Research on the Crack Detection of Conductive Components Using Pulsed Eddy Current Thermography

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Abstract: Crack of conductive component is one of the biggest threats to daily production. In order to detect the crack on conductive component, the pulsed eddy current thermography models were built according to different materials with the cracks based on finite element method (FEM) simulation. The influence of the induction heating temperature distribution with the different defect depths were simulated for the carbon fiber reinforced plastic (CFRP) materials and general metal materials. The grey value of image sequence was extracted to analyze its relationship with the depth of crack. Simulative and experimental results show that in the carbon fiber reinforced composite materials, the bigger depth of the crack is, the larger temperature rise of the crack during the heating phase is; and the bigger depth of the crack is, the faster the cooling rate of the crack during the cooling phase is. In general metal materials, the smaller depth of the crack is, the lager temperature rise of the crack during the heating phase is; and the smaller depth of the crack is, the faster the cooling rate of crack during the cooling phase is.

Key words: Pulsed Eddy Current Thermography; Finite Element Analysis; Carbon Fiber Reinforced Composite Material; Metal Material

1 Introduction

Pulsed eddy current thermography (PECT) detection technology, which is a new kind of pulsed eddy current nondestructive testing technology, integrates many advantages of eddy current testing technology and thermography detection technology: non-contact, non-interactive, high sensitivity, fast detection, large detection area, high efficiency, real-time measurement and so on[1]. This technology gets more in-depth research and rapid development in the world, which has been widely used in testing evaluation of metal materials and compositing materials[2-4]. Great progress has been achieved including the method of numerical simulation and experiment for the detection system, detection principle, defects qualitative recognition, etc. Oswald-Tranta studied the temperature distribution and the effect of eddy current penetration on the temperature rise when PECT was used to detect surface defects of different materials, the results show that the deeper the eddy current penetration has, the higher the temperature rises[5]. Walle made an investigation on the thermographic crack detection in ferritic steel components using inductive heating, and discussed the defect length, depth and dip angle on the influence of the test results[6]. Weekes studied the minimum detectable defects using PECT in the metal detection of steel, titanium, nickel and so on[7]. Cheng proposed the relationship among the crack depth, width and the thermal responses of the carbon fiber composite materials[8]. He put forward the delamination defects volume type heating[9]. Yang studied the different material eddy current heating mode, using PECT detection technology [10-12].

Based on the above background, the skin effect of different materials needs further investigation for crack defects detection based on PECT. In order to seek the research regulation of skin depth detection using PECT, this paper discusses the establishment of finite element simulation model between the carbon fiber reinforced composite materials and general metal materials using PECT defect detection. The eddy current distributions around the crack and temperature response characteristics were investigated.

2 Detection Theory of Conductive Component Based on PECT

PECT nondestructive testing technology uses pulses of eddy-currents induced in measured material to generate local heating inside the material. Firstly, the high frequency signal is applied on the conductive component to make the induction coil generating induction current. The transient diffusion of the heat inside the material, induced by pulsed induction heating, is imaged by measuring the transient temperature profiles on the surface of the material. The presence of internal defects in the material changes the heat transfer characteristics of the materials and the IR camera can record the difference of temperature. The temperature distribution in the image can rapidly identify the location of cracks, which can be used for the nondestructive evaluation (NDE) of conductive materials. Fig. 1 shows the diagram of PECT detection technology principle. Obviously, the PECT nondestructive testing technology mainly involves three physical processes: EC heating, heat conduction and IR radiation.

