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Experimental Detection of Composite Delamination Damage based on Ultrasonic Infrared Thermography

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ABSTRACT

An experimental setup is designed to detect composite delamination damage based on ultrasonic infrared thermography. The ultrasonic infrared thermography system is composed by ultrasonic excitation system, infrared thermal imager and data acquisition system and two damaged composite plate specimens are produced in the experiment. The image processing methods including thresholding, filters, edge detection and morphological processing method are combined to analyze infrared thermal images and accurately identify the location and size of the delamination damage. The temperature changes of defective composites under different preload of ultrasonic excitation are analyzed. The experiments demonstrate that the ultrasonic detection has the effect of the selection of heating in the defective area of the composite. The experimental results come to the conclusion that the ultrasonic infrared thermography is an effective quantitative method to detect the composite delamination damage.

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1. INTRODUCTION

In recent years, the field of composite materials has been widely used in the aerospace, energy, transportation, medicine, etc. The fiber-reinforced composites including carbon fiber, glass fiber and aramid fiber has become the main structural material [1-3]. Although composite materials can greatly reduce the structural weight and improve material performance, the internal structure of the composite material may have some defects in the production process such as inclusions, porosity, delamination, etc. The delamination damage of layered composites is the typical defect in the manufacture and operation process which results in the reduction of the material strength and rigidity and the affection of the integrity of the structure. When the delamination damage of the composites spreads, it may lead to the composite fracture.

The internal composite defect detection has received much attention in the field of non-destructive testing. The common nondestructive testing (NDT) methods [4-9] include radiographic examination (RT), ultrasonic testing (UT), magnetic particle testing (MT), liquid penetrant testing (PT), eddy current testing (ET), acoustic emission testing (ET), etc. The advantages of UT over other methods lie in that the internal defects can be sensitively and sized without any radiation hazard and only single-sided access is needed when the pulse-echo technique is used. Therefore, it is usually applied to fast detection of metal, non-metallic and composite materials with internal defects. However, the composites have the feature of non-uniform anisotropy and structural complexity and the coupling agent is generally required in the ultrasonic testing. The conventional NDT techniques, such as ultrasound method, acoustic emission testing, radiation detection methods, surface infiltration are difficult to effectively detect internal damage for a variety of composite materials.

The introduction of ultrasonic infrared thermography has overcome the weakness of traditional ultrasonic

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testing method. It is very sensitive and convenient to use the ultrasonic infrared thermography for rapid and accurate detection of the internal large-scale internal defects in composite materials [10-13]. The ultrasonic infrared thermography has wide applicability, intuitive and quantitative measurement, etc., which generates the defect thermography of test specimens based on the active controlled heating of the ultrasound. The heat sources of ultrasonic infrared thermography are selected to be high-power flash, hot wind, laser, etc. according to different specimen materials. Common infrared excitation sources, such as high-energy flash, hot air are the direct pulse thermography and the heat radiation is generated on the entire sample surface, where reflective of local areas are very serious and concentrative.

The ultrasonic infrared testing technology uses ultrasonic signal as the excitation source, which leads to thermal excitation of the samples and the significant higher temperature in the defective areas compared to the adjacent areas without defects [14]. Therefore, the advantages of the ultrasonic infrared thermography technology are high reliability, high sensitivity, high signal-to-noise ratio, which is suitable for non-destructive testing of composite materials. Some work has been done in the past modeling of ultrasonic infrared thermal imaging technology and analyzing the effects of high power ultrasonic energy on material properties. Han et al. constructed finite element models for sonic infrared imaging of cracks in alloys, composite, etc [15-17].

Ouyang and Favro proposed a theoretical model of ultrasonic infrared thermal imaging technology [18]. Perez et al. proposed a method of optimizing the ultrasonic method of infrared thermal signal [19]. Another studies have been investigated for detecting different defects and determining constitutive relation in thermographic testing. Favro and Han utilized ultrasonic welding generator as the excitation source and observed heat phenomenon of cracked aluminum plate and carbon fiber reinforced composites with the impact defects via infrared thermal images [20]. Han et al. applied the ultrasounic infrared thermography testing techniques to the detect large, irregular and slight brittle workpieces [21].

Han et al. studied chaotic phenomena in ultrasonic infrared thermography technology and revealed the relationship between the ultrasonic vibration frequency and the sample response [22]. Lu et al. studied the relationship between clamping force of ultrasonic impact gun and surface temperature distribution [23]. Holland et al. analyzed the relation between normal pressure in the crack, crack size, and heat in the ultrasonic infrared thermography [24]. Renshaw et al. analyzed the effects of crack closure status, load and vibration loading stress on heating and tested the effects of frequency and amplitude of vibration on the heating conditions [25, 26]. Zou proposed the defect detection of carbon fiber composite with foam sandwich structure with the use of ultrasounic infrared thermography testing method [27].

