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Application of lock-in thermography for the inspection of disbonds in titanium alloy honeycomb sandwich structure

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HIGHLIGHTS

- A 3D finite element model was used to optimize the excitation frequency.
- The phase variation of the surface temperature at different positions was analyzed.
- Two methods were proposed to prefabricate intimate contact disbonds.
- Lock-in thermography is proved effective in inspecting intimate contact disbonds.

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ABSTRACT

This paper investigates the lock-in thermography testing of skin-to-core disbonds in titanium alloy honeycomb structure. A three-dimensional finite element model of titanium alloy honeycomb sandwich structure is built. The phase difference between the disbond defect region and the nondefective region is used to optimize the excitation frequency. The phase variation of the surface temperature because of the discontinuity of the honeycomb structure is analyzed. And the relationship between the phase difference of the defect and the nondefective region and the thickness of the disbond is obtained. Two titanium alloy honeycomb sandwich structure specimens with skin-to-core disbond defects were manufactured. Different from the conventional method of simulating disbond defects, two methods of prefabricating intimate contact disbond are proposed to form real defects. The lock-in thermography experiments are carried out on the specimens. The digital correlation method is used to process the infrared image sequence. The experimental results show that lock-in thermography is effective in inspecting the intimate contact disbond in titanium alloy honeycomb sandwich structure.

1. Introduction

Honeycomb sandwich structures are widely used in the aerospace and aeronautics, which is due to their characteristics of light density, high specific strength and rigidity, good sound and heat insulation capability [1,2]. Honeycomb sandwich structures consist of two thin facing skins separated by a core material. In producing them, different materials are used according to the specific mission requirement. Potential materials for sandwich facings are aluminum alloys, high tensile steels, titanium alloys and composites [1]. While potential materials for core are Nomex, aluminum alloys and titanium alloys [3,4]. Among these materials, titanium alloys have excellent corrosion resistance, good damage tolerant properties, temperature capability up to 600 °C and well-established manufacturing process capability [5], which outperform others. So titanium alloy honeycomb sandwich structures are popular with hypersonic aerocraft [6,7]. As a typical example, titanium alloy honeycomb sandwich structures were used in the wing structure of the High Speed Civil Transport not only for its structural performance, but also because of its low effective thermal conductivity in order to minimize heating of the fuel stored in the wings [8].

Titanium alloy honeycomb sandwich structures are manufactured by means of a brazing method, upon which cannot be relied to produce defect free parts. In addition, new defects may emerge in high-speed flight [9,10]. Among these defects, the skin-to-core disbond defect is the most common one. The disbond defect affects the mechanical properties, thermal properties and the lifespan of these structures. So an effective and timely inspection must be performed both after manufacturing and during service.

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Several kinds of nondestructive testing techniques, including ultrasonic testing, thermography and X-ray computed tomography (CT) [4,11,12], have proven to be useful for the inspection of skin-to-core disbond defects in honeycomb sandwich structures. Among them, ultrasonic testing requires the use of couplant between the test part surface and the probe [11], while CT is time-consuming and needs safety protection, making them not suitable for the in-situ testing [13,14]. On the contrast, thermography is a high-speed, portable, non-contact and large area inspection technique, which fits for the in-situ testing [15,16]. The thermography technique is divided into pulsed thermography and lock-in thermography. Taylor et al. [4] have investigated the pulsed thermography testing of disbonds in titanium honeycomb. In this work, it was found that the practical limitation of pulsed thermography in honeycomb sandwich structures lies in the skin thickness; thicknesses of up to 0.8 mm are predicted to be inspectable.

In thermography testing of honeycomb sandwich structures, the skin-to-core disbond defect is usually identified by the disappearance of the cell wall in the testing result. For most conditions, the skin will bulge at a disbond region. So, an air gap exists between the skin and the core. When a honeycomb sandwich structure is excited by heat, the air gap prevents heat from conducting into the cell wall. As a result, the cell wall will disappear above a disbond region. However, on rare occasions, a mechanical contact between a skin and a core may emerge. Thus, the skin contacts the core closely, between which the air gap is extremely small. This kind of defect is usually called a "kissing" disbond [17] or an intimate contact disbond [18]. The existence of an intimate contact disbond weakens the joint strength of the structure. When an aerocraft flies at high velocity in the aerosphere, the skin above an intimate contact disbond will bulge, and disbond region will be enlarged. By now, the ultrasonic testing was proved an effective way for intimate contact disbond testing [18].