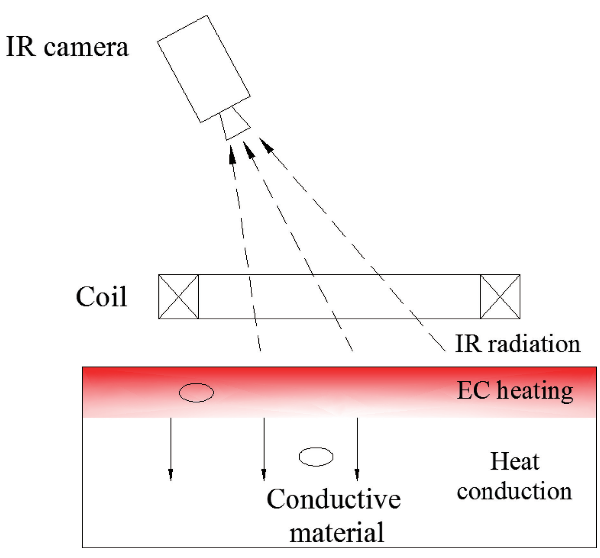


Fig. 1 The diagram of PEC thermography principle

In PECT system, the eddy current would gather on the surface of sample and decay from surface to center according to the index attenuation law, this is the skin effect. When the density of eddy current decreased to 1/e of the surface eddy current density, the depth is called the skin depth (δ) which is related to the excitation frequency, the relative permeability and the electrical conductivity of materials. The skin depth (δ) can be calculated by Eq. (1):

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

Where f is the excitation frequency (Hz), σ is the electrical conductivity (S/m), $\mu$is the relative permeability. According to Joule´s law, the material is caused by resistive heating from eddy currents. The generated resistive heat Q is proportional to the square of the eddy current density J_s and electric field intensity vector E, as shown in Eq. (2):

$$Q = \frac{1}{\sigma} \left| J_s \right|^2 = \frac{1}{\sigma} \left| \sigma E \right|^2 \tag{2}$$

The Joule heating Q will spread into the interior of specimen, which can be expressed by Eq. (3). ρ , C_p , k represent the material density, specific heat and thermal conductivity, respectively.

$$\rho C \frac{\partial T}{\partial t} - \nabla (k \nabla T) = Q \tag{3}$$

The Joule heating will spread to other areas of the specimens rapidly. The depth of the thermal diffusion is shown in Eq. (4):

$$\delta_{th} \approx \sqrt{\alpha t} \tag{4}$$

where $\alpha$is the thermal diffusion coefficient, t is the observation time. αcan be calculated according to Eq. (5):

$$\alpha = \frac{\sigma_T}{\rho C_p} \tag{5}$$

It is concluded that the induction heating is varied for different type of material, different materials have different skin depths. According to the different skin depth, eddy current heating mode can be summarized as surface heating or volumetric heating. Surface heating mode is aimed at metal materials, and the skin depth is much smaller than the thickness of the measured material that the surface is heated. Volumetric heating mode mainly targets for compositing materials, which skin depth is much larger than the thickness of the measured material when the whole heating in a short time.

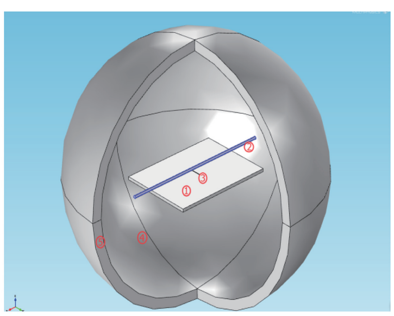
3 Simulation Setup and Simulated Analysis

3.1 Simulation Setup

In this section, the finite element simulation of defect detection models is built using COMSOL Multiphysics 4.3b, which consists of sample, coil, air and defect. Physical fields for induction heating under the AC/DC module are selected. Based on the defect of CFRP, ferromagnetic, non-ferromagnetic materials, the PECT simulation models were established. Cylindrical induction coil size is constant as $\varphi 3 \times 300$ located in the central samples. The crack defects are shallow groove, 1mm wide, 1 ~ 5mm depth, which are located in the center of the sample surface and are vertical with the sample surface. The model parameter settings of PECT detection simulation are as follows: the exciting current is 380Arms, excitation frequency is 256 kHz, the heating time is 200ms and the cooling time is 800ms. Iron and aluminum are chosen as ferromagnetic and non-ferromagnetic simulation sample, respectively. Parameters are shown in Tab. 1. The simulation model is shown in Fig. 2. Internal sample point is used in CRFP material, surface sample point is used in ferromagnetic and non-ferromagnetic materials.