Since the defect detection of ultrasonic infrared thermography is based on the temperature distribution on material surface at different times, there are many factors that affect the precision of defect detection, such as environmental temperature, stability of heat sources, efficiency of signal collecting, etc.

It is necessary to establish a testing system and image processing method for ultrasonic infrared thermography in defection of composite delamination defect detection. In this paper, carbon fiber reinforced epoxy composite laminates with defects is made and the localized heating mechanism of ultrasonic excitations for layered composite plates is analyzed based on the experiments. Section 2 introduces ultrasonic infrared thermography method. Section 3 describes the design of experimental setup and production of damaged composite plate specimens. Section 4 proposes the infrared thermography processing method. Section 5 determines the relationship between preload size and temperature change from the experimental results and conclusions are drawn in Section 6.

2. ULTRASONIC INFRARED THERMOGRAPHY

As a non-destructive testing method, the ultrasounic infrared thermography is widely used for the rapid and large area detection of fatigue cracks in aircraft fuselage, industrial parts and welding, which scans the specimens with short pulse (50-200ms) and low-frequency ultrasound (20-40kHz) via a coupling agent. Once the cracks happen, inclusions or other defects exist inside the composite. The effect of friction, thermoelastic hysteresis and other effects arising from the interaction between defects and ultrasound may cause the reduction of vibration energy and temperature rising in defective area because a great deal of ultrasound power is converted into the heat. The surface temperature distribution can be observed to determine the defect position [28-30].

A typical experimental system of ultrasonic infrared thermography is mainly composed of three parts: ultrasonic excitation system, infrared thermal imager and data acquisition system. Figure 1 shows a simplified schematic of experimental setup.

3. EXPERIMENTAL SETUP

The ultrasonic infrared experiment setup of carbon fiber reinforced layered epoxy composite plate with delamination damage is introduced in this section.

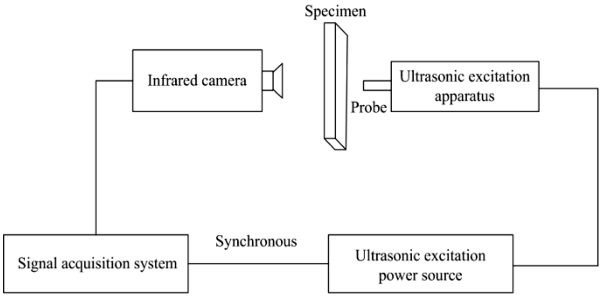


Figure 1. System schematic of ultrasonic Infrared thermography

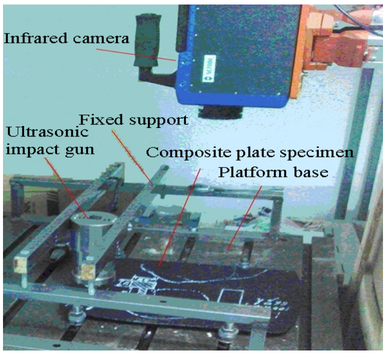
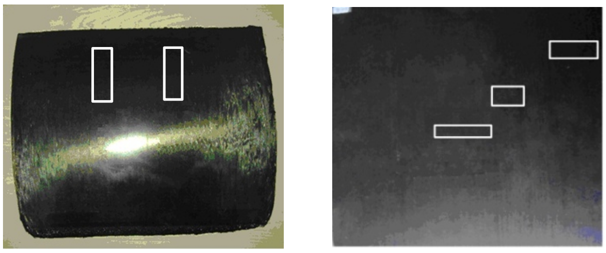


Figure 2. Experimental setup



(a) (b)

Figure 3. Damaged composite plates (a) 1# (b) 2#

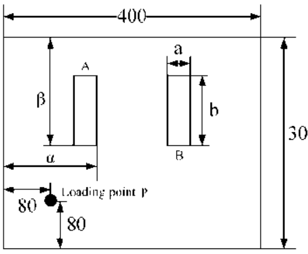


Figure 4. Plate 1 with two defects under the excitation signal

3. 1. Design of Experimental Setup

The composite plate specimen is heated by ultrasonic impact gun and the infrared camera is utilized to record the infrared thermal images. The location and size of composite plate defects can be extracted from the infrared thermal images. The ultrasonic infrared thermography system consists of ultrasonic excitation system, infrared imaging and data acquisition system shown in Figure 2. The experimental setup is composed by infrared camera, ultrasonic impact gun, the composite plate specimen, fixed support, platform base and other parts. The ultrasonic impact guns in Figure 2 can be moved along the rail beam structure of fixed support and the guide rail which fixes ultrasonic impact gun can be moved along the rail beam support. The composite plates can also move around and can be fixed on its four corners which makes ultrasonic impact gun be flexibly changed to ensure that the preload of ultrasonic excitation on the arbitrary point of composite plate. The experimental device uses the machine platform with lots of inverted T-shaped slot, which can be used as a test platform for the base.

