Non-contact Detection of Delamination in Cu/Al Laminated Plate with Laser Ultrasonic

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Abstract. In this paper, a non-contact non-destructive inspection method based on laser ultrasonic was proposed for the detection of interface delamination in Cu/Al laminated plates. The finite element model of laser ultrasonic Cu/Al laminated plates were built to analyze the propagation of laser ultrasound in Cu/Al laminated plates and the effects of interface delamination defects on the ultrasonic field distribution. The simulation results were verified by the laser ultrasonic detection system. The C-scan detection results realizes the visual detection of delamination defects, and provides precise information about the composite quality of the Cu/Al laminated plates. Experimental results show that laser ultrasonic technology has great potential for online non-contact detection of Cu/Al laminated plates.

1. Introduction

Cu/Al laminated plates not only have the properties of low density, easy processing and corrosion resistance of aluminum, but also have the properties of high electrical conductivity and high thermal conductivity of copper, which have been applied to modern industries such as heat dissipation, power and electricity, communication shielding extensively[1-4]. Cu/Al laminated plates have very important economic benefits, which not only reduces the quality of the products, but also greatly saves copper resources and alleviates the current situation of copper resource shortages[1,5]. In the manufacturing process, serious defects such as slags, voids and delamination, occur at the interface of Cu/Al laminates on account of the improper production process, which seriously impacts the compound quality. In addition, some factors in the process of use, such as static load, dynamic load, mechanical damage, fatigue and creep, will also cause the emergence of interface separation in the laminated plates, resulting in the deterioration of material properties and endangering the safety and reliability of major equipment[6]. Therefore, effective non-destructive testing methods must be used for detecting interface delamination defects in laminated plates.

Ultrasonic method, eddy current method and infrared thermography are the common methods to detect the interface separation defects of laminated plates [7-8]. In these non-destructive detection techniques, the ultrasonic methods are widely used for evaluation of metal laminated plates. However, the traditional ultrasonic methods are difficult to evaluate the composite quality of thinner laminates due to the limitation of the blind zone of ultrasonic testing. As a novel testing method, laser ultrasonic technique has great potential for developing non-contact detection and quantitative evaluation for the
delamination defects of metal laminated plates. Recently, researchers have done a lot of theoretical
and experimental investigation on the application of laser ultrasonic techniques to detect defects in
Multilayer structural material. Watanabe et al. monitored the interface separation of the surface coating by using laser ultrasonic technique, and visualized the delamination area by C-scan imaging
[9]. The laser-ultrasonic was applied to a thin carbon fiber reinforced polymer test sample, where two
different depth delamination have been created, and the delamination were detected by B-scan and C-
scan[10]. Zhang et al. detected the disbands in steel-lead bonded structure based on laser ultrasonic
with transmission mode and pulse-echo mode, and proposed quantitative methods to evaluate the
disbands sizes[11-12].

However, there are few studies on the testing of laminated plates with laser ultrasound. In this
paper, the characteristics of delamination defects in laminated plates had been investigated. The finite
element model of laser ultrasonic was built to analyze the propagation of laser ultrasound in Cu/Al
laminated plates and the effects of interface delamination defects on the ultrasonic field distribution.
Finally, C-scans were performed to visualize the interface delamination.

2. Theoretical model

2.1. Generation of laser ultrasonic

When the pulse laser is induced on the laminated plates, part of the laser energy is absorbed into the
thin surface of the laminated plates, and the temperature of the irradiated area increases, resulting in a
large temperature gradient field, which causes thermal expansion and generates ultrasonic waves.
The physical process of the thermoelastic mechanism can be explained by the classical thermoelastic
coupling theory. The thermoelastic coupling equations for isotropic materials is:

\[
[K][T] + [C][\dot{T}] = \{R_q\} + \{R_0\} \tag{1}
\]

\[
[M][\dot{U}] + [K][U] = \{R_{ext}\} \tag{2}
\]

where \([K]\) represents the conductivity matrix, \(\{T\}\) is the temperature vector, \(\{\dot{T}\}\) is the temperature change rate vector, \(\{R_q\}\) is the heat flux vector, \(\{R_0\}\) is the heat source vector, \([C]\) is the heat capacity matrix, \([M]\) is the mass matrix, \(\{R_{ext}\}\) is the external force vector, \(\{U\}\) is the displacement vector, \(\{\dot{U}\}\) is the acceleration vector[7].

In the finite element calculation process, considering the numerical solution precision and
calculation time, the time step and element size must be selected for the appropriate values, the
selection basis of the time step and element size are as follows[7]:

\[
\Delta t \leq \frac{1}{180 f_{\text{max}}} \tag{3}
\]

\[
L_e \leq \frac{\lambda_{\text{min}}}{20} \tag{4}
\]

where \(\Delta t\) is the time step, \(f_{\text{max}}\) is the maximum center frequency of laser ultrasound, \(L_e\) is the element
size, \(\lambda_{\text{min}}\) is the shortest wavelength of laser ultrasound.

