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Numerical simulation for estimating the location and orientation of a crack focus on ultrasonic mode conversion

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1. Introduction

Billets, the primary product of steel, may develop cavity defects during casting. If processed in this state, cracking can occur, which adversely affects the safety of the final product. Therefore, nondestructive inspection at the billet stage is essential. Ultrasonic testing is used to detect defects inside the billet. In recent years, studies have been conducted to detect internal defects using the transmission method[1-3], which utilizes the propagation time of ultrasonic waves. In these studies, it was possible to obtain information on the location and size of defects. However, obtaining detailed information about the orientation and shape of defects is difficult, and more detailed defect analysis methods are required. Acquiring more advanced information about defects is important as it can lead to improvements in the manufacturing process, and furthermore, it can influence the reliability of products, the improvement of manufacturing technology, and the reduction of manufacturing costs.

Therefore, this study aims to investigate under what conditions information regarding the orientation of a crack can be obtained. The study examines the effects of a crack in solid on the reflection and transmission characteristics of longitudinal and shear ultrasonic waves through numerical simulation.

2. Reflection, transmission, and mode conversion caused by the crack

Figure 1 shows the behavior of ultrasonic waves when they encounter a crack. When an incident wave, whether it is longitudinal or shear, strikes a crack, it splits into reflected and transmitted waves, both longitudinal and shear, respectively. This phenomenon, in which a part of the wave changes from longitudinal to shear or vice versa, is known as mode conversion. The direction of propagation of each wave, including the wave undergoing mode conversion, is expressed by the following equation (1).

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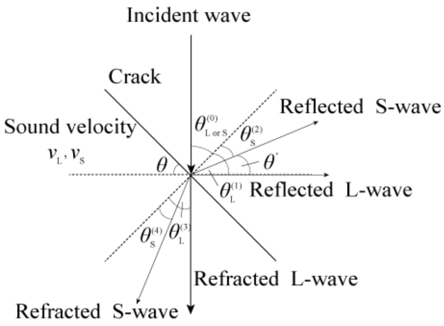

Fig.1 Behavior of ultrasonic waves when they encounter a crack.

$$\frac{\sin\theta^{(0)}_{\mathrm{L\,or\,S}}}{v_{\mathrm{L}\,or\,S}} = \frac{\sin\theta^{(1)}_{\mathrm{L}}}{v_{\mathrm{L}}} = \frac{\sin\theta^{(2)}_{\mathrm{S}}}{v_{\mathrm{S}}} = \frac{\sin\theta^{(3)}_{\mathrm{L}}}{v_{\mathrm{L}}} = \frac{\sin\theta^{(4)}_{\mathrm{S}}}{v_{\mathrm{S}}} \quad (1)$$

v_{L} and v_{S} are the velocities of the longitudinal and shear waves, respectively, and $\sin\theta^{(0)}_{\mathrm{L\,or\,S}}$ and are the incident angles of the longitudinal and shear waves, respectively. $\theta^{(1)}_{\mathrm{L}}$ and $\theta^{(2)}_{\mathrm{S}}$ are the reflection angles of the longitudinal and shear waves, and $\theta^{(3)}_{\mathrm{L}}$ and $\theta^{(4)}_{\mathrm{S}}$ are the refraction angles of the longitudinal and shear waves, respectively. Since each metal has specific velocities for longitudinal and shear waves, if the angles of the reflected and refracted waves can be estimated, it is possible to estimate the incident angle of the transmitted ultrasonic wave using Snell's law.

3. Numerical simulation condition

Figure 2 shows the numerical simulation conditions, in which the Finite-Difference Time-Domain (FDTD) method is used. The test billet is 100 × 100 (mm^2) steel with a density of 7700 kg/m^3, longitudinal wave velocity of 5950 m/s, and shear wave velocity of 3240 m/s. The mesh size is 0.1 mm, the mesh space is 1001 ×1001, and the time discrete width is 11.9 ns. The billet surface and defects are assumed to be free boundaries with zero stress. The transmitted signal is a 0.5 MHz sine burst wave with a Hann window, and 10 cycles are transmitted. The crack is reproduced as an ellipse with a major axis of 20 mm and a minor axis of 0.1 mm.In this simulation, the crack angles are set to 0, and 30 to 150 degrees in 5-degree increments, with the crack positioned at the center of the steel billet (x, y) = (50, 50). A transmitter of 2 mm diameter is placed at the top center of the billet to transmit longitudinal ultrasonic waves, which are then received by receivers placed on the right side, left side, and bottom of the billet after being reflected or transmitted by the crack.