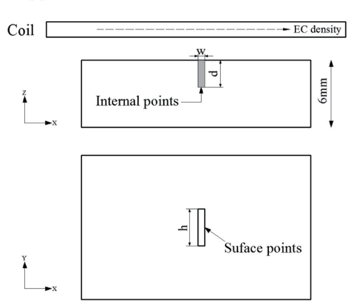
Table 1 Material parameters of Simulation

Parameter	CFRP	Iron	Aluminum
Electrical conductivities/($S \cdot m^{-1}$)	{10000, 100, 100}	1.12×10^7	3.774×10^7
Thermal diffusivity/[$W \cdot (m \cdot K)^{-1}$]	{2.225, 1.374, 0.615}	76.2	160
Specific heat/[$J \cdot (kg \cdot K)^{-1}$]	850	440	900
Density/($kg \cdot m^{-3}$)	1540	7870	2700
Relative permeability	1	4000	1



1- Conductive sample 2-Cylindrical coil 3-Sample surface defect
2- domain 4-The inner air domain 5-Infinite element domain

(a) Defect detection simulation of 3d model



(b) Defect detection simulation of two-dimensional model

Fig. 2 Defect detection simulation model

3.2 Simulation Analysis of Crack Detection of CFRP Using PECT

Fig.3 shows that the temperature distribution of CFRP in the area around the notch at the maximum PEC-induced heating time is 200ms. The interaction between the notch and the uniform eddy currents in the sample shows that the eddy currents always follow the path with least resistance. Therefore, they are mainly confined to the surface layer in a sample without a defect, as defined by the skin depth formula (1), along the sample thickness. When the eddy currents encounter a discontinuity, such as a notch, they will be forced to divert to the bottom of the notch, where the eddy current density increases to generate more heat. For CFRP materials, excitation varied direction can be used in PECT to investigate different layers, since the electrical and thermal conductivity are the greatest along the fiber orientation. The skin depth of CFRP materials is very big (9.95 mm) under the simulation conditions. The eddy current is hindered on the crack of surface edge, so the eddy current density at the bottom of the defect is larger than the eddy current density at the edge of the defect. Therefore, it is the maximum temperature at the bottom relative to other defective regions. As it is demonstrated in Fig.4 (a), during the heating phase, the smaller defect depth makes more eddy current transferring to the bottom of the cracks. The temperature increases with the increasing crack depth. The temperature response is linear with the defect depth, because the eddy current heating mode is volumetric heating mode. Resistance of the heat will gradually spread over time until heat balance in the material is achieved, then the crack temperature rises linearly. Fig.4 (b) shows that the normalized signal processing results, it can be observed that the temperature of the cracks with different depths are almost the same in the heating stage, temperature curves are linear. In the cooling stage, the greater depth of the crack is, the faster cooling rate of temperature has.

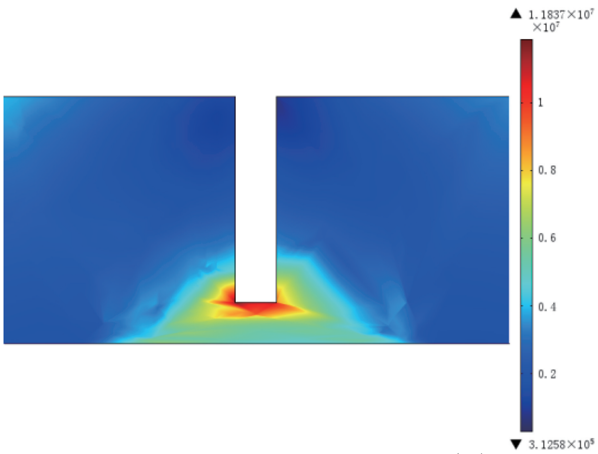
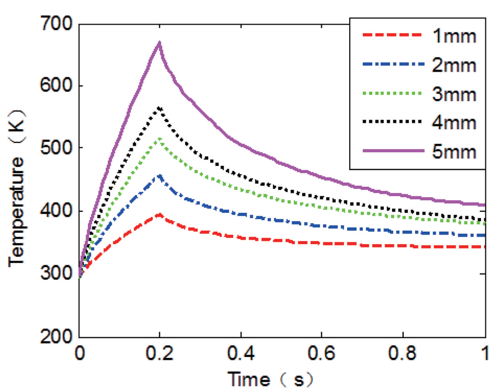
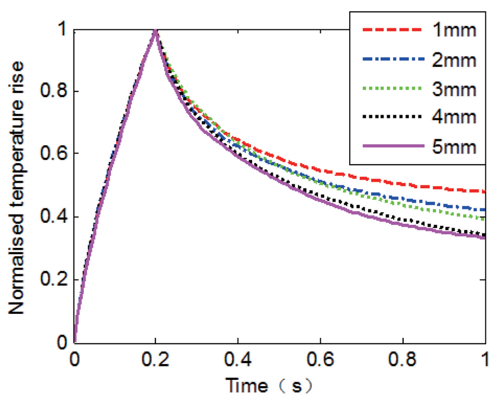


