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RESEARCH ARTICLE

RESEARCH ON ELECTROMAGNETIC ULTRASONIC TESTING TECHNOLOGY FOR BUTT WELD OF STEEL PLATE

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ABSTRACT

Lamb wave is widely used in the detection of butt weld defect of steel plate. In order to solve the high requirement of traditional piezoelectric ultrasonic on the surface of the specimen, the electromagnetic ultrasonic testing technology (EMAT) is adopted to stimulate Lamb wave. On the basis of solving the Lamb wave frequency scatter curve diagram of 3mm thick steel plate by MATLAB programming, COMSOL software was used to simulate the propagation of characteristic guided waves in steel plate welds. The simulation results showed that the characteristic guided waves in steel plate welds had an obvious effect on defect identification, and the error was about 2%. The experimental design of electromagnetic ultrasonic excitation Lamb wave detection of rectangular through-hole defects in steel plate welds. The results show that the excited characteristic guided wave can effectively detect the position of the through-hole defect, and the positioning error is about 2.9-3.5%. Both simulation and experiment show that the electromagnetic ultrasonic Lamb wave detection method has obvious effect on the positioning of the butt weld defects of the steel plate.

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INTRODUCTION

In the research of butt steel seam, Sargent first proposed the concept of "characteristic guided wave", the guided wave with a certain mode propagates only along the weld seam (Sargent, 2010). Then scholars of domestic and abroad began to use numerical methods to simulate the propagation characteristics of guided waves in welding seam (He, 2011; Wu and Ume, 2012; Yang, 2013). Liu *et al.* (2014) verified that the mode could detect the defects in the welding seam by using the same phase or inverse phase excitation of a single S_0 and A_0 mode on the upper and lower surface of the piezoelectric plates at the same position, and combined with the coefficient matrix method and data fusion method to locate the defects (Liu *et al.*, 2014). Tian *et al.* (2016) studied the combined detection method of pulse reflection method (PE) and ultrasonic reflection time difference method (TOFD), and made a comparison experiment with the common piezoelectric ultrasonic method for the detection of butt weld, and found that the accuracy and efficiency of the detection of butt weld defects were greatly improved (Tian *et al.*, 2016). Considering the coupling agent required by piezoelectric ultrasonic in the detection of butt weld defects and the extremely high requirements on the detection surface environment. Compared with traditional piezoelectric ultrasonic testing, electromagnetic ultrasonic testing technology does not require coupling agent, harmless to human body, the surface environment requirements of the inspected specimen are not high, get rid of the conventional detection limits of low efficiency and high cost (Huang *et al.,* 2018; Mirkhani *et al.,* 2004). In this paper, the electromagnetic ultrasonic Lamb wave of the butt weld detection method is proposed. The MATLAB software is used to analyze and map the dispersion curve of characteristics Lamb wave finite element model is established by COMSOL software. Simulation analysis of the ability of weld characteristic guided wave to locate defects. Finally, the electromagnetic guided ultrasonic transducer is used to excite the special guided wave of the single mode in the butt weld of the steel plate to verify the simulation result.

Theoretical Analysis of Electromagnetic Ultrasonic Lamb Wave Detection

Dispersion characteristics of Lamb waves: The steel plate with a thickness of 3mm is selected as the detection object. Therefore, the shear wave velocity and the longitudinal wave velocity are 3230m/s and 5900m/s, respectively. The mathematical simulation of Raleigh-Lamb wave equation is carried out by using MATLAB software. After extracting the data, the curve is drawn by ORANGE software. The group velocity dispersion curve of Lamb wave in the steel plate are plotted as shown in Fig.1 Young's modulus $\mathrm{E} = 207 \times 10^9\mathrm{Pa}$, Poisson's ratio and mass density are 0.3 and 7800kg/m^3, respectively.

