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Characteristics of laser ultrasound interaction with multi-layered dissimilar metals adhesive interface by numerical simulation

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ABSTRACT

The characteristics of laser-generated ultrasonic wave interaction with multi-layered dissimilar metals adhesive interface are investigated by finite element method (FEM). The physical model of laser-generated ultrasonic wave in the multi-layered dissimilar metals adhesive structure is built. The surface temperature evolution with different laser power densities is analyzed to obtain the parameters of pulsed laser with thermoelastic regime. The differences of laser ultrasonic waves with different center frequencies measured at the center of laser irradiation would verify the interfacial features of adhesive structures. The optimum frequency range and probe point would be beneficial for the detection of the small void defect. The numerical results indicate that the different frequency range and probe points would evidently influence the identification and quantitative characterization of the small void defect. The research findings would lay a foundation for testing interfacial integrity.

1. Introduction

Multi-layered adhesive structures have been widely applied to many important industries, especially in weapons and aerospace, because of their features of light weight, excellent performance and low-cost manufacture. Therefore, the integrity and reliability of the bonds in multi-layered structures are extremely important to the quality of products [1–3]. However, related to improper selection of adhesives, pretreatment of adhesive parts and adhesive technology, typical defects, affecting the strength of adhesion, are local debondings, poor adhesives and voids in the bonded structures [3]. Void defects originate from the remnants of air layers resulting in inferior mechanical properties in the adhesive interface. They are known as the most challenging problem for inspection of adhesive structures. This opens the way to novel nondestructive testing (NDT) methods which have the potential to detect particular the adhesive interface discontinuities. Recently, the quality of multi-layered adhesive structures has been inspected by acoustic method [4–6]. The traditional acoustic methods are very sensitive to the void defect, but need to contact with workpieces using couplant. Thus, these methods are not suitable for on-line monitoring of adhesive structures. As a consequence, it is important for characterization of adhesive quality using non-contact inspection method.

Laser ultrasonic technique (LUT) based on lasers for the generation and detection of ultrasonic waves, possessing the characters of non-contact, wide-band, and the advantages of high scanning speed in complex structural components inspection and in-situ testing, has demonstrated its great potential for NDT of adhesive structures [7–9]. The former research mainly concentrated in using laser-generated guided waves to monitor the quality of adhesive structures [10–12]. The study about inspection of void defect in adhesive interface using laser-generated bulk waves is very few, especially using pulse echo method of laser ultrasound for inspection. Therefore, it is significant for understanding the characters of the laser ultrasonic reflected longitudinal wave interaction with adhesive interface. The finite element method (FEM) is versatile in dealing with laser-generated ultrasonic waves due to its flexibility in modeling complicated geometries and its capability in obtaining full field numerical solutions. Many researchers utilized FEM to analyze the laser-generated ultrasound in different occasions [13–16]. Therefore, this paper mainly investigates the interaction of laser induced ultrasonic waves with the interface of three-layered adhesive structures of steel-epoxy-lead by FEM.

2. Theory model and numerical method

2.1. Thermoelastic theory

Fig. 1 schematically shows the geometry of laser irradiation on the top surface of the multi-layered dissimilar metals adhesive

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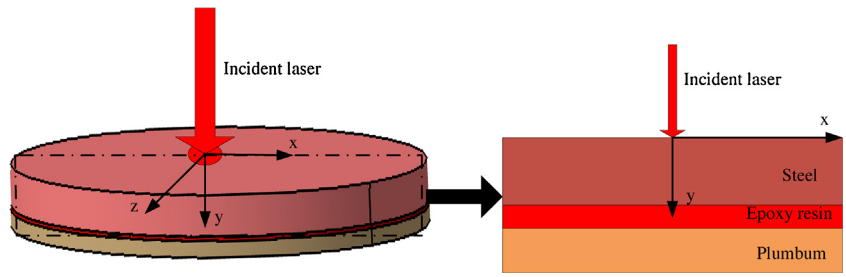

Fig. 1. Schematic diagram of laser irradiation on the multi-layered dissimilar metals adhesive structure.

structure. The three-dimensional model can be simplified as two-dimensional model due to the symmetry of geometrical model and loading condition.

The material's surface irradiated by a laser pulse absorbs parts of laser energy which results in rapid temperature rising, and then the temperature spreads from the center of light source to other regions based on thermal conduction. When ignoring the influence of convection and radiation, the two-dimensional thermal-conduction equation of isotropic materials can be described as:

$$\rho C_v \frac{\partial T(x,y,t)}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial T(x,y,t)}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T(x,y,t)}{\partial y}\right) \quad (1)$$

where $T(x,y,t)$ represents the temperature distribution in material at time t, and ρ, C_v and k are the density, thermal capacity and thermal conduction coefficient, respectively.