Fig. 3 Simulation results of thermal images at the maximum heating (200ms) for w=1mm, d=5mm notch



(a) Defect sample point temperature change of CFRP

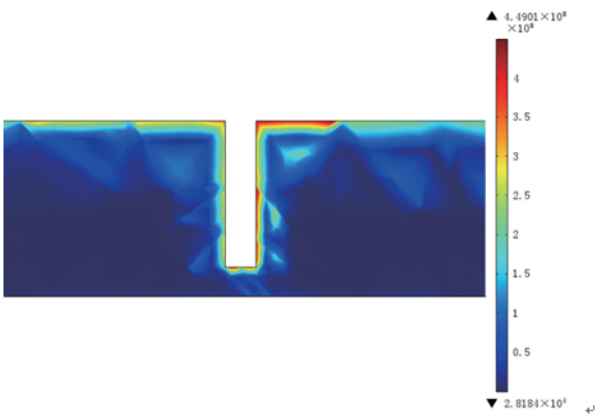


(b) CFRP sampling points of normalized grey value changes

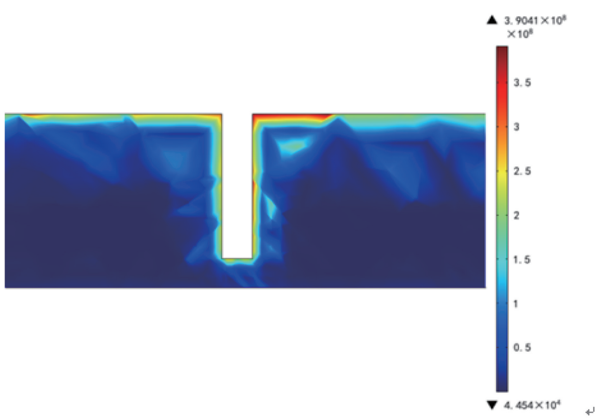
Fig. 4 Defect sample point transient temperature change

3.3 Simulation Analysis of Crack Detection of Metal Materials Using PECT

Fig.5 shows the temperature distribution of iron and aluminum, respectively, in the area around the notch at the maximum PEC-induced heating time of 200ms. More heating is observed at the surface edge due to the skin depth. Ferromagnetic metals with high permeability have a much smaller skin depth (about 0.028 mm), whereas for non-ferromagnetic materials, the skin depth is slightly bigger (about 0.21 mm). As the eddy current heating mode is surface heating mode, eddy currents are mainly concentrated on the surface of the sample. Due to the existence of defects, eddy currents will be forced to divert to the edge. The internal temperature of sample is mainly caused by the heat conduction. The presence of crack will hinder the heat conduction and the heat will be reflected to the conductor surface from the crack. Fig.6 (a) and (b) are the sample points of temperature change for iron, aluminum plate, respectively. It can be seen that the crack peak is in 0.2s, and the curve slope of temperature gradually decreases and tends to be gentle. With the increase of crack depth, the temperature gradually decreases. The 1 mm defect is the maximum temperature in all defect depth. The temperature rise of the aluminum plate is smaller than iron plate's. The relative permeability of iron plate is higher than aluminum's, distribution of eddy current focuses on the surface of the sample. The penetration depth of eddy current is bigger in aluminum plate, so the thermal diffusion rate is faster. Eddy current density is much smaller than iron plate's. The electrical conductivity and specific heat capacity are greater than iron plate's in the same position. Therefore, the temperature change of aluminum plate is much smaller than iron plate's. Fig.6 (c) and (d) are normalized temperatures of crack sample point on iron, aluminum plate, respectively. In the heating stage, the temperature rising tendency for different crack depth are quiet similar. But in the cooling stage, the smaller the crack depth is, the faster the cooling rate is.

