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Numerical simulation of nondestructive inspection for billet using multiple plane waves with transmission method
複数平面波を用いた超音波透過法による
角鋼片内部欠陥検出の数値シミュレーション

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1. Introduction

As a inspection method for a billet, which is a semi-finished products of steel products, we have proposed ultrasonic transmission method using time-of-flight (TOF) of longtitudinal wave[1,2]. This method can detect defects near the surface of a billet, which is difficult to detect by conventional pulse echo method. To speed up the inspection, the authors proposed one-shot measurement using plane-wave with TOF based transimission method[3]. Althogh this method accelerate the speed of the inspection of steel billet using transmission method, the position of a defect in depth direction can not be measured. The information of the defect position can contribute to the inprovement of manufacturing processes of the billet.

In this study, we propose defect detection and position estimation inside billet by ultrasonic transmission method using multiple plane-waves at different angles. Although multiple plane-waves has been researched and adopted for pulse echo method[4], few studies adopted plane-waves to transmission method. In this study, the validity of proposed method using multiple plane-waves with transmission method is evaluated by wave propagation simulations.

2. Principle of defect detection

Figure 1 shows a scheme of defect detection by transmission method using multiple plane-waves. Ultrasonic signals are projected to a billet from transmitter arrays and received at opposite side by receiver arrays. Plane-wave is transmitted by transmitter arrays setting time-delays to create an angle θ of the wave. This proposed method uses deviation of TOF ($\Delta\tau$) of transmitted plane-waves for defect detection. If there is a defect on the ultrasonic propagation path, TOF deviates by $\Delta\tau$ owing to diffraction at the defect. The deviation $\Delta\tau$ appears as a time shift between the received signals $r(t)$ measured in the reference plane, which has no

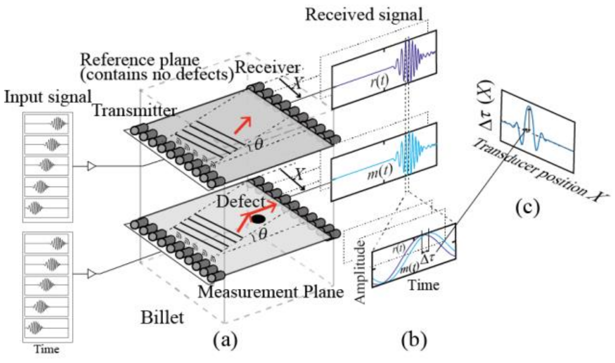

Fig. 1 Outline of defect detection by multiple plane-wave with TOF based transmission method: (a) measurements of cross sections of billets along reference and measurement plane, (b) difference in received waveforms between measurement and reference signals, and (c) TOF profile.

defect, and $m(t)$, measured in the measurement plane, which may contain defects, as shown in Fig. 1(a). $\Delta\tau$ is obtained by calculating the time shift τ, where the cross-correlation function between $m(t)$ and $r(t)$ is maximum. If there are no defects in the measurement plane, $m(t)$ and $r(t)$ are the same and $\Delta\tau$ becomes zero. As shown in Fig. 1(a) and (c), TOF profile, which is the relationship between receiver position X and $\Delta\tau$, is obtained at each angle θ. The receiver position X where $\Delta\tau$ has some value due to a defect shifts as angle of plane-wave θ increases or decreases. The amount of this shift in TOF profile increases when the defect is near the transmitters. TOF profiles obtained using multiple plane-waves at different angles are used to detect defects and estimate the position.

3. Numerical simulation

To simulate the wave propagation for defect detection by the proposed method, two-dimensional finite-difference time-domain (FDTD) method for elastic wave in solid was employed[5]. In this simulation, isotropic elastic material was assumed.

