Quality evaluation of laser welds based on air-coupled ultrasound

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Abstract With the wide application of laser welding technology in automobiles and rail transportation, the non-destructive testing technology for laser welding seams is also getting better. Aiming at the laser welding seam of two-layer metal sheet below 3 mm, the possibility of laser welding seam detection by air-coupling ultrasonic detection technology is discussed. By numerical analysis and experimental analysis, Lamb wave is excited on aluminum plate in air. Through the propagation simulation of Lamb wave in laser weld specimen, the influence of laser weld width and weld quality on reflectivity and transmittance is analyzed. The propagation law of Lamb wave in laser weld specimen is clarified. The results show that the quality of laser weld can be evaluated by the mode of Lamb wave A0.

Key words air-coupling, Lamb wave, sheet, laser welding

0 Introduction

In recent years, with the rapid development of automobile and rail transit vehicle manufacturing industry, in order to meet the requirements of automation and high-speed production, laser welding technology is widely used in vehicle structure, but the focus spot of laser welding is small, easy to produce large processing error[1−7]. Therefore, it is very important to evaluate the weld quality effectively. The common testing methods include radiographic testing, electromagnetic testing, ultrasonic testing and so on. Among them, ultrasonic has little impact on human body, and can be used to test the interior of workpiece, so it is widely used[8]. However, the conventional contact ultrasonic testing method requires that the inspected surface should be smooth and clean, and coupling agent should be used, so the test results are easily affected by the surface state and coupling degree of the workpiece[9], these factors are not suitable for in-service detection. The water immersion ultrasonic testing method needs to immerse the whole or part of the test piece into the water during the testing process, so that the ultrasonic sensor and the workpiece are filled with water medium, so it is only suitable for part of the production line testing. The air-coupling ultrasonic testing method has the characteristics of non-contact, non-destructive, non immersion, safe and harmless, which can make up for the shortcomings of the above methods.

At present, air coupled ultrasonic testing has been used in surface crack, concrete, lithium battery and so on[10−14], however, there is no relevant research on laser weld detection, so the air coupled Lamb wave laser weld detection technology is proposed. Firstly, the excitation mode of

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Lamb wave is studied theoretically. Then, the optimal excitation mode is selected to test the welding lap joint by simulation and test analysis, the application of air coupling ultrasonic testing method in the quality control of laser welding thin plate is discussed. The results show that this method has great application value in the evaluation and control of laser welding quality.

1 Characteristics of air coupled Lamb wave detection

Lamb wave is a kind of guided wave propagating in the plate. It is a special form of stress wave formed by the reflection, interference and scattering of P-wave and S-wave through the upper and lower surfaces of the plate. When Lamb wave propagates in the plate, because of the influence of the thickness of the plate and the frequency of the wave, it has the characteristics of dispersion[15, 21]. Fig. 1 is 2 mm thick aluminum plate dispersion curve calculated by dispersion curve calculation software, Lamb wave can be divided into symmetrical (S) and asymmetric (A), and its modes will be more and more with the increase of frequency. However, the dispersion and multimode characteristics of Lamb wave make the identification and extraction of defect signals very complex in the process of ultrasonic Lamb wave detection. Therefore, it is particularly important to study the dispersion and multimode characteristics of Lamb wave to select the appropriate Lamb wave mode[16–19].

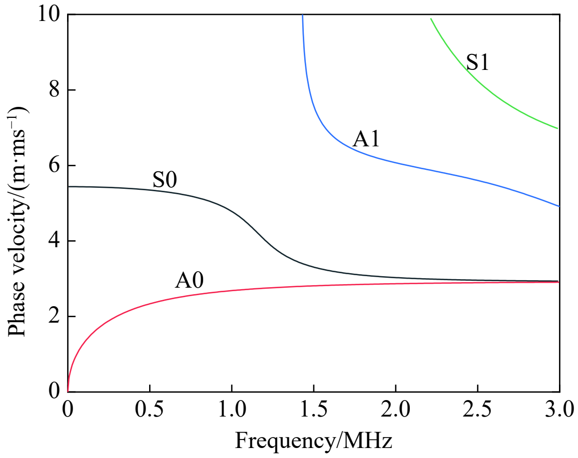

Fig. 1 Dispersion curves

Before discussing the application of the air-coupled ultrasonic method to evaluate the laser welding seam of the thin plate, we study this possibility through the Lamb wave characteristics and the energy transmission of the oblique incident thin plate (Fig. 2). Such as air, enters the thin plate with a frequency f harmonic from a certain angle, and the energy transmittance at this time is derived from the following:

$$T = \frac{4N^2}{(M^2 - N^2 + 1)^2 + 4N^2} \tag{1}$$

where

$$N = \frac{Z_l}{Z}\frac{\cos^2(2\theta_t)}{\sin k_{ly}d} + \frac{Z_t}{Z}\frac{\sin^2(2\theta_t)}{\sin k_{ty}d}$$

$$M = \frac{Z_l}{Z}\frac{\cos^2(2\theta_t)}{\tan k_{ly}d} + \frac{Z_t}{Z}\frac{\sin^2(2\theta_t)}{\tan k_{ty}d}$$

$$Z = \frac{\rho_a c_a}{\cos\theta},\ Z_l = \frac{\rho_s c_l}{\cos\theta_l}$$

$$\theta_l = \arcsin\left(\frac{c_l}{c_a}\right),\ \theta_t = \arcsin\left(\frac{c_t}{c_a}\right)$$

$$k_{ly} = \frac{w}{c_l}\cos\theta_l,\ k_{ty} = \frac{w}{c_t}\cos\theta_t,\ \omega = 2\pi f$$

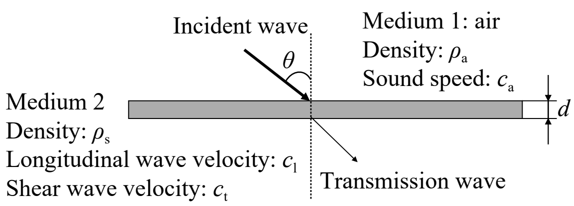

Fig. 2 Oblique incidence of ultrasonic waves in thin plates

In addition to the density and sound velocity of the two media, the energy transmission T is also related to the angle of incidence (θ)[20]. From the air or water incident on the steel plate, Fig. 3 shows the relationship between the transmittance and the angle of incidence when an ultrasonic wave with a frequency of 1 MHz is obliquely incident into the workpiece. It can be seen that a certain incidence angle can be completely transmitted, this particular angle is the critical angle. As described above, the phenomenon of oblique incidence leading to an increase in the transmittance of ultrasonic waves has been experimentally confirmed so far. Therefore, by using the oblique incidence method, the best transmitted wave can be received, and the welding part can be evaluated by adjusting the appropriate incident angle even under various plate thickness conditions. The critical angle is related to the thickness of the plate, the speed of sound in the air, and the phase velocity of the Lamb wave obtained from the dispersion curve, the critical angle is calculated according to Snell's law[21]:

$$\theta = \arcsin \frac{c_{\text{air}}}{c_p} \tag{2}$$

where c_{air} is the propagation speed of ultrasonic waves in air taken at 340 m/s; c_{p} is the phase velocity of the ultrasonic guided waves in the aluminum plate. From the dispersion curve shown in Fig. 1, the phase velocity of ultrasonic waves of different frequencies in a 2 mm thick aluminum alloy sheet can be obtained.