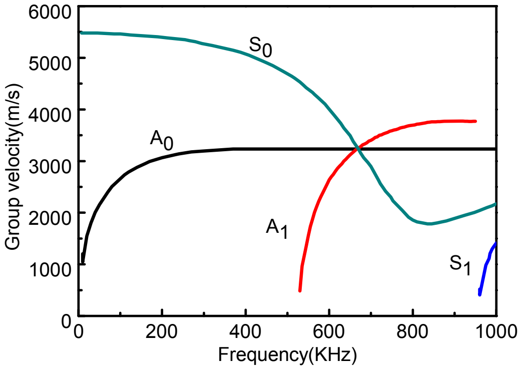

Fig. 1 dispersion curve of Lamb wave in a steel plate with a thickness of 3mm

As can be seen from the Figure1, the number of the Lamb wave modes increases with the increase of frequency, and the velocity of the same mode in different frequencies is also different. This multi-modal characteristic makes the Lamb wave not only receive a single signal during detection, but also has a negative impact on the evaluation of the defect. In severe cases, the defect signal even cannot be detected. In order to reduce the influence of multi-modal characteristics on defect signal recognition, this paper adopted EMAT detection method. Based on Fig. 1 and a single mode of characteristic guided waves is generated to detect defects.

Electromagnetic ultrasound produces Lamb waves: The electromagnetic ultrasonic sensor is composed of three parts: a permanent magnet that provides bias magnetic field, a coil that passes a high-frequency alternating current, and a test piece that generates and propagates ultrasonic waves. When the excited ultrasonic wavelength is 7~10 times the thickness of the plate, the Lamb wave can be formed in the plate [9]. By changing the position relationship between the coil and the magnet, different single mode guided waves can be generated in the butt weld of the steel plate. Fig.2 shows the working principle of the electromagnetic ultrasonic Lamb wave transducer.

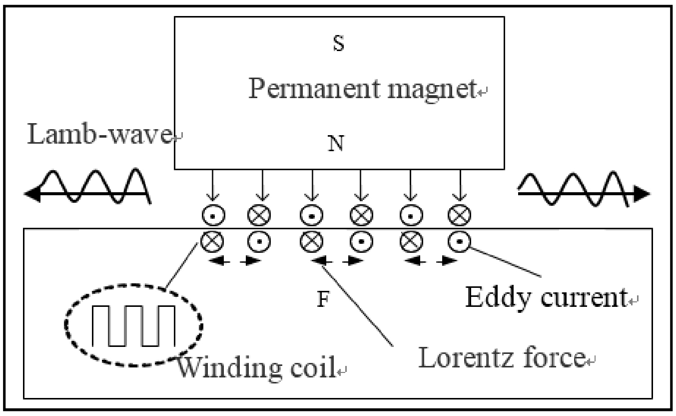

Fig. 2. Energy exchange mechanism of Lamb wave EMAT excited by lorentz force

Simulation and experimental research

Finite element analysis model: The 3D model was drawn using SOLID WORKS software and imported directly into COMSOL software. According to the structure of the electromagnetic ultrasonic transducer, the selected unit types are: coil, permanent magnet, steel plate weld and air. The product of the static magnetic field strength generated by the bias magnetic field and the pulsed eddy current density is taken as a coupling variable; the product of the static magnetic induction intensity and the magnetic permeability of the steel sheet and the particle velocity is taken as the current density. The steel plate to be tested is divided into triangles freely, and the steel plate around the meandering coil is subdivided, and the permanent magnet is divided into rectangles. In the case that the mode wavelength of no defect excitation is the minimum, 1/10 of the wavelength is taken as the size of the meshing unit to ensure the accuracy of the numerical simulation results, that is, the number of units in the y direction is 10.Under the condition that the mode wavelength of the defect excitation is the minimum, 1% of the Lamb wave length is taken as the unit size of the grid, that is, the number of units in the y direction is 100, which should satisfy Eq.(1):

$$\frac{\lambda}{n} \gg max(\delta l_x, \delta l_y) \tag{1}$$

In Eq.(1) λ and n represent the smallest wavelength of Lamb wave and the selected mesh partition coefficient, δl_x and δl_y represent the discretization size of space. For the detailed division, the time step was controlled to less than 1/(100f), while the maximum grid size of the steel plate was controlled to be more than $\lambda/10$. The mesh size of the air was set to 2.2mm; the mesh size of permanent magnet is set as 1.2mm.The mesh size of the coil was set at 0.06mm; the weld seam and mesh size distribution of the steel plate were set as 0.03 and 0.6mm, and the solving step size was set as 0.00000002s.