Considering the skin effect of metallic materials, the entire laser beam is assumed to be absorbed on the surface. Thus, optical penetration depth is neglected and the incident laser pulse can be represented by a heat flux. Therefore, the boundary condition of the irradiated region is

$$-k\frac{\partial T(x,y,t)}{\partial z}|_{z=0} = I_0(1-R)f(x)g(t) \quad (2)$$

where I_0 is the power density of incident laser pulse and R is the reflection ration of steel plate surface. $f(x)$ and $g(t)$ are the spatial and temporal distributions of laser pulse, respectively. The two functions can be written as:

$$f(x) = \exp\left(-\frac{x^2}{r^2}\right) \quad (3)$$

$$g(t) = \frac{t}{\tau}\exp\left(-\frac{t}{\tau}\right) \quad (4)$$

where r denotes the radius of the point-source laser pulse, andτ is the rise time. There is also an initial condition, which is expressed as:

$$T(x,y,t)|_{t=0} = 300\,\text{K}, \quad \dot{T}(x,y,t)|_{t=0} = 0 \quad (5)$$

When the power density of incident laser lowers the thermal ablation threshold of material, the phase transition of materials surface would not occur and a transient displacement field is generated due to thermoelastic expansion. The displacement field satisfies Navier-Stokes equation, namely

$$(\lambda+2\mu)\nabla(\nabla\mathbf{U}) - \mu\nabla\times\nabla\times\mathbf{U} - (3\lambda+2\mu)\alpha\nabla T(x,y,t) = \rho\frac{\partial^2\mathbf{U}}{\partial t^2} \quad (6)$$

where $\mathbf{U} = \mathbf{U}(x,y,t)$ denotes ultrasonic displacement field, λ and μ are the Lamé constants and α is the thermal expansion coefficient of the steel plate. The boundary conditions at irradiated region $z = 0$ is

$$\mathbf{n}[\sigma - (3\lambda+2\mu)\alpha\Delta T(x,y,t)\mathbf{I}] = 0 \quad (7)$$

where $\mathbf{n}$ is the unit vector normal to the material surface, $\mathbf{I}$ the unit tensor and $\boldsymbol{\sigma}$ the stress tensor. There is also an initial condition, which is expressed as

$$\mathbf{U}(x,y,t)|_{t=0} = \dot{\mathbf{U}}(x,y,t)|_{t=0} = 0 \quad (8)$$

2.2. Finite element method

The classical thermal condition equation for elements with heat capacity matrix $[C]$, conductivity matrix $[K]$, heat flux vector $\{p_1\}$, and heat source vector $\{p_2\}$ can be expressed as

$$[K]\{T\} + [C]\{\dot{T}\} = \{p_1\} + \{p_2\} \quad (9)$$

where $\{T\}$ is the temperature vector, and $\{\dot{T}\}$ is the temperature rise rate vector. Regarding ultrasonic waves generated by thermoelastic regime propagating in the elastic mediums, ignoring damping, the governing finite element equation is

$$[M]\{\ddot{\mathbf{U}}\} + [K]\{\mathbf{U}\} = \{\mathbf{F}_{\text{ext}}\} \quad (10)$$

where $[M]$ is the mass matrix, $[K]$ is the stiffness matrix, $\{\mathbf{U}\}$ is displacement vector, $\{\ddot{\mathbf{U}}\}$ is the acceleration vector and $\{\mathbf{F}_{\text{ext}}\}$ is the external force vector. Loading force vector based on thermal effect can be described as $\int_V [B]^T[D]\{\varepsilon_0\}\,dV$ in all elements of the finite element model, $[B]^T$ is the transpose of derivative of the shape functions and $[D]$ is the material matrix. Eq. (9) is solved using the central difference method. The procedure for the solution of Eq. (9) is the generalized trapezoidal rule, namely

$$\{T_{n+1}\} = \{T_n\} + (1-\theta)\Delta t\{\dot{T}_n\} + \theta\Delta t\{\dot{T}_{n+1}\} \quad (11)$$

where θ is a transient integration parameter, $\Delta t = t_{n+1} - t_n$ is the time step, $\{T_n\}$ is the nodal temperature value at time t_n and $\{\dot{T}_n\}$ is the time rate of the nodal temperature value at time t_n. Substituting $\{\dot{T}_{n+1}\}$ from Eq. (11) into Eq. (9) yields

$$\left(\frac{1}{\theta\Delta t}[C] + [K]\right)\{T_{n+1}\} = \{p_1\} + \{p_2\} + [C]\left(\frac{1}{\theta\Delta t}\{T_n\} + \frac{1-\theta}{\theta}\{\dot{T}_n\}\right) \quad (12)$$

By choosing $\theta = 1/2$ the scheme becomes unconditionally stable.

For the implementation of Eq. (10) an implicit time integration scheme based on Newmark's algorithm has been selected. Therefore, Eq. (10) is converted into

$$\left([K] + \frac{1}{\alpha\Delta t^2}[M]\right)\{U_t\} = \{F_{\text{ext}}\} + [M]\left[\frac{1}{\alpha\Delta t^2}\{U_{t-\Delta t}\} + \frac{1}{\alpha\Delta t}\{\dot{U}_{t-\Delta t}\} + \left(\frac{1}{2\alpha} - 1\right)\{\ddot{U}_{t-\Delta t}\}\right] \quad (13)$$