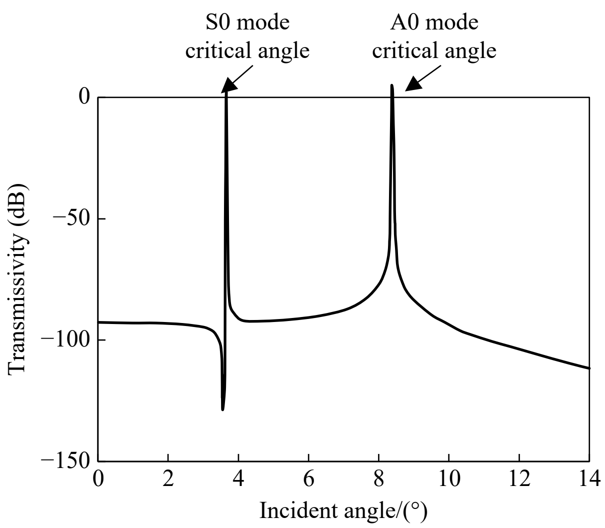

Fig. 3 Relationship between incident angle and transmittance

2 Simulation of laser welding seam quality inspection of thin plate

Use Wave2000 software to simulate the propagation process of air-coupled ultrasonic Lamb wave, as shown in Fig. 4, the simulation material is aluminum plate, the thickness of the two layers is 2 mm. The center point of the transmitting probe is 2.5 mm away from the upper steel plate, and on the left side of the welding seam, the two receiving probes are 2.5 mm away from the upper and lower steel plates, and are located on the right side of the weld. In order to prevent too many echoes from making the signal complex and difficult to analyze the signal, the upper and lower sides of the aluminum plate and the left and right sides are set as infinite boundaries. The frequency of the air-coupled ultrasonic probe is usually 0.2–1 MHz, the dispersion curve shown in Fig. 1, When the frequency is less than 1 MHz, only two modes A0 and S0 can be motivated in the 2 mm aluminum plate, and the A0 mode is easier to motivated, so the A0 mode is selected for simulation and experiment.

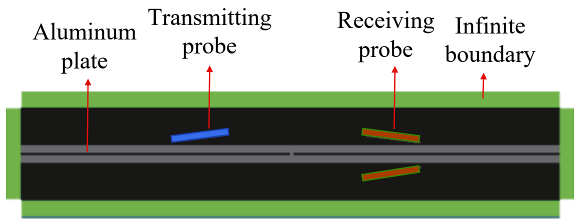

Fig. 4 Lamb wave propagation simulation model

When it is perpendicular to the incident, the transmission rate between the wedge resin and aluminum is 0.565 3 and the transmission rate between air and aluminum is 1×10^{-5}. In order to receive the signal and evaluate the welding seam, Use the oblique incidence method to match the incident angle with the selected mode and phase velocity of the Lamb wave, use the best angle of incidence to increase the transmittance, and use the A0 mode to stimulate the Lamb wave. Fig. 5 shows the propagation process of ultrasonic waves. The white part indicates that the ultrasonic energy is large. As shown in Fig. 5a, the ultrasonic wave propagates in the form of longitudinal waves in the air at 3 µs, and the energy is large. As shown in Fig. 5b, the ultrasonic wave starts to propagate into the steel plate at 10 µs, and propagates forward in the Lamb wave A0 symmetrical mode, In Fig. 5c, the ultrasonic wave propagates to the lower layer through the weld at 15 µs, and also propagates to both sides in the Lam wave A0 symmetrical mode. In Fig. 5d, the signal at 30 µs is received by the receiving sensor when the ultrasonic wave leaks outward, the upper probe receives the reflected leak wave, and the lower probe receives the transmitted leak wave.

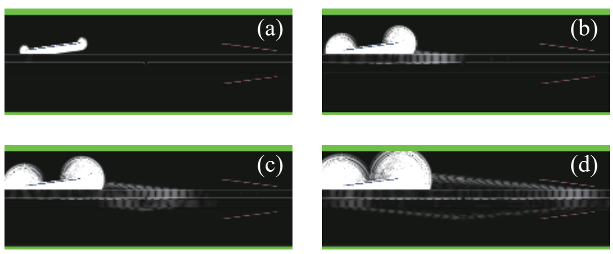

Fig. 5 A0 mode lamb wave propagates through the model (a) 3 µs (b) 10 µs (c) 15 µs (d) 30 µs