The operating frequency of ultrasonic impact gun is 17.5kHz, work amplitude: 24.00μm. Working adjustable amplitude, frequency is not adjustable. The maximum output power of ultrasonic impact gun is 600W. The resolution of FLIR's SC7000 infrared camera used in the experiment is up to 320×256 pixel image, the temperature sensitivity is 0.03 ℃ , temperature spectral wavelength bands are 1.5-5μm and 8-12 μm, sampling frequency is in the range of 5-400kHz.

3. 2. Production of Damaged Composite Plate Specimens

Two damaged composite plate specimens 1# and 2# are produced with 12 layers in the experiment and the thickness of each layer is 0.5mm. The composite plate 1# is manufactured using hand-laying process, and the composite plate 2# is produced using the molding process of winding machine. The local defects are identified by the white box. The composite plate 1 is made by hand lay-up process and the composite plate 2 is produced by wrapped molding process. In the molding process, 6 composite material layers are placed with poly tetrafluoroethylene material on two specific location to simulate the delamination defects.

4. INFRARED THERMOGRAPHY PROCESSING METHOD

4. 1. Defect Detection of Composite Plates

Figure 4 shows plate 1 with two defects under the excitation signal on the point P. The shock preload, the amplitude and frequency of the ultrasonic gun are regulated and ordinary lenses are used to record partial visual field defective area. The loading position of composite plate 1# with delamination defect is shown in Figure 4. The delamination defect location and size of the composite are also given in Figure 4. The inferred thermographies at the time 20s, 30s, 60s and 90s relative to the initial time (0s) are given in Figures 5. The process of grayscale graph is obtained by the subtraction of the thermal images at the initial time from those at a given time, and filtering, wavelet denoising, edge detection, and the corresponding morphological operations. It can be found from Figure 5 that the thermal diffusion around the defective area become more serious. However, the thermal images get more blurred as the heating time become longer. The defects can be detected in the condition that time is not required as long as possible. Other than, there is an optimal viewing time which is about 20s-30s. From the micro level point of view, because of the junction between the defective area and non-defective area, the micro particles and macromolecules around the defective area are rougher and the friction effect is more severe, which resulted in higher temperature distribution at the edge of the defects than that of the other region.

4. 2. Procedure of Infrared Thermal Image Processing Method The extraction of the entire defect image processing includes the following steps:

(1) Generate the subtracted images by the subtraction of the infrared thermal color images at the initial time from those at a certain time. The purpose of image subtraction is to remove the surface impurities of the specimens and noise signal caused by testing environment.

(2) Transform the subtracted images into grayscale images and use gray change to represent temperature change.

(3) Adjust and enhance the contrast of the gray images.

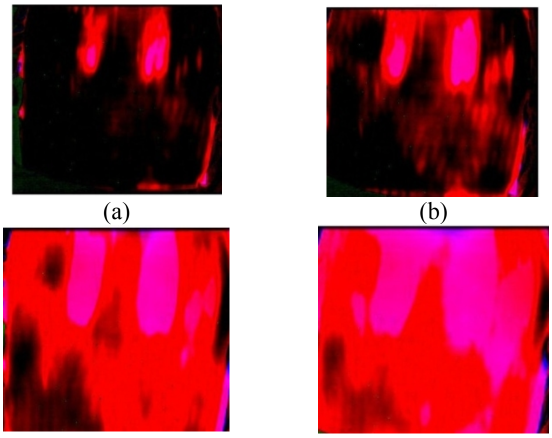
(4) Use wavelet denoising method to remove low gray noise signal.

(5) Extract the defect edge of the images using Canny operator and detect rough outline of the defect image.

(6) Implement morphological image processing, use image expansion, fill the edge gap and smooth the images. The boundary effects of the images can be effectively eliminated by the erosion and dilation operations.

