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Non-contact characterization of debonding in lead-alloy steel bonding structure with laser ultrasound

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ABSTRACT

This paper presents the non-contact characterization of debonding defects in lead-alloy steel bonding structure with ultrasonic waves generated and detected by lasers. Using the 3D finite element (FE) method, the thermoelastic excitation and propagation of ultrasonic waves are simulated. The effect of debonding defects on wave field distribution are clarified. Combining experiment method, the feature signal for characterizing the debonding defects are extracted, the appropriate wave frequency and probe position are obtained. The characterization of debonding defects in different sizes are analyzed, and the laser ultrasonic C-scan imaging of the specimen with simulated debonding defects is realized. The results prove that the noncontact characterization of debonding defects in lead-alloy steel bonding structure can be realized with laser ultrasound, and the circular debonding defects greater than 4 mm in diameter are characterized through C-scan method.

1. Introduction

In the nuclear industry, the lead-alloy steel bonding structures are used widely due to their superior performance such as anti-radiation, high specific strength, and fatigue resistance [1]. This kind of structure exposes to the intense radiation and high temperature environment in long term, and the interface adhesive quality is one of the key factors affecting the structure performance [1–3]. Fig. 1 shows a 3D geometric model of the lead-alloy steel bonding structure. This kind of structure consists of three layers, including the lead-alloy layer, epoxy resin layer and the steel layer. The lead-alloy and steel layer are bonded together by the epoxy resin layer, thus the bonding interfaces with different status are formed. The bonding status mainly include good bonding, weak bonding, and debonding. The debonding is the most serious defect that will decrease the performance of the structure. As there exist debonding defects, the mechanical strength and fatigue performance of the bonding structures decrease significantly, and then jeopardize the performance of the nuclear equipment or facility. Therefore, the debonding defects must be detected in time and characterized precisely using the effective testing methods. It is vital to guarantee the performance of the lead-alloy steel bonding structures [1,4–6].

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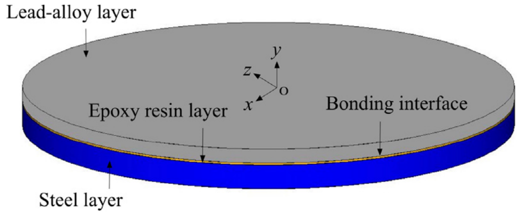

Fig. 1. Schematic of the lead-alloy steel bonding specimen with simulate debonding defects.

The primary methods used for the testing of debonding defects include ultrasound, X-ray, laser speckle, infrared thermography and so on. In these approaches, the ultrasonic testing method is widely used for the accurate detection of structure debonding. But the special working environment of the lead-alloy steel bonding structure limits the application of conventional ultrasonic methods which are full-contact or need coupling agent. Besides, the geometrical shapes of the actual lead-alloy steel bonding structures are very complex, the transmitting and receiving probe should be placed on the same side of the bonding structure. Thus, the precise, non-contact and shape adaptable ultrasonic testing method for this kind of bonding structure is urgently needed. Different from traditional ultrasonic methods, the laser ultrasound approach uses lasers to excite and receive wave signals. It has the characters of non-contact, high resolution and high sensitivity, and it is capable of testing the structures with complex shapes in remote control mode as the probes are arranged on the same side.

Some studies have been conducted on the testing of various defects using laser ultrasound. The wave signals generated by a pulse laser in a composite laminate are measured experimentally, and the modes of the waves are analyzed [7]. The effects of the pulse duration and optical penetration on the excitation of laser ultrasound and the relative wave features are analyzed [8]. A hybrid ultrasonic testing system combines laser exciting and air-coupled receiving is constructed, and the effectiveness of the system for the testing of surface defects in composite laminates is verified [9]. Through the laser-based point-by-point scanning, the characterization of simulated defects in a composite structure is realized based on adjacent wave subtraction and anomalous wave imaging [10]. The internal defects located at different depth in a composite laminate are characterized by B-scan and C-scan imaging with laser ultrasound [11]. Through spectroscopy measurement, the effects of the internal defects on the attenuation of laser ultrasound in composite laminates are analyzed quantitatively. The high precision testing of delamination near the edge of the hole in a composite laminate is realized by ultrasonic C-scan based on single side laser excitation and reception [12]. A laser-based scattering wave field imaging method is proposed in [13], and the internal delamination in a composite structure is visualized [14]. To promote the application of laser ultrasound approach in aeronautic industry, an industrial testing system based on multi-joint robot and scanning laser device is developed, and the C-scan imaging of large size composite structures with laser ultrasound is realized [15]. In the current study, the testing of lead-alloy steel bonding structure with laser ultrasound is not well-studied yet. The characterization of debonding defects in lead-alloy steel bonding structure demands detailed study. On the subject of detail, the effect of debonding on wave field distribution, the reflection characteristics of the interfaces at different bonding status, the appropriate frequency and probe position for the characterization of debonding in different dimension, all these problems should be resolved.

To solve the above problems, this paper studies the characterization of debonding defect in lead-alloy steel bonding structure with laser ultrasound. The thermoelastic generation and propagation of ultrasonic waves are simulated. The reflection of the waves from different bonding interfaces and the variation induced by debonding are shown. The spectral characteristics of the original laser generated wave signals are analyzed. The feature signal characterizing the debonding defect is extracted, and the appropriate frequency and probe position are obtained. The characterization of debonding defects in different sizes are analyzed, and the C-scan imaging of a specimen with debonding defects is realized using laser ultrasound. The outline of this paper is as follows. The theoretical model and calculation method are described in Section 2. The sample and experiment setup are presented in Section 3. Results and discussion and conclusions are elucidated in Sections 4 and 5, respectively.

2. Theoretical model

2.1. Finite element method

As a pulse laser is focused on the surface of the structure and the laser power density is lower than the ablation threshold of the material, portions of the pulse energy are absorbed and a temperature gradient field is formed [16–18]. Then thermal expansion occurs and functions as the source of elastic waves. This process is the thermoelastic excitation of laser ultrasound. Using the thermoelastic theory and the 3D finite element (FE) method, the excitation and propagation of laser ultrasound in lead-alloy steel bonding structure can be simulated, and the governing FE equations can be expressed as:

$$[K]\left\{T\right\}+[C]\left\{\dot{T}\right\}=\left\{R_q\right\}+\left\{R_Q\right\} \tag{1}$$

$$[M]\left\{\ddot{U}\right\}+[K]\left\{U\right\}=\left\{R_{ext}\right\} \tag{2}$$