The received waveforms are shown in Fig. 6 and Fig. 7. The figure shows the typical 0.8 MHz frequency, 0.2 mm and 2.0 mm weld width of the upper and lower probes. It can be seen from the figure that the workpiece with a wider welding seam has a greater energy of leakage wave reflection, and the workpiece with a narrower welding seam has a larger energy of leakage wave transmission. Considering the actual situation of the project, the width d of the joint part of the welding seam is less than 3 mm, and the board spacing h is less than 0.2 mm, Use air-coupled ultrasonic probes with frequencies of 0.2, 0.4, and 0.8 MHz to detect workpieces with weld widths of 0.2, 0.4,⋯, 3 mm (total 15 different weld widths), And from the Eq.(2) to derive the angle of incidence of the Lamb wave, the detection conditions are shown in Table 1. The relationship between the obtained weld width and the normalized amplitude is shown in Fig. 8. It can be seen that when using 0.8 MHz for detection, the linear relationship between the weld width and the leakage wave energy is good, As the weld width gradually increases, more ultrasonic waves are transmitted to the bottom side of the second steel plate through the weld and are received by the receiving probe below, so the transmitted wave energy increases as the weld width increases; On the contrary, because a large amount of ultrasonic waves are transmitted to the bottom through the weld, the reflected leaked wave energy received by the upper probe will be reduced, but the reflected leaked wave energy is generally higher than the transmitted wave energy, which can be used to evaluate the quality of laser weld width in practical applications. When using 0.2 MHz and 0.4 MHz probes for detection, special points will appear at 0.4 mm and 1.4 mm, The analysis may be due to the fact that when the wave with a low excitation frequency and a large wavelength passes through the weld, the phenomenon of reflection echo will be generated at the junction of the weld and the workpiece, that is, at the end angle, superimposed with the normally propagating wave in the two-layer steel plate. The author will explore this in depth in the subsequent research.

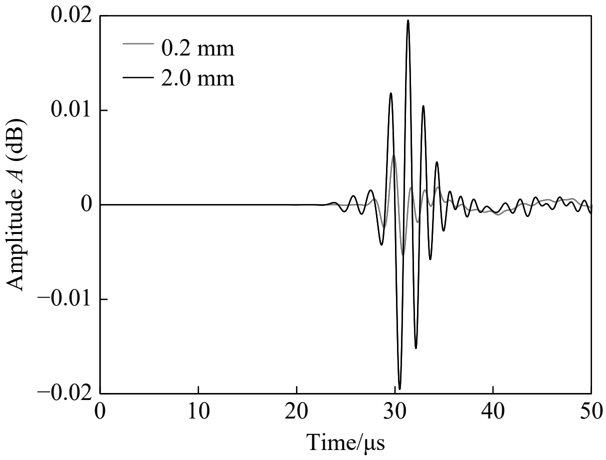

Fig. 6 Transmission leakage wave waveform

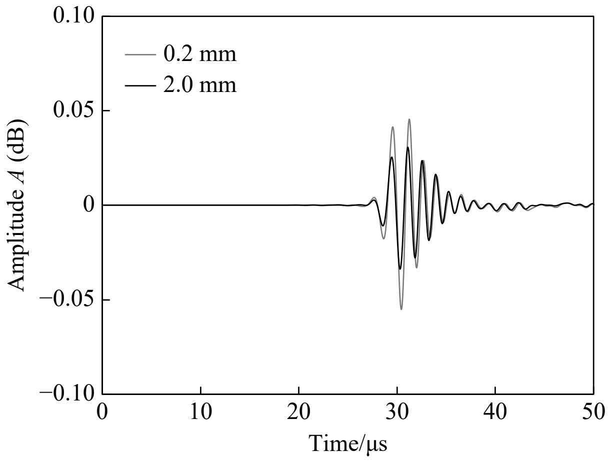

Fig. 7 Reflection leakage wave waveform

Table 1 Detection conditions for different frequency

	Frequency f/ MHz	Phase velocity v_g/ $(m\cdot s^{-1})$	Incident angle θ/(°)
1	0.2	1 739.0	11.27
2	0.4	2 193.1	8.93
3	0.8	2 591.5	7.56

3 Test method and result analysis

3.1 C-scan imaging of simulated welds

In the previous section, the simulation method was used for research. In this section, the test method was used to verify the evaluation of the quality of the laser welding seam by air-coupled guided waves, The material of the test piece is aluminum alloy. Due to the limitation of laser welding process, it is impossible to control the width of the weld to make standard test block. Therefore, the method of bonding is used to make artificial simulated weld wide, the propagation mode of the guided wave through the welding seam or the glue joint is similar. To ensure the integrity of the glue joint, first use an air-coupled ultrasonic scanning system to scan the simulated weld seam. On the one hand, the accuracy of the test is increase, on the other hand, the quality of the weld is evaluated by means of air-coupled scanning.