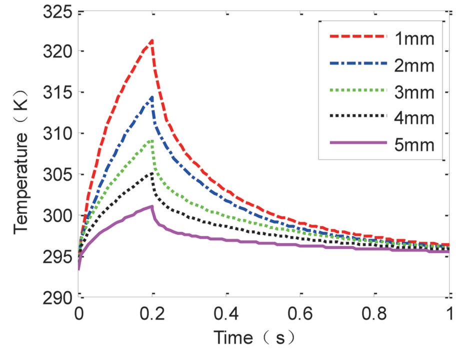


(a) Iron plate

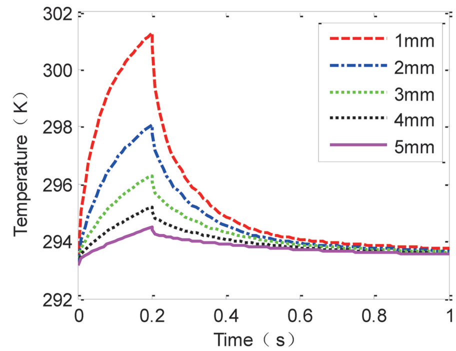


(b) Aluminum plate

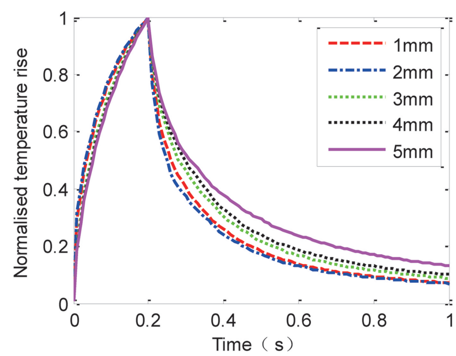
Fig. 5 Simulation results of thermal images at the maximum heating (200ms) for w = 1mm, d = 5mm notch in iron (a) and aluminum (b) plate



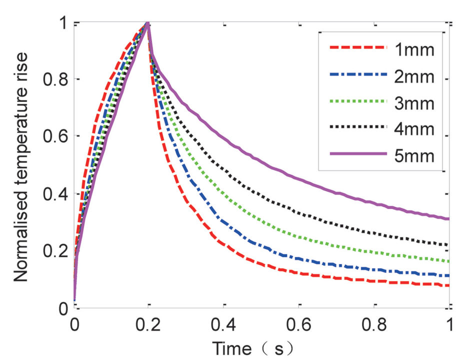
(a) Defect sample point temperature change of iron plate