Meanwhile, the sinusoidal wave modulated by hamming window is selected as the excitation, and the expression is as follows:

$$H(t) = \left[\frac{1}{2}\left(1 - cos\frac{2\pi \cdot f_c \cdot t}{N}\right)\right] \tag{2}$$

In Eq.2, N and f_c represent the number of sinusoidal wave periods and the central frequency of signals, respectively. The initial conditions of the electromagnetic ultrasonic transducer system are set as static. When simulating the electromagnetic ultrasonic transducer system, the air is set as infinite and the magnetic induction intensity at infinite distance is zero.Fig.3 and Fig.4 show the compositional structure of the ultrasonic Lamb wave EMAT transducer and the finite element meshing model of the EMAT model, respectively.

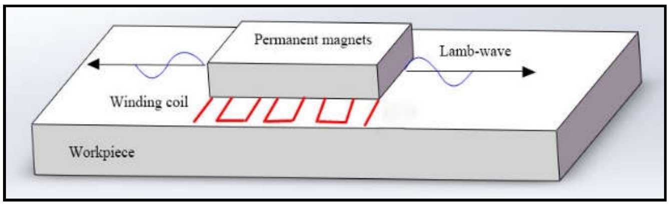

Fig. 3. Structure diagram of Lamb wave transducer for EMAT

The steel plate size in the model in Fig.3 is$600\text{mm} \times 300\text{mm} \times 3\text{mm}$, the weld is the intermediate weld, the weld height is 1mm, the width is 5mm, and the load is applied above the edge of the weld, so that the EMAT transducer excites the characteristic guided wave in the weld and excites

Lamb wave at the edge of the weld. The time step is set to $2e^{-8}$, and the load is applied to the weld at the left end of the steel plate. Applying a load of x or y direction at the welding seam of the left end of the steel plate, as shown in Fig.5.