The scanning system developed by Japan probe Co., Ltd. is used here, as shown in Fig. 9, it is composed of computer (system control software NUAT-21 based on Labview), NI data collector (PXT-1 033), high power ultrasonic signal transmitter receiver (JPR-600C), preamplifier (gain: 60 dB), scanning frame and air coupling flat prob. In this paper, 1 mm (test piece A), 2 mm (test piece B), 3 mm (test piece C), 4 mm (test piece D) and 0 mm (test piece E) simulated weld test blocks are scanned. The ultrasonic wave

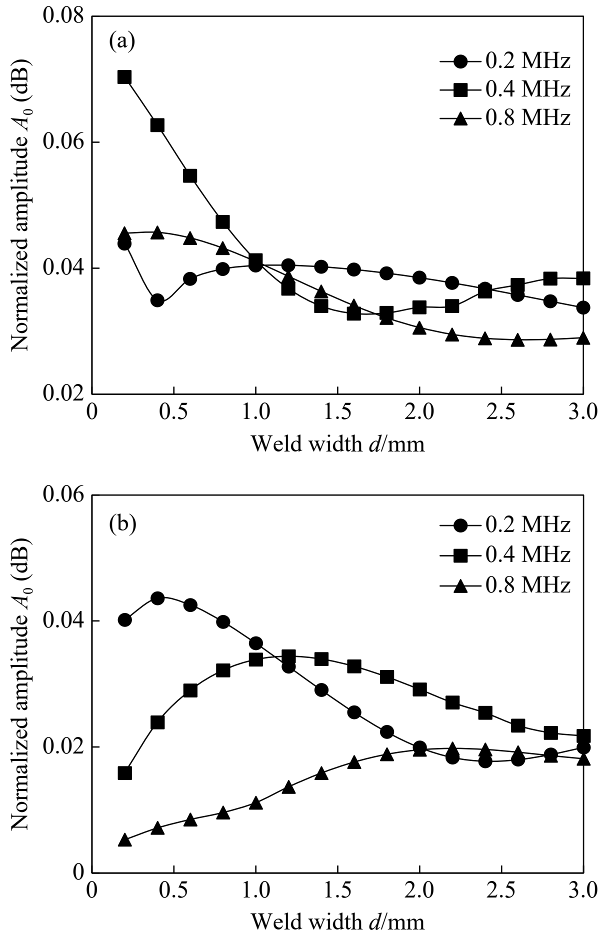

Fig. 8 **Relationship between weld width and amplitude (a) Reflection leakage wave (b) Transmission leakage wave**

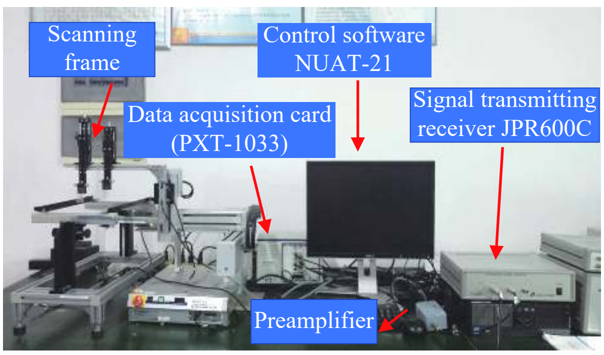

Fig. 9 **Air coupled scanning system**

is transmitted from the 0.4 MHz transmitting probe, and the through detection workpiece is received by the receiving probe, so the intensity distribution of the transmitted wave is obtained by displaying the signal amplitude of the position. Typical test results of test piece D are as shown in Fig. 10. Ultrasonic can penetrate to the bottom through simulated weld. When it passes through the well bonded part (part A), it can obtain more energy, while it shows less energy through the non-bonded part (Part B). Through the scanning of 5 laser welding test blocks, only the test piece D has incomplete adhesion in a small range of simulated weld, In the following paper, the influence of the width of laser weld on the reflectivity and transmissivity is analyzed, and the detection comparison between the good bonding area and the non-bonding area is carried out on the test piece D.

