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Original Research Article

Quantitative analysis of voids in multi-layer bonded structures based on transmitted laser ultrasonic waves

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ABSTRACT

A laser ultrasonic method based on transmission has been investigated to characterize voids in the bonded layer and its corresponding quantitative strategy has been proposed to feed back accurate manufacturing information on multi-layer metal bonded structures. Characteristics of laser ultrasonic waves obtained at epicentre in a bonded joint were analyzed and interaction of laser ultrasound with voids in the bonded layer was explained with aids of simulation results and experimental data. The longitudinal wave amplitude gradually increases and then decreases with the increase of distances off epicentre, while the shear wave amplitude shows a monotonic decline with distances off epicentre rising. Moreover, the relative sensitivity has been proposed to quantitatively measure the sizes of voids and its variation is from −2.48 dB to −2.44 dB with defects of 3 mm to 15 mm in diameter. The laser ultrasonic C-scan result based on shear waves with transmission can find the small void with 3 mm size and other natural defects. The proposed quantitative method is effective for measurement of void sizes. As a result, laser ultrasonic C-scans on basis of transmitted shear waves jointed with the proposed quantitative method have great potential for quantitative characterization of voids in bonded structures.

1. Introduction

Multi-layer bonded structures have been applied to modern industries such as aerospace, automobile and civil engineering extensively, due to their excellent mechanical properties. Some adhesively bonded assemblies used as key essential elements are the core and basis of devices and systems, for example a bonded structure that is composed of an AISI 1045 steel plate connected with a lead alloy plate by using an epoxy

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resin adhesive, is served as an important part of a nuclear radiation protection system, so their bonded pair directly affects the quality of products. In the manufacturing process, gross defects such as voids, porosity and disbonds, occur in the bondline on account of the improper adhesive technology, which seriously impact the bonded quality [1]. Disbonds can occur during manufacture due to the presence of a contaminant, such as grease, on adherends, thus they can be eliminated by used of the correct surface treatment prior to bonding [2]. Voids and porosity may be caused by a lack of adhesive or the presence of air bubbles in the adherends [1]. In comparison with voids, the size of porosity is much smaller. As a result, the voids at the adhesive layer can do great damage to the integrity of adhesive interfaces and seriously threaten the bonded strength. Therefore, nondestructive testing (NDT) methods should be used for detecting voids in bonded structures.

Ultrasonic techniques based on transmission, reflection and dispersion of ultrasonic waves have been used for testing discontinuities, and they have been proven to find the voids in the adhesive structures effectively [3]. The traditional ultrasonic methods need the couplant to couple the medium, so they are limited to the complicated structures and special testing environment [4]. The laser ultrasonic technique as a novel testing method using lasers for generation and measurement of ultrasonic waves has great potential for developing noncontact detection of material [5]. Heller et al. demonstrated the effectiveness of combining laser ultrasonic techniques with two-dimensional Fourier transform for characterization of adhesive bond conditions [6]. Cerniglia et al. investigated the noncontact NDT method for detection of disbonds in aluminum bonded samples on basis of a laser for generation of ultrasonic waves and an air-coupled transducer for measurement of ultrasonic signals [7]. They used two configurations to detect disbonded areas: pitch-catch with unidirectional guided wave scan and through-transmission with bidirectional scan [7]. These results show the potential of laser ultrasonic techniques for characterization of voids in multi-layer bonded assemblies. However, the quantitative evaluation of voids in the bondline based on laser ultrasonics needs further development.

In this paper, characteristics of laser ultrasonic wave at epicentre in a steel-lead bonded structure have been investigated, and then interaction of laser ultrasonic wave modes with voids in the bonded joint has been revealed to obtain reasonable detection parameters. Moreover, detection of voids in multi-layer bonded samples with simulated void areas has been performed using a noncontact laser ultrasonic system with through-transmission configuration to verify effectiveness of the proposed quantitative method for evaluating the void sizes.

2. Fundamental theory

2.1. Laser-generated ultrasonic waves

A pulsed laser irradiates on material and its optical energy is lower than the ablation threshold value of material, thus the material surface absorbs the energy to produce thermal expansions and thermal stresses, and then the material surface occur vibrational displacements namely ultrasonic waves. Consequently, the process of laser generated ultrasonic waves can be described by the thermal conduction equation and the thermoelastic displacement equation [5]:

$$\rho C \frac{\partial T}{\partial t} = k \nabla^2 T, \tag{1}$$

$$(\lambda + \mu)\nabla(\nabla \bullet \mathbf{u}_1) - \mu \nabla \times \nabla \times \mathbf{u}_1 - \rho \frac{\partial^2 \mathbf{u}_1}{\partial t^2} = \alpha(3\lambda + 2\mu)\nabla T, \tag{2}$$

where T is the temperature rise in material, k is the thermal conductivity, ρ is the material density, C is the constant volume specific heat, α is the linear thermal expansion coefficient, λ and μ are the Lamé constants, and $\mathbf{u}_1$ is the displacement vector.

The absorption coefficient β for metals are typically large, so at least 63% of light is absorbed within small depth of $1/\beta$ from the surface, so the laser beam striking an opaque surface can be modeled by surface source of heat. Thus, optical penetration depth is neglected and the incident laser pulse can be represented by a heat flux. Therefore, in two-dimensional cylindrical coordinates (r, z), the boundary condition of the temperature equation at the irradiated region $z = 0$ is

$$-k \frac{\partial T(r,z,t)}{\partial z}\bigg|_{z=0} = Q(1-R) f(r) g(t) \tag{3}$$

where Q is the power density of incident laser pulse and R is the reflectivity of the steel plate surface. $f(r)$ and $g(t)$ are the spatial and temporal distributions of laser pulse, respectively. The two functions can be written as:

$$f(r) = \exp\left(-\frac{r^2}{r_0^2}\right), \tag{4}$$

$$g(t) = \frac{t}{\tau}\exp\left(-\frac{t}{\tau}\right), \tag{5}$$

where r_0 is the laser spot radius, and τ is the laser pulse rise time. There is also an initial condition, which is expressed as:

$$T(r,z,t)|_{t=0} = 300\,\mathrm{K}, \quad \dot{T}(r,z,t)\Big|_{t=0} = 0,$$

2.2. Numerical model

The physical equations of laser-induced ultrasound present the characteristics of time-varying, high non-linearity and strong couples, so analytic methods are difficult for solving these equations with complex structures. The finite element method (FEM) is very suitable for dealing with the coupled thermal-solid equation because it is competent to obtain complete numerical solutions [8]. Calculation of the thermoelastic coupled equation using the FEM can be stable with given parameters [9].