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The numerical simulation of Lamb wave propagation in laser welding of stainless steel

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Abstract. In order to explore the Lamb wave propagation in laser welding of stainless steel, the numerical simulation is used to show the feature of Lamb wave. In this paper, according to Lamb dispersion equation, excites the Lamb wave on the edge of thin stainless steel plate, and presents the reflection coefficient for quantizing the Lamb wave energy, the results show that the reflection coefficient is increased with the welding width increasing,

1. Introduction

The laser welding of stainless steel is an important connecting structure of high-speed train, which is directly related to operation security [1-2]. Because the laser welding process is very complex and the welding quality is related to many parameters, such as laser energy, welding speed, welding defects are inevitable generated. Therefore, detecting weld defects as early as possible is an essential step for the safety and continuity of operation of such structures [3-4].

Existing conventional non-destructive testing (NDT) techniques such as ultrasound testing is the most commonly used techniques to inspect welding defects [5]. Many NDT applications with Lamb waves are focused and the characteristic of Lamb wave propagation is the basis of inspecting welding defects. The numerical simulation of Lamb wave propagation is a useful method for studying the interaction rule of the Lamb and transmission medium. In this paper, based on numerical simulation, excites the Lamb wave on the edge of thin stainless steel plate, analyzes the Lamb wave characteristic.

2. Theoretical bases

The Lamb dispersion equation is shown in Eq.(1).

$$\begin{aligned} \frac{\tan(qd)}{\tan(pd)} &= -\frac{4k^2pq}{(q^2-k^2)^2} \quad \text{(S mode)} \\ \frac{\tan(qd)}{\tan(pd)} &= -\frac{(q^2-k^2)^2}{4k^2pq} \quad \text{(A mode)} \end{aligned} \tag{1}$$

Where $p^2=\frac{\omega^2}{c_L^2}-k^2$, $q^2=\frac{\omega^2}{c_T^2}-k^2$,and $k=\frac{\omega}{c_P}$, ω=$2\pi f$. Therefore, $p^2=\frac{(2\pi f)^2}{c_L^2}-\frac{(2\pi f)^2}{c_P^2}$, $q^2=\frac{(2\pi f)^2}{c_T^2}-\frac{(2\pi f)^2}{c_P^2}$.

Because the Eq.(1) roots have imaginary number, the real is only considered. According to the range of cp, the roots range is divided into three parts, $0<c_P\le c_T$, $c_T<c_P\le c_\mathrm{L}$ and $c_\mathrm{L}<c_P$.

When $0<c_P\le c_T$, the A mode and S mode is shown in Eq.(2).

$$\begin{gathered}\frac{th(\frac{2\pi fd}{c_Tc_P}\sqrt{c_T^{\ 2}-c_P^{\ 2}})}{th(\frac{2\pi fd}{c_Lc_P}\sqrt{c_L^{\ 2}-c_P^{\ 2}})}=\frac{4c_T^{\ 3}\sqrt{(c_L^{\ 2}-c_P^{\ 2})(c_T^{\ 2}-c_P^{\ 2})}}{c_L(2c_T^{\ 2}-c_P^{\ 2})^2}\\ \frac{th(\frac{2\pi fd}{c_Tc_P}\sqrt{c_T^{\ 2}-c_P^{\ 2}})}{th(\frac{2\pi fd}{c_Lc_P}\sqrt{c_L^{\ 2}-c_P^{\ 2}})}=\frac{c_L(2c_T^{\ 2}-c_P^{\ 2})^2}{4c_T^{\ 3}\sqrt{(c_L^{\ 2}-c_P^{\ 2})(c_T^{\ 2}-c_P^{\ 2})}}\end{gathered}\tag{2}$$

When $c_T<c_P\le c_\mathrm{L}$, the A mode and S mode is shown in Eq.(3).

$$\begin{gathered}\frac{th(\frac{2\pi fd}{c_Tc_P}\sqrt{c_P^{\ 2}\text{-}c_T^{\ 2}})}{th(\frac{2\pi fd}{c_Lc_P}\sqrt{c_L^{\ 2}-c_P^{\ 2}})}=\frac{4c_T^{\ 3}\sqrt{(c_L^{\ 2}-c_P^{\ 2})(c_P^{\ 2}\text{-}c_T^{\ 2})}}{c_L(2c_T^{\ 2}-c_P^{\ 2})^2}\\ \frac{th(\frac{2\pi fd}{c_Tc_P}\sqrt{c_P^{\ 2}\text{-}c_T^{\ 2}})}{th(\frac{2\pi fd}{c_Lc_P}\sqrt{c_L^{\ 2}-c_P^{\ 2}})}=\frac{c_L(2c_T^{\ 2}-c_P^{\ 2})^2}{4c_T^{\ 3}\sqrt{(c_L^{\ 2}-c_P^{\ 2})(c_P^{\ 2}\text{-}c_T^{\ 2})}}\end{gathered}\tag{3}$$

When $c_\mathrm{L}<c_P$, the A mode and S mode is shown in Eq.(4).