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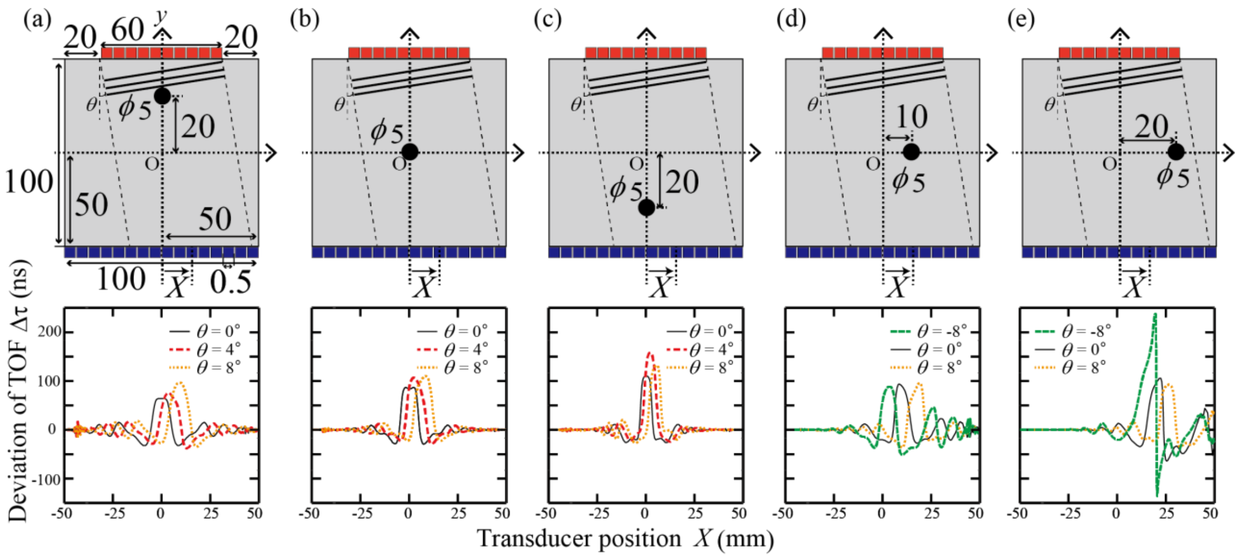

Fig. 2 Simulation conditions and TOF profile using multiple plane-waves when the defect size was 5 mm and defect position (*x*, *y*) was: (a): (0, 20), (b): (0, 0), (c): (0, -20), (d): (10, 0), and (e): (20,0).

The upper side of **Fig. 2** shows the conditions of simulations. Tested billet was assumed to be steel which has cross section of 100×100 mm^2, the density was 7,700 kg/m^3, and the velocities of longitudinal wave and shear wave were 5,950 and 3,240 (m/s), respectively. The surface and a defect of a billet was assumed to be a free boundary, on which stress is zero. The mesh size and the time step were 0.1 mm and 11.88 ns, respectively. The input signal was 5 cycle burst wave of 2 MHz with duration of 2.5 μs. The aperture of the array transmitters and receivers with pitch of 0.5 mm are 60 mm and 100 mm, respectively. Plane-wave with angle θ is transmitted from the transmitters and received by the receivers. A defect with diameter of 5 mm is located at (*x*, *y*) in the cross section of measurement plane.

Figure 2 shows the simulation conditions and the TOF profiles obtained by multiple plane-waves at angle θ for each defect position. Transducer position X where $\Delta\tau$ is maximum shifts as angle of plane-wave θ increases. The amount of shift differs depending on the y position of the defect as shown in Figs. 2 (a)-(c). The defect position of y can be estimated by the shifts in TOF profiles at multiple angle θ. The defect position of x can be estimated by the TOF profiles at $\theta = 0$. The defect position y can be estimated even if x is not zero as shown in Figs. 2 (d) and (e), in the same way at x = 0 as shown in Figs. 2 (a)-(c). $\Delta\tau$ at defect position X differs at each defect position x and each angle of plane-wave θ. The shape of TOF profile is distorted at various x, y and θ. This is caused by asymmetrical form of the ultrasonic propagation path at each situation. The TOF profiles were significantly distorted in Fig. 2 (e) at θ = -8°. In this condition, the defect is located at almost outside of the plane-wave and received wave becomes weak. Weak received signal tends to be affected by the reflected waves from the defect or walls of billet, and calculated deviation of TOF $\Delta\tau$ is highly affected by the reflected waves. Although the shape of TOF profiles is distorted in some cases, the shift in TOF profiles appears depending on the position of defect (*x*, *y*) and angle of a plane-wave θ are observed. These results show that the position of a defect can be estimated using multiple plane-waves.

4. Conclusion

In this study, we validated defect detection inside billet by ultrasonic transmission method using multiple plane-waves in numerical simulation. The defect can be detected and the position can be estimated by the shifts in TOF profiles at angle θ of multiple plane-waves. As the future work, the experimental verification is planned.

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