(b) Defect sample point temperature change of aluminum plate



(c) Iron plate sampling points of normalized grey value changes



(d) Aluminum plate sampling points of normalized grey value changes

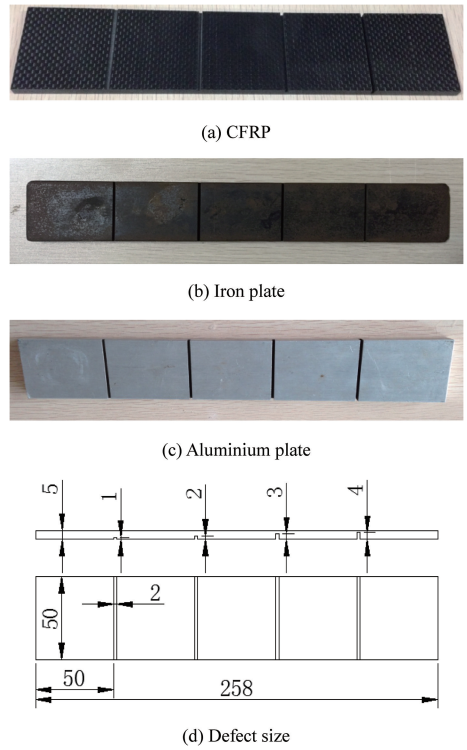
Fig. 6 Sample point instantaneous grey value changes

3.4 Simulation Analysis of Crack Detection of Conductive Materials Using PECT

In the PECT detection of the simulation, the skin depth of CFRP is very big, which makes eddy currents almost cover the whole CFRP samples. With the increase of crack depth, temperature rises rapidly, because eddy current heating is volumetric heating mode in CFRP. The temperature response is linear with the defect depth in the heating stage. In the cooling stage, the smaller the crack depth is, the faster the cooling rate is. For metals, the skin depth is much smaller than the defect depth. Eddy current is mainly concentrated on the sample surface and eddy current density is the largest in defect surface edge. Eddy current heating method belongs to surface heating, the response curve slope of heating stage temperature decreases. The smaller the crack depth is, the greater the temperature rise of the crack in the heating stage has, and the faster the cooling rate in the cooling stage is.

4 Experiment Devices

Fig.7 (a), (b) and (c) are different depths of CFRP, iron and aluminum plate checked sample, respectively. Fig.7 (d) is the defect of CFRP, iron and aluminum plate size. Experimental apparatus was shown in Fig.8. The experimental devices consist of an infrared thermal imager, induction coil, induction heating source, water-cooling system, other equipment and samples. The type of infrared thermal imager is the FLIR T440. Resolution is 640 x 480, sensitive wavelength is 7.5~13μm. Induction drive coil adopts hollow copper pipe materials, copper pipe diameter is 6mm. Coil shape is flat circular spiral structure. The test sample is placed under the coil and parallel to it. The type of induction heating source is EASYHEAT 0224. For the excitation source of commercial precision inductive heating module, the maximum power is 2.4kw, maximum current is 400A, excitation frequency ranges from 150 KHz to 400 KHz.



(a) CFRP

(b) Iron plate

(c) Aluminium plate

(d) Defect size

Fig. 7 Experimental sample and defect size

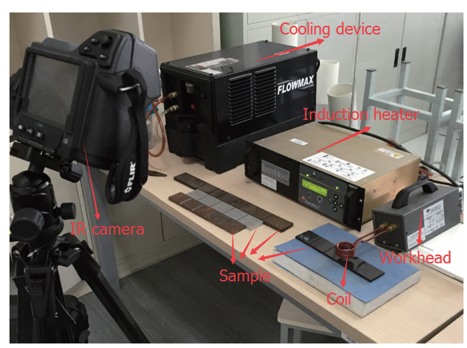


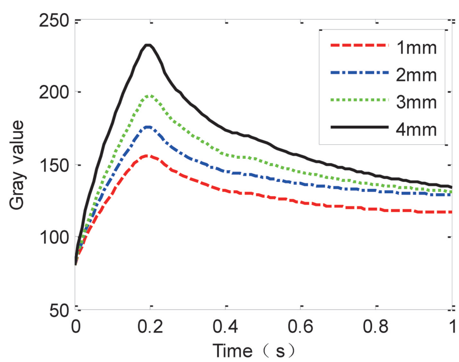
Fig. 8 The experiment devices

5 Experimental Results

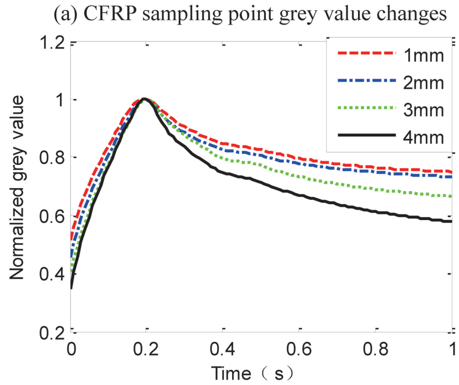
5.1 Experimental Result of Crack Detection of CFRP Materials Using PECT

