded environment

Jen-Tzong Jeng ^a, Herng-Er Horng ^{a,*}, Hong-Chang Yang ^b

^a Department of Physics, National Taiwan Normal University, Ting-Chou Road 88, Sec. 4, Taipei 116, Taiwan, ROC

^b Department of Physics, National Taiwan University, Taipei 106, Taiwan, ROC

Abstract

The nondestructive evaluation (NDE) for the crack inside a graphite slab was investigated by using the high- T_c SQUID NDE system in unshielded environment. The crack-depth dependence of the crack signal was explored with the excitation frequency varied from 2 to 20 kHz. It was found that the phase of the crack signal is a linear function of the crack depth for various excitation frequencies. In addition, for both graphite and aluminum, the slope of the linear phase depth relation scaled in an empirical equation with the skin depth as the only variable. The empirical equation was useful in determining the proper excitation frequency for the eddy-current NDE of conductive samples.

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Keywords: SQUID; Nondestructive evaluation; Graphite; Skin depth

1. Introduction

The SQUID-based eddy-current nondestructive evaluation (NDE) system is a powerful tool in detecting the buried flaws because of the high sensitivity of the SQUID in measuring the magnetic field. It was demonstrated that very deep flaws in a good conductor is detectable with the SQUID NDE system [1–3] with low excitation frequencies of a few Hz. It was also shown that the phase of the defect field, which is the magnetic field due to the excited eddy current around a

flaw, changes for different flaw depths excited with higher excitation frequencies [1,5]. As a result, it is necessary to choose the proper excitation frequency in order to achieve the better resolution in estimating the flaw depth. Nevertheless, the proper excitation frequencies were not the same for various conductors because of the variation in conductivities. Therefore, it is important to clarify the relationship between the conductivity and the proper excitation frequency for different conductors. In this work, the NDE of the crack in a graphite slab is investigated by using a high- T_c rf SQUID gradiometer NDE system. The phase of the differential defect field is measured for flaws buried in different depths. The results are compared to those of aluminum slabs to find an empirical relation for the proper excitation frequency.

* Corresponding author. Tel.: +886-2-8931-6233; fax: +886-2-2930-9439.

E-mail address: phyfv001@scs.ntnu.edu.tw (H.-E. Horng).

2. Experimental

The NDE system used in this work consists of an electronic high- T_c rf SQUID first order gradiometer and related electronics was reported in Ref. [5]. The rf SQUID was manufactured by the Ju-licher SQUID Company in Germany. The gradiometer consists of two magnetometers arranged in an axial configuration with a baseline of 12 cm. The ambient noise in unshielded environment was suppressed by using the gradiometer to enhance the signal-to-noise ratio. In order to compare the results for graphite with those for aluminum, the distance from the SQUID to the double-D coil and the distance from the coil to the sample were kept the same as those reported in Ref. [5].

The excitation frequency for graphite was different from the excitation frequency of aluminum. Typically, the excitation frequency for aluminum ranges from a few Hz to several hundred Hz [2–5]. As the conductivity of graphite is $\sigma_{\text{graphite}} = 0.9 \times 10^5 \Omega^{-1} \text{m}^{-1}$, which is smaller than that of the aluminum slab by a factor of 400, the excitation frequency for graphite should be greater than that of aluminum by a factor of 400 in order to have the same skin depth $\delta = (2\pi f \sigma \mu)^{-1/2}$. This means the excitation frequency from 1 to 100 kHz should be suitable for graphite. At this frequency range, the phase shift due to the SQUID electronics is not negligible. The phase shift due to the SQUID electronics was found to be 1.4°, 4.7°, 8.5°, and 18° for the excitation frequencies of 2, 5, 10, and 20 kHz respectively. These values of the phase shift were used to correct the phase of the defect field measured by the SQUID.

In order to probe the phase difference between the defect field and the excitation field, the in-phase, B_i , and the quadrature, B_q , components of the defect field were measured with an analog lock-in amplifier. To further remove the signal shift resulted from things other than the flaw, the measured B_i and B_q were differentiated by the spatial coordinate, x , to obtain the differential defect fields, dB_i/dx and dB_q/dx , respectively [6]. The phase of the defect field above the buried flaw was then calculated with the differential defect fields.

3. Results and discussion

The graphite sample with a buried flaw is shown in Fig. 1. The sample consists of graphite plates with the thickness varied from 1 to 16 mm. The overall dimension of the sample is 16 cm $\times$ 8 cm $\times$ 4 cm. To simulate the crack-like flaw buried at various depths in the sample, a 2 mm thick graphite plate with a slot of 6 mm $\times$ 0.5 mm $\times$ 2 mm in dimension was inserted into these plates. Thus, the dimension of the flaw was the same as that of the slot, and the depth of the flaw, z , was the distance measured from the top surface of the stacked plates to the middle of the height of the flaw as shown in Fig. 1.