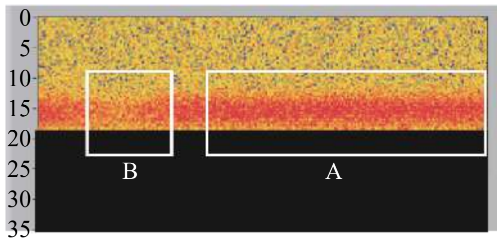

Fig. 10 **Typical scan results (Test piece D)**

3.2 Test results and analysis

As shown in Fig. 11, JPR600c is used as the signal transmitting receiver to excite the air coupling probe with a center frequency of 800 kHz. In the Fig. 11a, two probes are placed above the workpiece to be tested and distributed on both sides of the simulated weld. The ultrasonic wave excited by the transmitting probe propagates through the plate in the form of Lamb wave, and the reflected leakage wave will be received by the receiving probe; In the Fig. 11b, two probes are placed on the upper and lower sides of the workpiece to be tested, which are equally distributed on both sides of the simulated weld. The transverse distance between the two detection methods is 90 mm, the distance between the center point of the transmitting probe and the receiving probe is 3 mm from the surface of the test piece, and the deflection angle is 7.56 °. The received effective signal is transmitted to the preamplifier, the signal near 800 kHz frequency is amplified, and the high frequency component is further removed by the low-pass filter, and the receiving waveform is optimized The effective signal of weld width is analyzed below.

Firstly, the effective bonding parts of A, B, C, D and E

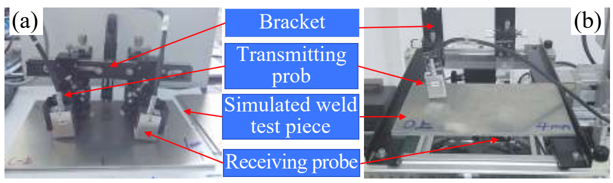

Fig. 11 **Schematic diagram of the experimental device (a) Receiving reflected leakage wave (b) Receiving transmitted leakage wave**

test blocks are tested respectively. Fig. 12 shows the maximum normalized amplitude of effective waveform of each test piece with different weld width. With the increase of weld width, the transmitted leakage wave energy increases gradually, and the reflected leakage wave energy decreases, which is the same as the analysis result in simulation. For laser welding parts, the control of weld width is a very important quality evaluation standard. In the practical production application, according to the actual application position of laser welding parts, two probes can be placed on the upper side of the workpiece to analyze the reflected leakage wave, or two probes can be separately placed on both sides of the workpiece to analyze the reflected leakage wave, Therefore, with the standard laser welding test block and the air coupled ultrasonic guided wave testing method, the quality assessment of weld width can be carried out quickly, accurately and in batches.