Fig.9 is the experimental results of thermal images at the maximum heating (200ms) for w=1mm, d=2mm notch. The excitation time is 200ms, cooling time is 800ms, coil distance test piece is 9mm and sample frequency is 50Hz. The sample point is consistent with the simulation. The gray value of the sample point is used to represent the instantaneous temperature change, as shown in Fig.10 (a). By comparing different crack depths in grey value in Fig.10 (a), it can be seen that grey value response curve is linearly increasing. The larger the crack depth within skin depth is, the greater the temperature change of gray value has. Because the deep crack can make the eddy current transfer to the bottom of the defect and increase the temperature of crack. This is consistent with the simulations. The crack temperature rises to the maximum when the crack is 4mm. In Fig.10 (b), the crack temperature rise is not obvious and the temperature curve is linearly rising by the method of normalized signal processing in the heating stage. On the contrary, in the cooling stage, the greater depth of the crack is, the faster cooling rate of temperature is.

Fig. 9 The experimental results of thermal images at the maximum heating (200ms) for w=1mm, d=2mm notch.



(a) CFRP sampling point grey value changes

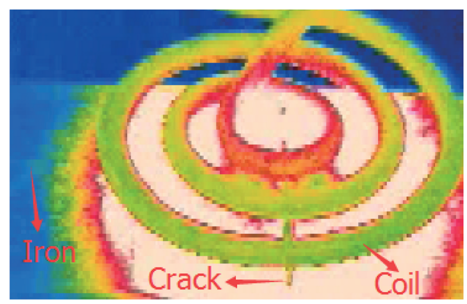


(b) CFRP sampling points of normalized grey value changes

Fig. 10 Sample point instantaneous grey value changes

5.2 Experimental Results of Crack Detection of Metal Materials Using PECT

Fig.11 is the experimental results of thermal images at the maximum heating (200ms) for w = 1mm, d=2mm notch. The sample point is consistent with the simulation, which is used to represent the instantaneous temperature change of the crack. From the comparison of different crack depth in gray value, the crack depth of iron, aluminum plate are not within the skin depth, internal temperature change of specimen is mainly caused by the surface temperature of heat conduction. The presence of crack will hinder the heat conduction and the heat is reflected to the conductor surface from cracking. Therefore, the smaller of its gray value changes, the smaller of the temperature changes.

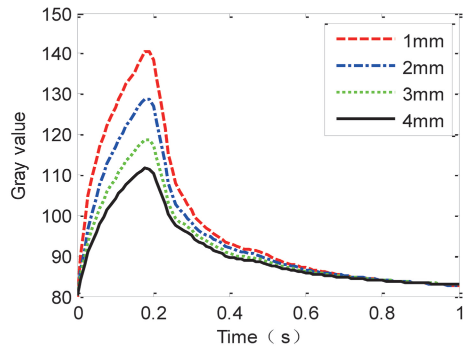


(a) Iron Plate

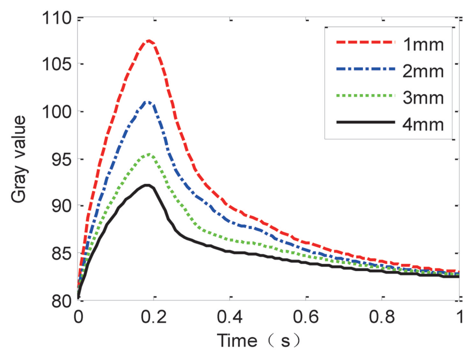
(b) Aluminum Plate

Fig. 11 The experimental results of thermal images at the maximum heating (200ms) for w=1mm, d=2mm notch.