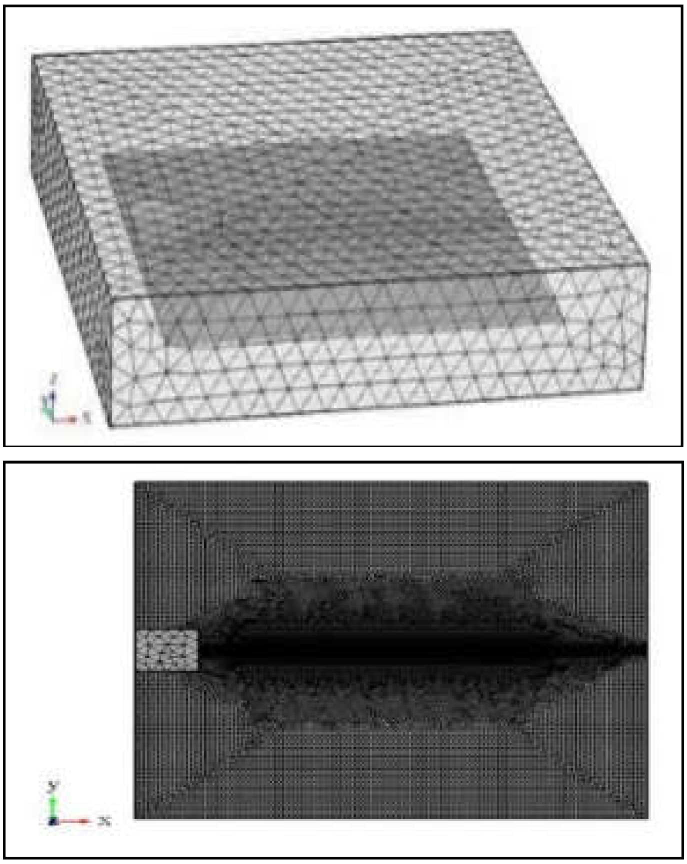

Fig. 4. Finite element mesh model

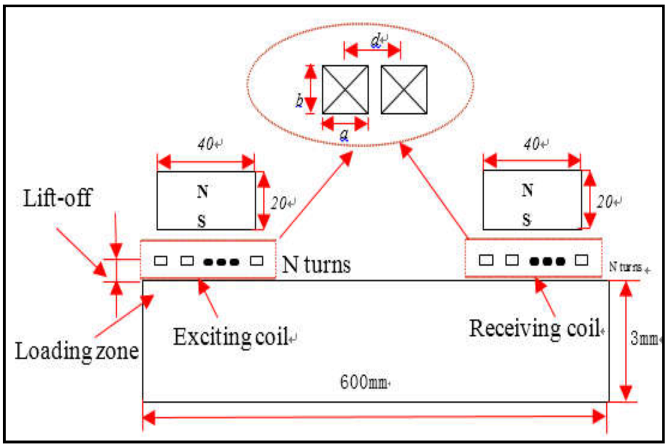

Fig. 5. Schematic diagram of Lamb wave excitation and reception of EMAT

The processing of finite element simulation results: The simulated waveforms which explore the ability of characteristic guided wave of A0 mode weld to identify defects in weld are shown in Fig.6. Fig.6 (a) and Fig.6 (b) are the waveforms received when there is no defect and when there is defect, respectively. According to the Figure.6, the amplitude of the initial wave is higher than that of the defect echo, the initial wave is received at the earliest, and the surface guided wave energy is mainly concentrated in the welding seam. There is a smaller wave packet behind the initial wave, with a relatively large amplitude. According to the frequency dispersion curve of Lamb wave in Fig.1 and the theoretical propagation velocity and time， the result is close to the defect location of the simulation design, so it can be determined that the wave packet is defect echo. The arrival time before the wave is set as the arrival time of defect echo, which can reduce errors. The calculated results is as follows:

$$x = \frac{v_{A0} \cdot \Delta t}{2} = \frac{5044 \times 1.62 \times 10^{-4}}{2} = 0.408m \qquad (3)$$

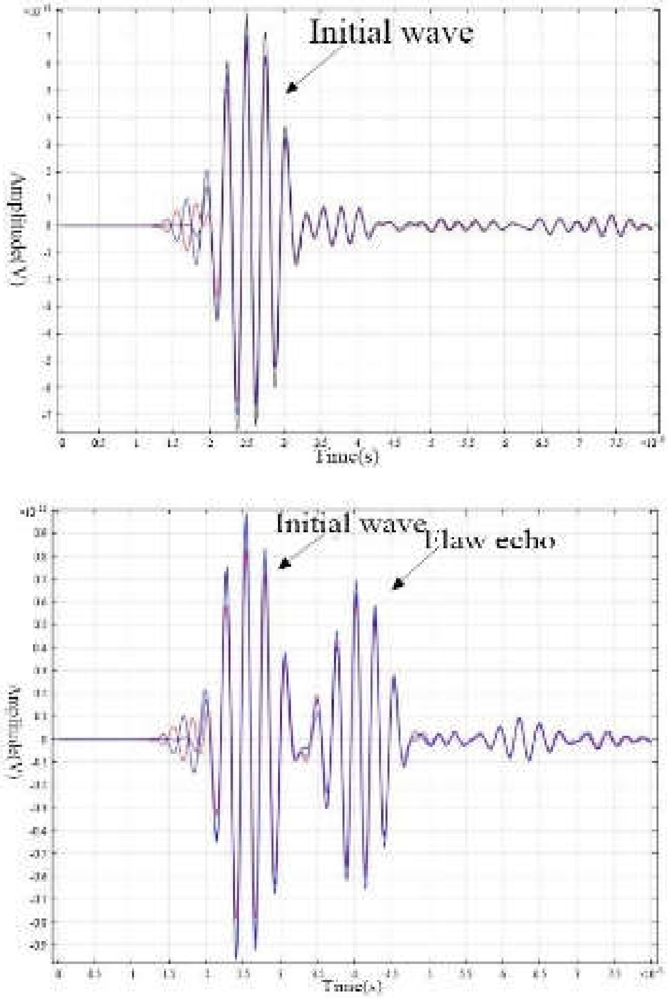

Fig 6 (a) Waveform in defect-free steel plate under A0 mode. (b)Waveform in defective steel plate under A0 mode

In the simulation model, the position of the rectangular defect in the welding seam is 400mm away from the left end of the welding seam. The corresponding position of the wave packet shown in the above results is 408mm. There is a certain error in the results, and the error is only 2%. It can be basically determined that the wave packet is the rectangular defect echo. These results indicate that the Lamb wave model excited is correct.