4.Simulation results

Figure 3 shows the change in horizontal particle velocity when a longitudinal ultrasonic wave is incident at a crack angle of 45 degrees. This figure illustrates the difference in horizontal particle velocity between the case when a longitudinal ultrasonic wave is incident with a crack and the case without a crack, allowing the observation of the effects caused by the crack. In the absence of a crack, ultrasonic reflections occur at the sides and bottom surfaces, but these effects have been eliminated in this analysis. Fig. 3(a) depicts the propagation of the shear wave component in the steel billet at a specific time. Although a longitudinal ultrasonic wave was incident, it is evident that a shear wave was generated due to mode conversion. Additionally, strong reflected waves are observed.

Figure 3 (b) and (c) show the ultrasound waves arriving on the left and right, sides of the billet, respectively, with time on the horizontal axis and position on the vertical axis. Fig. 3(d) shows the ultrasound waves arriving on the bottom sides of the billet, respectively, with position on the horizontal axis and time on the vertical axis.It can be seen that the ultrasound is received as time progresses. The wave observed at 25 μs in Fig. 3(c) is the earliest wave observed, and thus is most likely a longitudinal wave. Although longitudinal waves should not have a lateral component, the reflected longitudinal waves probably had a horizontal component because of the orientation of the fracture. The circled area is presumed to be a horizontal wave reflected by the crack, since it was observed after the longitudinal wave.

The actual crack angle was estimated from Fig. 3(c). If the apparent ultrasonic velocity along with the boundary with of the shear wave observed in the circled area is v_S', the relationship with the velocity v_S propagating in the billet is expressed by the following equation (2), where θ' is the reflection angle of the shear wave.

$$\frac{\sin\theta'}{v_S} = \frac{1}{v_S'} \tag{2}$$

The apparent ultrasonic velocity of the shear wave was calculated from Fig. 3(c). The crack angle is calculated to be about 35 degrees from equations (1) and (2). The estimation error is considered to be due to the calculation of the apparent velocity.

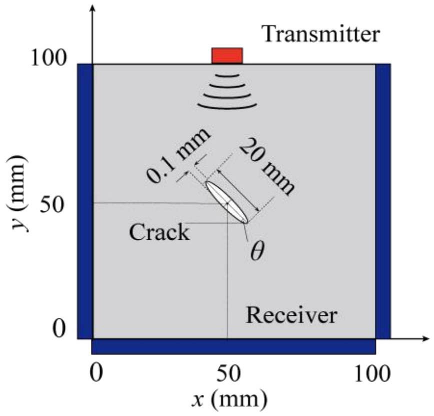

Fig. 2 Simulation condition

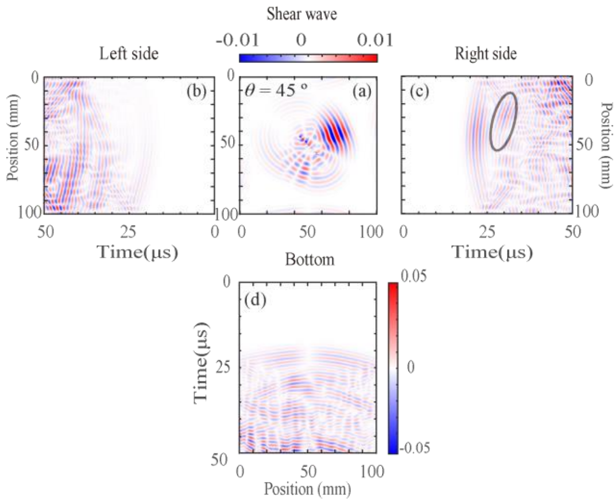

Fig. 3 Differences in the distributions of horizontal vibrations between cases with and without a crack.

5. Conclusion

In this study, the effect of cracks on the reflection and transmission characteristics of longitudinal and shear ultrasonic waves was investigated by numerical simulation. It is suggested that the crack angle can be estimated using Snell's law by observing the mode-converted reflected ultrasonic waves caused by the cracks. In the future, we aim to develop a method that will enable us to estimate the direction and location of cracks based on the observed data.

References

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