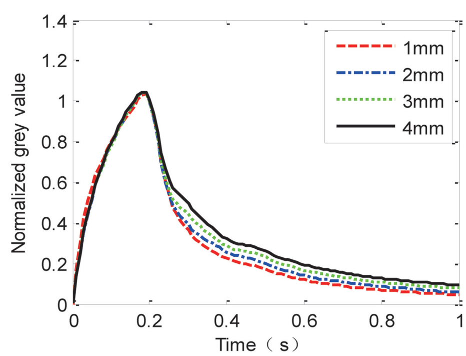
Fig.12 (a) and (b) are the changes of gray value of sample point in the iron, aluminum plate, respectively. It can be seen that the gray value rapidly increases during the heating stage and the slope of curve is gradually decreasing. The gray value of 1 mm crack depth is the biggest among all investigated cracks. From Fig.12 (c) and (d), in the cooling



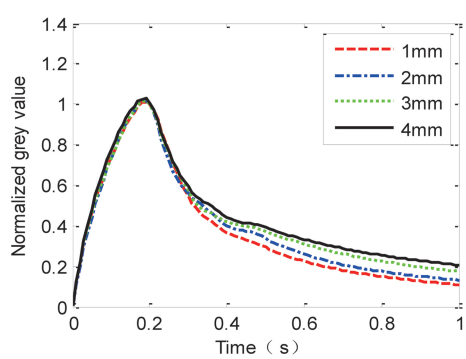
(a) Iron plate sampling point grey value changes



(b) Aluminum plate sampling point grey value changes



(c) Iron plate sampling points of normalized grey value changes



(d) Aluminum plate sampling points of normalized grey value changes

Fig. 12 Sample point instantaneous grey value changes

stage, In the cooling phase, the temperature of the smaller defects decreases more rapidly. using the method of normalized signal processing. The experimental results of the defect depth are consistent with the simulation of transient temperature changes.

5.3 Experimental Results of Crack Detection of Conductive Materials Using PECT

The temperature rise of the crack is extracted from the collected image, which is consistent with the simulation results. The internal thermal gradient is small and the rate of the temperature rise is fast in the early stages. However, with the accumulation of heat, the internal thermal gradient of materials increases gradually, the spread rate of heat accelerates into the surrounding and the rise of the temperature gradually slows down. In the CFRP material, the temperature gradually rises with the increase of crack depth and the temperature response increases linearly in heating stage. Obviously, the deeper crack is, the greater the temperature rises. In the iron plate and the aluminum plate, the temperature gradually decreases with the increasing depth and the response curve slope gradually decreases. Also, the shallower crack is, the greater the temperature rises. After the heating is stopped, the heat continues to spread across the sample. In the cooling stage of the CFRP material, the deeper the crack is, the faster the temperature decreases. In the iron plate and the aluminum plate, the smaller the crack is, the faster the cooling rate is. Iron's temperature is much higher than aluminum, because the aluminum plate has good thermal conductivity to transfer thermal diffusion and it has small absolute value of the temperature change. As a result, non-ferromagnetic material has higher requirements to the camera. The crack detection's effect is very obvious in the ferromagnetic material.

6 Conclusion

In view of the CFRP, ferromagnetic and non-ferromagnetic materials defects, the models of PECT finite element detection are established. The conclusions are as follows:

(1) Due to the skin effect, eddy currents are mainly concentrated on the surface of ferromagnetic materials and non-ferromagnetic materials, while eddy current almost covers the whole plate for the CFRP materials. It's obvious that in the CFRP materials, the temperature increases gradually when the crack depth increases and the response curve is linearly increasing. However, the temperature gradually decreased with the increasing crack depth in the ferromagnetic and non-ferromagnetic materials and the slope of response curve gradually decreases.

(2) PECT is very effective for the defect detection in CFRP and ferromagnetic material, but not so effective for non-ferromagnetic material which requires a high sensitivity of the infrared thermal imager.

(3) During the process of defect detection in CFRP material using PECT, the larger defect depth is, the greater temperature rises in heating phase and the faster cooling rate in cooling phase has. Comparing with CFRP materials, the cooling rate of ferromagnetic and non-ferromagnetic materials is faster.

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