Defect location experiment verification: Experiments were carried out on butt welding plates with artificial rectangular holes. The size of the rectangular through-hole defect is 5mm long and 2mm wide, the defects are set in the middle of the steel plate welding seam, that is, the distance from both ends of the welding seam is 300mm. Place the exciter EMAT probe at a distance of 100mm, 200mm and 300mm respectively. Fig.7 shows the defect echo signals received at different positions of the distance defect:

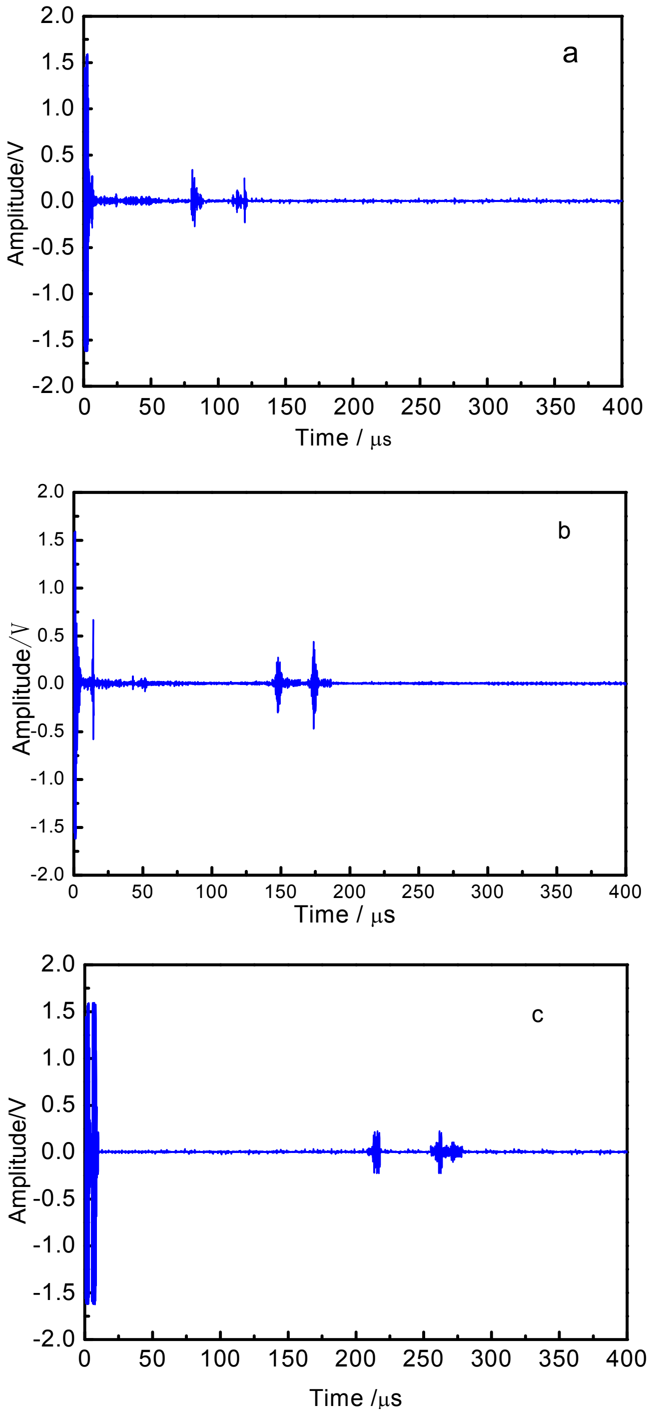

Fig. 7. E Defect echo signals received at (a) 100mm, (b) 200mm, and (c) 300mm from the excitation probe

Table.1 shows the time corresponding to the peak value of the defect echo wave packet and the location of the defect measured according to the calculated experiment. It can be seen from table1 that characteristic guided wave has a strong ability to identify the through-hole defect in the steel seam with a high positioning accuracy and an error of less than 3.5%. And as the increase of the distance between the probe and the defect, the amplitude of echo decreases.

Table 1. Analysis of defect location error

Distance from defect (mm)	Defect echo time (µs)	Defect location (mm)	Position error (%)
100	70	102.9	2.9%
200	139	204. 4	2.2%
300	214	310.5	3.5%

Conclusion

In this paper, the dispersion characteristics of Lamb waves in a plate are calculated by MATLAB, and the dispersion curve of Lamb waves in a 3mm thick plate is drawn. Then, COMSOL software was used to set parameters, and the finite element model of EMAT excitation A_0 mode was designed, and the simulation results were processed numerically. Finally, the electromagnetic Lamb wave is used to detect the rectangular through-hole defect in the welding seam of steel plate. The experimental results show that the characteristic guided wave can effectively detect the position of the through-hole defect with small positioning error, indicating the characteristic guided wave produced by electromagnetic ultrasound is effective in detecting defects in welding seams.

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