Infrared Physics & Technology 77 (2016) 296–301

Contents lists available at ScienceDirect

Infrared Physics & Technology

journal homepage: www.elsevier.com/locate/infrared

Regular article

Study on probability of detection for fatigue cracks in sonic infrared imaging

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HIGHLIGHTS

- In our study, a set of C45 ferritic steel plates with artificial fatigue cracks were tested by sonic infrared imaging NDT.
- Experimental results show that the crack heating response increases with the increasing crack length, and the relationship between the logarithmic form of heat response signal and the crack length appears to be linear.
- Based on the above statistic characteristics, the linear regression analysis and the Wald method are adopted to estimate the POD function and its confidence interval.
- The study aims to provide a quantitative evaluation method for detection reliability in sonic infrared imaging.

ARTICLE INFO

Article history:
Received 22 October 2015
Revised 12 June 2016
Accepted 14 June 2016
Available online 18 June 2016

Keywords:
Sonic IR imaging
Crack heating
POD

ABSTRACT

Detection reliability of sonic infrared imaging is one of the increasingly important aspects for out of lab applications. And for the detection reliability evaluation, probability of detection (POD) for different defects under given test conditions has been successfully used as an accepted quantitative measurement. In this study, we test a set of C45 ferritic steel plates with artificial fatigue cracks. Experimental results show that the crack heating response increases with the increasing crack length, and the relationship between the logarithmic form of heat response signal and the crack length appears to be linear. Based on the above statistic characteristics, the linear regression analysis and the Wald method are adopted to estimate the POD function and its confidence interval. The study aims to provide a quantitative evaluation method for detection reliability in sonic infrared imaging.

1. Introduction

Sonic infrared imaging [1], also known as vibrothermography [2] and thermosonics [3], is a multi-wave NDT method [4], which employs high power ultrasonic pulses to excite the test specimen resulting in frictional heating at the defect surface. And the temperature changes at the surface of the test specimen are captured by the thermal infrared imager so as to achieve the defect detection. In order to identify the small cracks, the detection conditions of the sonic IR imaging system need to be optimized to obtain the extreme capacity. However, when the system reaches the optimum state, not all the cracks of the same lengths, even the repeated detection of an identical crack, can be detected. The probabilistic characteristics of this phenomenon can be expressed by the probability of detection (POD), which is used to statistically evaluate the detection reliability in sonic IR imaging [5].

At present, the POD function can be estimated only through reliability experiments on the test specimen with known defect lengths. In 2007, Stephen Holland et al. applied the resonance excitation on the simple beam structure in order to eliminate the influence of other factors. They further built the theoretical model to describe the relationship between the excitation amplitude, cracks lengths and their thermal signals, and presented the method of calculating stress and heat generation [6,7]. In 2011, Ming Li et al. introduced the noise interference model to improve the accuracy of the POD curves, which could be further applied to different detection systems [8]. In 2012, Yuxia Duan et al. studied the reliability of the defect detection in pulsed infrared thermography and compared the capabilities of different image processing methods on the POD [9]. The signal to noise ratio (SNR) of the defective and non-defective areas is employed to calculate the POD in eddy current thermography (ECT) by Ben Weeks et al. And they further

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http://dx.doi.org/10.1016/j.infrared.2016.06.012
1350-4495/

used this method to verify the defect detection ability of ECT for different Metal Materials [10]. In 2015, Junyan Liu et al., by using the laser lock-in thermography to the carbon-fiber-reinforced polymer, utilized the phase difference of the defective and non-defective areas to build a POD model based on the continuous phase response data and the hit/miss data [11]. However, the chaotic acoustic excitation is typically used in sonic IR imaging detection, and it is hard to make test specimen reach the resonance state [12]. So the above methods are hardly to be extended to typical sonic IR imaging.

In the present study, a set of 45 steel plates with artificial fatigue cracks of different lengths have been used to investigate the relationship between the POD and the crack lengths under given test conditions. An attempt is made to find the thermal responses, which are the maximum difference between the defect area and background area, of different crack lengths. Based on the experimental data, the forms of the response and explanatory variables have been determined. Furthermore, the maximum likelihood estimation (MLE) and the Wald method have been employed to estimate the POD model parameters and the confidence interval of the POD curves.

2. Experimental analysis

2.1. Experimental setup

The sonic infrared imaging system typically consists of an ultrasonic excitation system, a thermal infrared imager, a preload unit, and mounting devices, as shown in Fig. 1.

The ultrasonic excitation system includes a Branson DCX-S ultrasonic generator with the 20 kHz working frequency and 1.25 kW maximum power (included, but not shown in Fig. 1) and an ultrasonic gun, which consists of a Branson CJ20 ultrasonic transducer, a booster and a horn.