2.2. Finite element model

As shown in Figure 1, to reduce the calculation load and shorten the simulation time, the 2D
axisymmetric models have been built to simulate the Cu/Al laminated plate with various delamination
defects. The dimensions of the Cu layer and the Al 1050 layer were 20mm×0.5mm and
20mm×2.5mm. Some elements on the aluminum side of the interface are removed to simulate the
interface delamination defects. The physical parameters of Al 1050 and Cu used in the finite element
model are listed in Table 1. In the numerical simulation, the spot diameter of the pulsed laser is 1mm,
the duration of the pulsed laser is 8ns, and the power density of the pulsed laser is 5MW/cm². The grid size of the laser irradiation region is 5μm, and the maximum grid size of other regions is 25μm with the gradual grid division technology. To ensure the accuracy of numerical simulation, the integration time step is 0.5ns. The simulation time was 10μs. The coupled thermo-mechanical analysis module of the ABAQUS software was used for simulation.

![Laser ultrasonic in Cu/Al laminated plate: (a) a good model, and (b) a model with delamination.](image)

**Figure 1.** Laser ultrasonic in Cu/Al laminated plate: (a) a good model, and (b) a model with delamination.

|                  | Cu       | Al 1050  |
|------------------|----------|----------|
| Thermal conductivity (W m⁻¹ K⁻¹) | 386.4    | 209      |
| Density (g cm⁻³)  | 8.96     | 2.71     |
| Poisson's ratio   | 0.326    | 0.33     |
| Thermal expansion coefficient (10⁻⁶K⁻¹) | 17.2     | 23.6     |
| Elastic Young's modulus (GPa)       | 119      | 68       |
| Specific heat (J kg⁻¹ K⁻¹)          | 394      | 880      |

**Table 1.** The material parameters of Cu/Al laminated plate used in numerical calculation.

2.3. **Simulation results and discussion**
Figure 2 shows the distribution of the wave field of laser ultrasonic in a good model and the one with the delamination size of 2mm at 1μs. By comparing Figure 2(a) and (b), the interface delamination defects have a great influence on the distribution of wave field of laser ultrasonic, the displacement in the area with delamination is much higher than that in a good model, because the energy is reflected from the interface delamination. Figure 3 shows the out-of-plane displacement waveforms of the nodes located at 1mm from the laser source in a good area and the areas with delamination, with the delamination width of 2, 4, 6, 8 and 10 mm, respectively. The out-of-plane displacement amplitude gradually increases with increase of delamination sizes, and they can be used to characterize delamination defects.
3. Experimental analysis

3.1. Laminated plate sample

The Cu/Al laminated plate sample was manufactured by rolling cladding method, as shown in Figure 4. The dimensions of the Cu layer and the Al 1050 layer were 80mm×40mm×0.5mm and 80mm×40mm×2.5mm. The artificial T slots were finished by high-speed wire electrical discharge machining with the width of 0.2 mm and delamination width of 2, 4, 6, 8 and 10 mm, respectively.

3.2. Experimental setup

The laser ultrasonic experimental setup is shown in Figure 5. The Q switch Nd:YAG pulse laser produced by Quantel is focused onto the Cu/Al laminated plate to excite the ultrasonic. The wavelength of the pulsed laser is 1064nm, the duration of the pulsed laser is 8ns, the maximum repetition frequency is 20Hz, and the energy range of a single pulse laser is 0mJ-50mJ. The two-wave mixing laser interferometer manufactured by Intelligent Optical Systems Inc is used to detect ultrasonic signals. The wavelength of detection laser is 1550nm, the range of laser power is 0W-2W, and the spectrum range of interferometer is 50kHz-125MHz. The program controls the precise two-dimensional displacement platform to drive the sample to move and complete the C-scan detection and imaging.
3.3. Experimental results

The ultrasonic wave in the Cu/Al laminated plate is generated exploiting a pulsed laser ($\lambda=532$nm, energy=10mJ, pulse duration=8ns, spot size=1mm). The detection laser power is 0.2W and the spot diameter is about 200μm. The laser ultrasonic signals were collected at a distance of 1mm from the irradiation point of the excitation laser. As shown in Figure 6, the amplitudes of laser ultrasonic...
signals in the areas with delamination are much higher than that in the areas with no delamination, which is consistent with the trend of numerical simulation results shown in Figure 3. The C-scan imaging result obtained from the 2D scan over the delamination defects is shown in Figure 7. Figure 8 shows the amplitude curve at y=8mm in the C-scan result. The delamination areas are easily distinguished from the normal areas, the detection results of the width and position of delamination defects are consistent with the simulated delamination defects in the sample as shown in Figure 4.

4. Conclusion
The out-of-plane displacement amplitude can effectively characterize delamination defects. The experimental results verify the correctness of the simulation results. The C-scan results of the delamination defects are consistent with the simulated delamination defects in the Cu/Al laminated plate sample. The laser ultrasonic technology can realize long-distance non-contact non-destructive detection of interface delamination defects in laminated plates, it has great potential for online non-contact inspection of Cu/Al laminated plates.

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