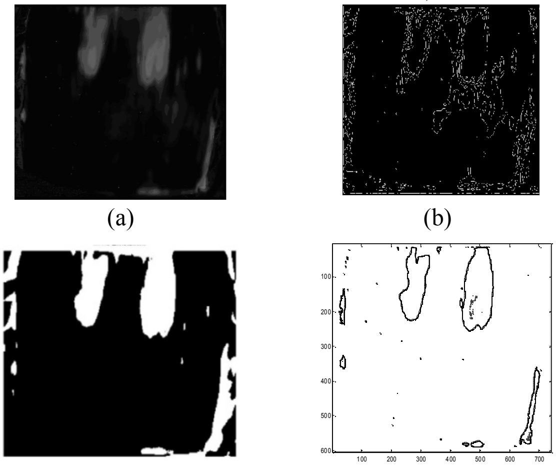
(7) Implement filter operation and binarization processing to the images in the step (6), then extract contour images.

Note that the infrared thermography image processing method is implemented in Matlab program. In the procedure (4), the infrared thermography image is decomposed by the coif3 wavelet at level 2, the horizontal, vertical and diagonal coefficients are obtained by the de-noising function in MATLAB software, named "wthcoef2". The function "Edge" using Canny operator is used to extract the defect edge of the images in the procedure (5). The processed images are shown in Figure. 6. Table 1 illustrates the detection results of two composite defects. The presence of contour image outside the contour image of the defects in the Figure 6(d) is because of much porosity or residual bubbles in the process of coating the resin and einforced fibers of different composite layers. It is illustrated that the detection error of the defect size is more than that of the defect location. This is because of thermal diffusion effect in the junction between the defective area and non-defective area of the composite plate.


(a) (b)

(c) (d)

Figure 5. Relative inferred thermographies at the time (a) 20s (b) 30s (c) 60s (d) 90s



(a) (b)

(c) (d)

Figure 6. Image of precessing results on the time 20s (a) grayscale image;(b) extracted image using Canny operator;(c) binarized image;(d) contour image

TABLE 1. Defect detection results

Case	Defect A			Defect B		
Results	Experiment	Exact (%)	Error (%)	Experiment	Exact	Error (%)
α	106.6	120	11.2	232	230	0.9
β	198.6	205	3.1	206	205	0.5
a	43	40	7.5	49	40	22.5
b	103	80	28.8	102	80	27.5

5. RELATIONSHIP BETWEEN PRELOAD SIZE AND TEMPERATURE CHANGE

Figure 7 shows temperature measuring points P1, P2, P3, P4, P5, P6, P7 on composite plate 2. The frequency of ultrasonic impact gun is set to be 17.5 kHz and the work amplitude is 20.00μm (Case Capture1), 24.00μm (Case Capture2) and 28.00μm (Case Capture3), respectively. Figure 8 shows the temperature differences $[t_{P(i)Capture(2)}-t_{P(i)Capture(1)}]$ (Curve A), $[t_{P(i)Capture(3)}-t_{P(i)Capture(1)}]$ (Curve B) and $[t_{P(i)Capture(3)}-t_{P(i)Capture(2)}]$ (Curve C) (i=1,2, …, 7) between three kinds of work amplitude on the points P1, P2, P4, P5. These points are computed according to the temperature record over a given frames or time, where the red line represents the temperature difference between the Capture2 and Capture1, blue line represents the temperature difference between Capture3 and Capture1, green line represents the temperature difference between Capture3 and Capture2.

It can be seen from temperature difference under different loads in Figure 8 that the temperature difference on the P1, P2 near the defect domain is up to 7 ℃ and 5 ℃ and the temperature difference on the P4, P5 distant from the defect is in the range of 1℃ to 1.5℃. The reason why the preload has little effect on the temperature far from the defect domain is that ultrasonic signal attenuates sharply in the domain far from the defect. The temperature difference on P4, P5 under various preload verifies the feature which the defect regions can be selectively heated by the ultrasounic infrared thermography method. The temperature difference on the P1, P2 near the defect domain increases before the time 90s and changes a little after that time. It means that the heating process on the defect domain is relatively stable irrespective of the amplitude of preload after a certain time 90s (4500 frames). It can be concluded that the ultrasounic infrared thermography is sensitive and accurate to detect composite defects.