$$\begin{gathered}\frac{th(\frac{2\pi fd}{c_Tc_P}\sqrt{c_P^{\ 2}\text{-}c_T^{\ 2}})}{th(\frac{2\pi fd}{c_Lc_P}\sqrt{c_P^{\ 2}\text{-}c_L^{\ 2}})}=\text{-}\frac{4c_T^{\ 3}\sqrt{(c_P^{\ 2}\text{-}c_\mathrm{L}^{\ 2})(c_P^{\ 2}\text{-}c_T^{\ 2})}}{c_L(2c_T^{\ 2}-c_P^{\ 2})^2}\\ \frac{th(\frac{2\pi fd}{c_Tc_P}\sqrt{c_P^{\ 2}\text{-}c_T^{\ 2}})}{th(\frac{2\pi fd}{c_Lc_P}\sqrt{c_P^{\ 2}\text{-}c_L^{\ 2}})}=\text{-}\frac{c_L(2c_T^{\ 2}-c_P^{\ 2})^2}{4c_T^{\ 3}\sqrt{(c_P^{\ 2}\text{-}c_\mathrm{L}^{\ 2})(c_P^{\ 2}\text{-}c_T^{\ 2})}}\end{gathered}\tag{4}$$

Based on numerical simulation, the Lamb dispersion curves can be obtained. The calculation step is as follows:

1) set the frequency-thickness product fd;
2) estimate the initial phase velocity cp0 and cp1;
3) if Eq.(2) are the same sign, repeat step 2) until the contrary sign;
4) exact phase velocity based on bisection method;

5) repeat step 2)-step4) for calculate Eq.(2)-Eq.(4);
6)choose another frequency-thickness product, repeat step2)-step5) for phase velocity calculation.

3. Result and Discussion

The ANSYS software is used to numerical simulation, the stainless steel material parameters include density 7932kg•m-3, elasticity modulus 2.169E-11 Pa and Poisson's ratio 0.287. Assume the laser weld and the bottom material have the same parameters, meshing size l is less than the minimum wavelength λ, $l \le \frac{\lambda}{10}$, and the time step δt is also less than the wave travel time, $\delta t \le \frac{l}{v}$.

The Lamb wave propagation at different time in the welding plate model is shown in Figure 1, excites the Lamb wave on the edge of thin stainless steel plate, the receive positions is 1mm to the right of thin stainless steel plate and the frequency is 5MHz.

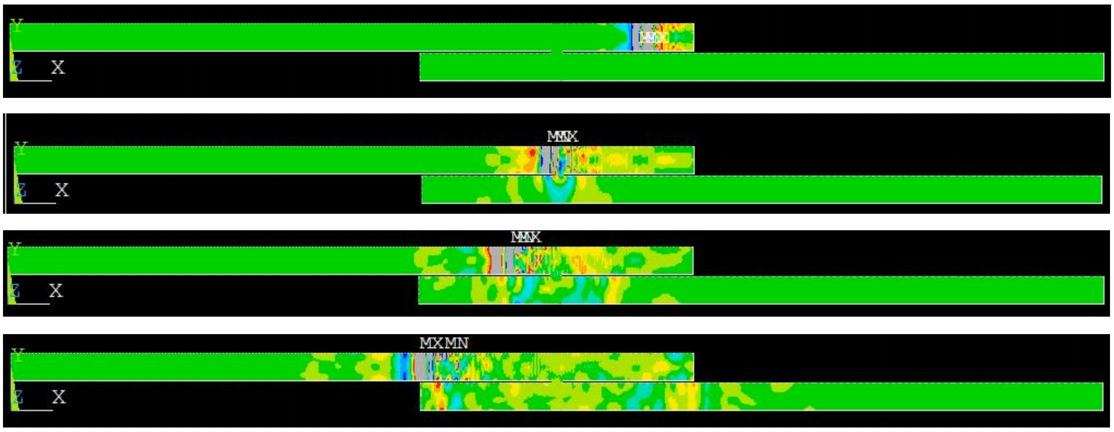

Figure 1. The Lamb wave propagation at different time in the welding plate model.

The structural complexity leads to the Lamb wave has diffuse feature, the reflection of Lamb wave cannot be analysis, therefore the reflection coefficient is used to quantize the received Lamb wave energy, which is defined as the ration between reflection wave and incident wave. As shown in Figure 2，the reflection coefficient is increased with the welding width increasing, which results in the amplitude of reflection wave is increased.

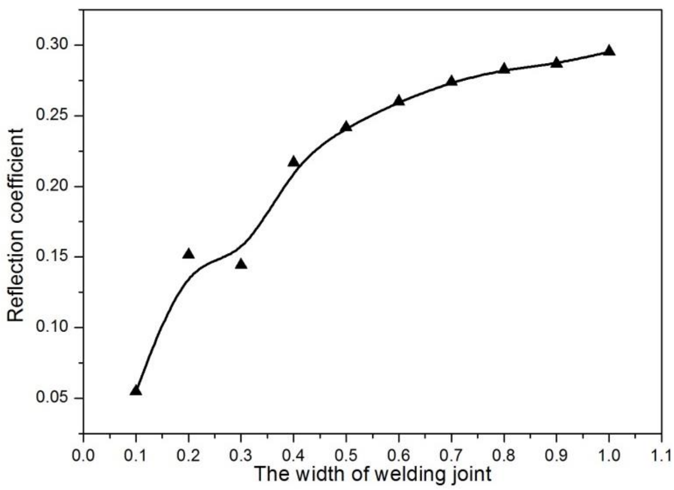

Figure 2. The reflection coefficient of different weld width.

4. Conclusion

In order to study the Lamb wave propagation, the numerical simulation based on dispersion equation is implemented by ANSYS software. According to the numerical simulation results, we consider the structural complexity leads to the Lamb wave has diffuse feature, therefore, the reflection coefficient is defined as the ration between reflection wave and incident wave which is used to quantize the received Lamb wave. In addition, the reflection coefficient is increased with the welding width increasing, which result in the amplitude of reflection wave is increased.

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