In previous works on thermography testing, foreign material inclusions, such as Teflon, were inserted between the skin and the core to simulate disbonds [19–21]. The foreign object inclusions form an air gap, but they differ from air in thermophysical properties and show different response compared with real disbond. Different from the former, this paper simulates the disbonds by shortening part of the core and by cutting off part of the solder, as a result, intimate contact disbonds are manufactured in the specimen. The outline of the paper is as follows. The paper first introduces the theory and algorithm of lock-in thermography in Section 2. Then the numerical simulation of titanium alloy honeycomb sandwich structures by lock-in thermography is presented in Section 3. Section 4 presents and discusses the experimental results and the processing results by lock-in thermography algorithm. Finally, conclusions are made in Section 5.

2. Theory

2.1. Lock-in thermography (LT)

LT was first introduced by Busse et al. [22] in 1992. In LT, the specimen is subjected to periodic heating using sinusoidally modulated heating source. The surface temperature of the specimen varies with the same frequency as the heating source. The amplitude and phase of the surface temperature signal related to the properties of the specimen. An anomalous region and a sound region have different response signals. Subsurface discontinuities will result in the arising of a phase or amplitude contrast of the surface temperature signal compared with sound region. These discontinuities can be inner structural changes or unexpected defects. The harmonic heating source has the form as Eq. (1).

$$q(t) = q_0[1 - \cos(2\pi f_e t)] \tag{1}$$

where $q(t)$ is the heat flux density, q_0 is the average of the heat flux density, f_e is the excitation frequency or lock-in frequency, and t is the time.

As the heating source consists of a constant heat flux and a harmonic heat flux, the temperature signal $T(z,t)$ consists of a steady state solution and a transient state solution correspondingly. Considering an opaque, homogenous and infinitely large plate with a finite thickness of L, when a steady state is reached in the plate, the temperature distribution obeys Eq. (2) [23].

$$\frac{\partial T(z,t)_S}{\partial t} = \frac{k}{\rho c}\frac{\partial^2 T(z,t)_S}{\partial z^2} \tag{2}$$

where $T(z,t)_S$ is the harmonic temperature distribution in steady state, k is the thermal conductivity, ρ is the density, and c is the specific heat.

The steady state solution of $T(z,t)_S$ has the expression as Eq. (3) [24].

$$T(z,t)_S = A_S \exp\left(-\frac{z}{\mu}\right)\exp\left[i\left(2\pi f_e t - \frac{z}{\mu}\right)\right] \tag{3}$$

where A_S is the amplitude of the harmonic temperature, and $\mu = \sqrt{\frac{k}{\pi f_e \rho c}}$ is the thermal diffusion length.

The temperature distribution in transient state $T(z,t)_T$ follows the differential equation [24]:

$$mc\frac{\partial T(z,t)_T}{\partial t} = P - \frac{T(z,t)_T - T_0}{R_h} \tag{4}$$

where m is the mass of the specimen, P is the power of the heating source, T_0 is the ambient temperature, and R_h is the thermal resistance of specimen material.

The transient solution $T(z,t)_T$ has the expression as Eq. (5).

$$T(z,t)_T = T_0 + \Delta T(1 - e^{-t/\tau}) \tag{5}$$

where $\Delta T = PR_h$, and $\tau = mcR_h$ is called time constant.

So far, the temperature distribution $T(z,t)$ can be obtained by synthesizing Eqs. (3) and (5), as Eq. (6) shows.

$$T(z,t) = T(z,t)_T + T(z,t)_S \tag{6}$$

In actual testing of LT, the surface temperature signals of the specimen consist of white noise, harmonic and DC component [25]. A lot of algorithms are used to extract the harmonic component at selected frequency from them, such as the four-point correlation method, the Fourier transforms method, the digital correlation method, and the time constant method [26]. These algorithms can eliminate the influence of uneven heating on the inspection results and can prompt the characterization of the defects.

2.2. Digital correlation method (DCM)

The DCM extracts the harmonic component, which has the same frequency as the excitation signal, by using the principle of the white noise being uncorrelated to the reference signal. As a result, it can realize the elimination of the white noise and the suppression of DC component. The DCM expression can be obtained by Eq. (7) [24].

$$S = \frac{1}{N}\sum_{n=1}^{N}[F_n(x,y)\cdot c(n)] \tag{7}$$

where S is the output of the DCM, $F_n(x,y)$ are the thermal image sequence, N is the number of samples per lock-in period, and $c(n)$ is the correlation function.