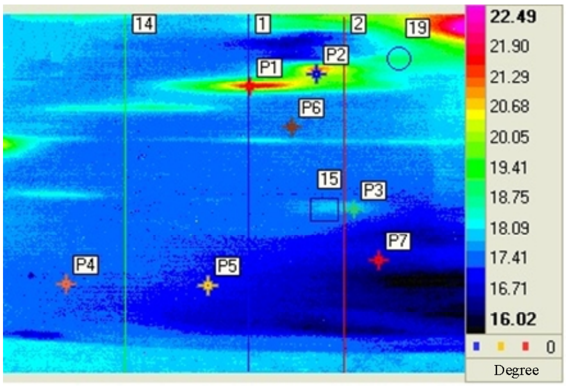
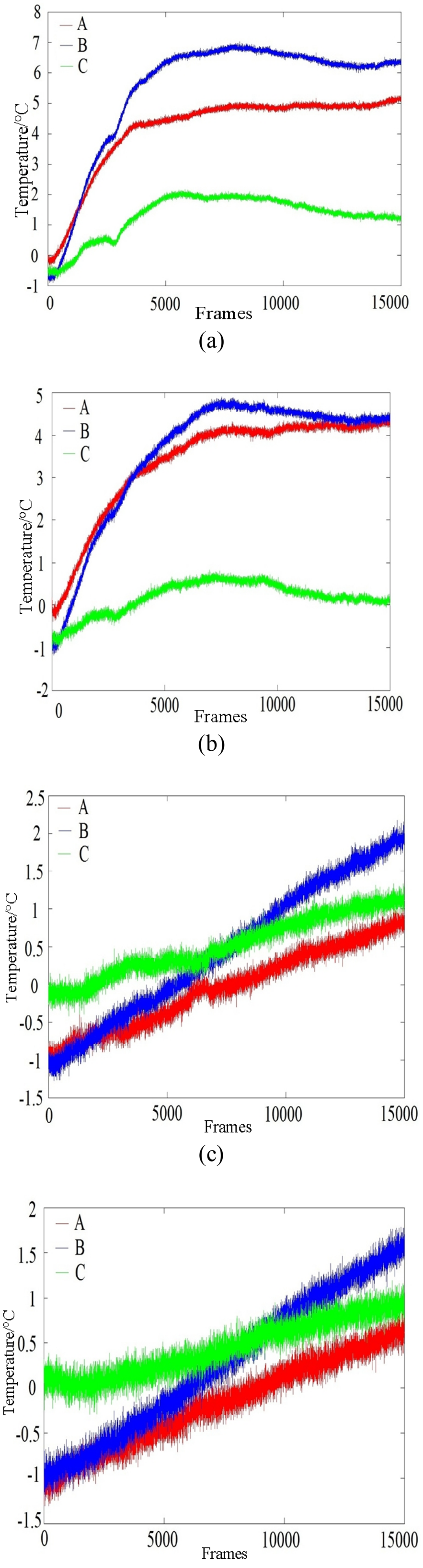


Figure 7. Temperature measuring points P1-P7 of composite plate 2



(a)

(b)

(c)

(d)

Figure 8. Temperature difference on P1, P2, P4, P5 under different preload (a) P1 (b) P2 (c) P4 (d) P5

6. CONCLUDING REMARKS

An ultrasonic infrared imaging method is used to detect delamination damage of the carbon fiber reinforced epoxy composites. An image processing method including edge detection filters, morphological processing methods is presented to accurately detect the location of the composite delaminating damage. According to the experimental results, the image processing methods are combined to extract the location of the delamination defects. The errors of the extracted defect are also given. The temperature distribution analysis of infrared thermography verifies the selective heating feature of the ultrasounic infrared thermography on the defective regions. The relationship between preload size and temperature change is also analyzed. It can be found that the preload has little effect on the temperature far from the defect domain. In conclusion, the ultrasonic infrared thermography is an effective method to detect the composite delamination damage which can be made based on the experiments.

7. ACKNOWLEDGEMENT

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چکیده

یک آزمایش تجربی برای تشخیص آسیب لایه لایه شدن کامپوزیت بر اساس دمانگاری مادون قرمز مافوق صوت طراحی شده است. سیستم دمانگاری مادون قرمز مافوق صوت از سیستم تحریک اولتراسونیک، تصویرساز حرارتی مادون قرمز و سیستم های اکتساب داده ها تشکیل شده است و دو نمونه صفحه کامپوزیت آسیب دیده در آزمایش تولید شده است. روش های پردازش تصویر از جمله آستانه ها، فیلترها، تشخیص لبه و روش پردازش مورفولوژیکی برای تجزیه و تحلیل تصاویر حرارتی مادون قرمز و شناسایی دقیق محل و اندازه آسیب لایه لایه شدن با هم ترکیب می شوند. تغییرات دمای کامپوزیت های معیوب تحت پیش بارگذاری های مختلف تحریک مافوق صوت تحلیل شده است. این آزمایش نشان می دهد که تشخیص اولتراسونیک، اثر انتخاب حرارت در منطقه معیوب از کامپوزیت را دارد. نتایج تجربی نتیجه داد که دمانگاری مادون قرمز اولتراسونیک یک روش کمی موثر برای تشخیص آسیب لایه لایه شدن کامپوزیت است.

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