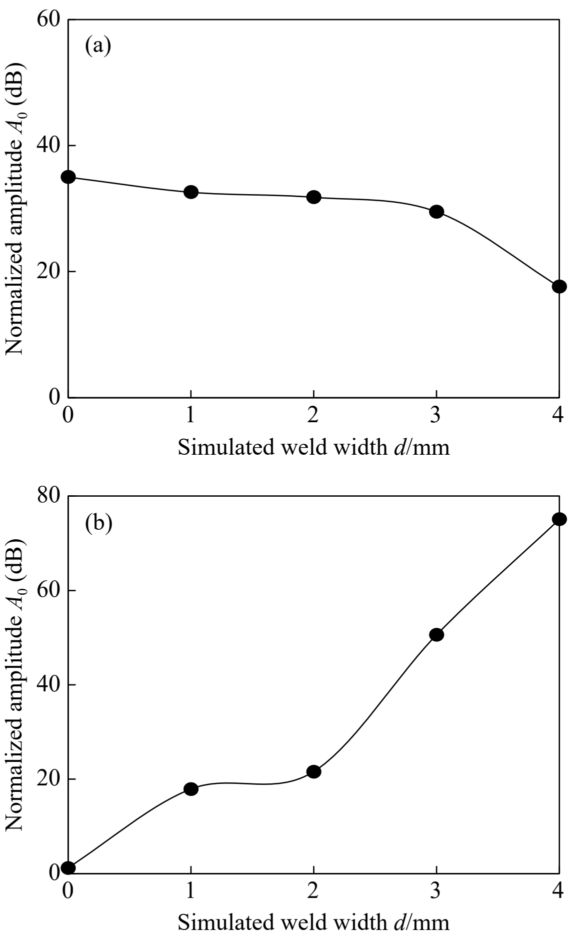

Fig. 12 Relationship between weld width and amplitude in experiment (a) Reflected leakage wave (b) Transmission leakage wave

Further, the well bonded part (part A) and not well bonded part (Part B) of test piece D are tested respectively, and the test method of receiving the transmitted leakage wave in Fig. 11b is adopted. The Lamb wave is excited by the air coupled ultrasonic probe to the thin plate specimen in the air. The Lamb wave enters the specimen through the simulated weld area, one part continues to propagate forward, and the other part propagates to the lower plate through the weld area. Take the effective signal of transmission leakage wave for analysis, as shown in Fig. 13, and detect the part in Fig. 10 that is not well bonded, the waveform is shown in Fig. 13a, the signal-to-noise ratio is low, and the energy of receiving ultrasonic wave is small; Fig. 13b shows the waveform of the bonding intact area, with high signal-to-noise ratio and high transmission wave energy. Compared with the two, using air coupled Lamb wave can effectively evaluate the bonding strength of the simulated weld, so it is considered that this method can be applied to the quality evaluation of the actual laser welding fusion state

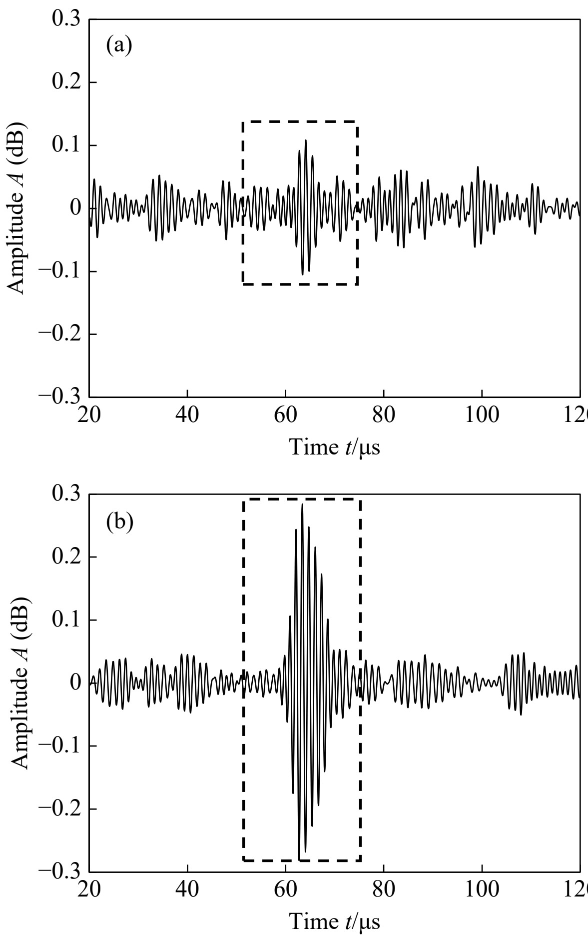

Fig. 13 The test piece D is used to simulate the good bonding between the weld and the intact part. (a) Not well bonded(Part B) (b) Well bonded(Part A)

4 Conclusion

(1) In this paper, the ultrasonic Lamb wave is motivit-

ated to the laser welded plate by the air coupling probe, and the A0 mode which is sensitive to the weld width is selected.

(2)The influence of the change of the weld width on the amplitude of the transmitted and reflected leakage waves is discussed by means of simulation and experimental analysis. The results show that there is a good linear relationship between the weld width and the signal amplitude when the appropriate frequency is selected;

(3)It is proved that the air coupled ultrasonic is effective in detecting the laser welding seam. This method can meet the requirements of rapid in-service detection of laser welding structure quality, and has great practical value.

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