The FLIR T640 camera is employed to capture thermal images, which has a resolution of 640 × 480 pixels, a maximum frame rate of 30 Hz and a thermal sensitivity of 0.035 °C.

A pressure sensor, fixed between preload unit and ultrasonic gun, monitors the engagement force in real time. A support slipper, which is fixed under the ultrasonic gun, restrains all but the axial direction motion. The engagement force can be adjusted by rotating the thread worm. In order to prevent the vibration energy dissipating from posts, the damping material is placed between the test plate and the post. For the purpose of decreasing the complexity of this study, there is no coupling material placed between horn tip and the test specimen despite it helps eliminate the impact damage between the horn tip and the test specimen. In addition, a piece of double-layer shading cloth is employed to build a darkroom to shield the environmental radiation and air convection.

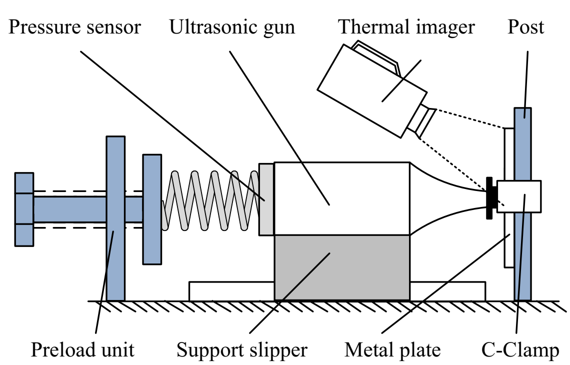

Fig. 1. Schematic diagram of experimental setup. Ultrasonic excitation source is from Branson DCX-S ultrasonic generator, working frequency 20 kHz, maximum power 1.25 kW. Thermal infrared imager is FLIR T640. Infrared camera and ultrasonic gun are arranged on the same side of the specimen.

2.2. Test specimen

The raw artificial fatigue crack specimen is the C45 ferritic steel plate, as shown in Fig. 2 [13], the tensile strength and lower yield strength of which are 620 MPa and 451 MPa, respectively.

The two pin holes on both sides of the raw specimen are used for clamping by the fatigue testing machine. The middle hole is used to make notch so as to generate cracks. And the four holes arranged on both sides of the middle hole are used to install the crack opening displacement gauge. Note that the crack length needs to be controlled elaborately, and the compliance method is introduced to monitor the crack length between 0.4 mm and 9.5 mm.

The wire electrical discharge machining (WEDM) method is used to cut 10 pieces of the raw specimens according to the dot dash line shown in Fig. 2, and each of them yields two pieces of the test specimens. And one of the obtained 20 pieces of the test specimens is shown in Fig. 3. The excitation position is 50 mm off the central point along horizontal direction. Two 50 mm × 20 mm × 2 mm cardboards are used as damping material.

The crack lengths are measured by the optical microscope. And the mean values of the 20 crack lengths are taken as the crack characterization, which are shown in Table 1. After measuring, the surfaces of the test specimens are blackened by the flat lacquer so as to increase the emissivity.

2.3. Data analysis

In sonic IR imaging test, it is usually to consider the temperature difference between the interesting area and background area as the response signal. Suppose "a" and "$\hat{a}$" represent the crack length and the response signal, respectively. The different relationships between "a" and "$\hat{a}$", under given test conditions where the engagement force is 20 kg, the excitation amplitude is 25% and the excitation duration is 1s, are shown in Fig. 4. From these figures, it can be seen that the response signal increases with the crack length, and the "$\ln(\hat{a})$" vs. "a" appear to have the most linear relationship in general as shown in Fig. 4(b).

Further, Fig. 5 shows the fitting model of the linear relationship between "$\ln(\hat{a})$" vs. "a" with different excitation intensity. From the figure, the response signal increases with the increasing excitation intensity, and when the crack length is less than 2 mm, the response signal is submerged in the noise. For fear of causing probability of false alarm (PFA), the decision threshold "$\hat{a}_{dec}$" is set to 0.5 °C, which means only when the response signal "$\hat{a}$" greater than "$\hat{a}_{dec}$", it can be regarded as a crack.

3. Model calculation

The POD(a) function can be obtained from the relationship between "a" and "$\hat{a}$" [12]. Suppose $g_a(\hat{a})$ is the probability density of the "$\hat{a}$" values for fixed crack length "a", then:

$$\mathrm{POD}(a) = \int_{\hat{a}_{dec}}^{\infty} g_a(\hat{a})d\hat{a} \tag{1}$$

Generally, the correlating function of "a" and "$\hat{a}$" defines the mean value of $g_a(\hat{a})$, which is:

$$\hat{a} = \mu(a) + \delta \tag{2}$$

where $\mu(a)$ is the mean value of $g_a(\hat{a})$ and δ is a random error term describing the differences between "$\hat{a}$" and $\mu(a)$.Since $\ln(\hat{a})$ and "a"