During a scan, the in-phase, B_i , and the quadrature, B_q , components of the defect field, B , around the flaw located at $x = 0$ were measured with the SQUID NDE system as shown in the top of Fig. 2. The corresponding differential defect field, dB/dx , and the differential phase, ϕ_{diff} , calculated from the measured defect field were also shown in the middle and the bottom of Fig. 2 respectively. The B_i and B_q change their sign across the flaw because the excitation field is 180° out of phase in the two branches of the double-D coil. For the differential defect field, the in-phase, dB_i/dx , and the quadrature, dB_q/dx , components have maximum magnitudes above the flaw, and the corresponding differential phase $\phi_{\text{diff}} = \tan^{-1}[(dB_q/dx)/(dB_i/dx)]$ varies slowly around the flaw. It can be easily shown that the phase of the defect field near the flaw is approximately equal to that of the corresponding differential phase [6].

Fig. 1. The configuration of a graphite sample with a buried flaw is shown.

Fig. 2. Defect field, B , differential defect field, dB/dx , and the differential phase, ϕ_{diff} , over the graphite sample detected by SQUID when the flaw depth is 1 mm. The flaw is located at $x = 0$.

$$\tan^{-1} [B_q/B_i]_{x=0} \approx \tan^{-1} [(dB_q/dx)/(dB_i/dx)]_{x=0} = \phi_{\text{diff}}(x = 0). \quad (1)$$

To describe the relationship between the flaw depth and the phase, it was found the differential phase, ϕ_{diff} is more suitable to describe the relation than the phase calculated from $\tan^{-1}[B_q/B_i]$ because the shift accompanying B_i and B_q is removed by taking the spatial derivative [6].

The differential phase ϕ_{diff} at $x = 0$ as for various excitation frequencies was plotted a function of the flaw depth, z , as shown in Fig. 3. For an excitation frequency of 2 kHz, the ϕ_{diff} is not sensitive to the depth of flaws. However, with a higher excitation frequency, the ϕ_{diff} changes more significantly. The variation in ϕ_{diff} with z shows a linear behavior for various excitation frequencies. In addition, the slope, $d\phi_{\text{diff}}/dz$, was increased when the excitation frequency was increased. The relationship between $d\phi_{\text{diff}}/dz$ and the square root of the excitation frequency f was plotted in the

Fig. 3. Differential phase, $\phi_{\text{diff}}(z)$ at $x = 0$ for various excitation frequencies f . The inset shows $d\phi_{\text{diff}}/dz$ as a function of $f^{1/2}$.

inset of Fig. 3. It was found that the $d\phi_{\text{diff}}/dz$ increases linearly with $f^{1/2}$. This means that the $d\phi_{\text{diff}}/dz$ changes linearly with respect to δ^{-1} . These behaviors are very similar to those reported in Ref. [5], in which the aluminum slab was used instead of the graphite slab. Hence, the linear phase–depth relation of the buried flaw is a common behavior for both graphite and aluminum.

Since the linear phase–depth relation is common for both graphite and aluminum, therefore it is interesting to plot $d\phi_{\text{diff}}/dz$ as a function of the skin depth δ . In Fig. 4, the values of $d\phi_{\text{diff}}/dz$ for aluminum with the excitation frequency of 90, 130, 200, and 400 Hz were plotted along with data for graphite with the excitation frequency of 2, 5, 10, and 20 kHz. The skin depth is shorter than the thickness of each sample for the excitation frequencies used in these measurements. According to the results shown in Fig. 4, the $(d\phi_{\text{diff}}/dz)$ – z relation for graphite and for aluminum were found to scale in the following empirical equation shown in Fig. 4 as a dashed line,

$$\frac{d\phi_{\text{diff}}}{dz} = \left(\frac{120}{\delta} - 1.9 \right) \quad (2)$$

Fig. 4. The values of the $d\phi_{\text{diff}}/dz$ for graphite and aluminum with respect to the skin depth δ . The dashed line is the empirical equation: $d\phi_{\text{diff}}/dz = (120/\delta - 1.9)$, in which δ is in mm, and $d\phi_{\text{diff}}/dz$ is in $^{\circ}/\text{mm}$.

in which δ is in mm, and $d\phi_{\text{diff}}/dz$ is in $^{\circ}/\text{mm}$. The above equation was obtained from the data shown in the inset of Fig. 3. With the help of Eq. (2), it is possible to choose a proper excitation frequency for the graphite or the aluminum according to the skin depth $\delta = (2\pi f \sigma \mu)^{-1/2}$ in Eq. (2). Moreover, Eq. (2) should be applicable to most nonmagnetic metals with conductivities between those of aluminum and graphite.

4. Conclusion

The SQUID-based gradiometer NDE system was used to detect the flaws buried in a graphite slab. For the crack-like flaw with the width and the height less than the skin depth, the linear phase–depth relation holds well for both graphite and aluminum. Besides, it is possible to choose the proper excitation frequency for a conductive sample according to its conductivity by using the empirical relation described by Eq. (2).

Acknowledgements

This work is supported by the National Science Council of the ROC under grant nos.: NSC89-2112-M-003-040 and NSC89-2112-M-002-071.

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