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# Defect Size Estimation in Billet from Profile of Time of Flight Using Ultrasonic Transmission Method with Linear Scanning
伝搬時間プロファイルに基づく超音波透過法と平行走査による角鋼片内部欠陥径推定

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## 1. Introduction

Billet, semifinished product of steel producs, sometimes contains defects. A kind of typical defects are caused by gas inclusions such as $CO_2$ which remains inside billet during manufacturing processes[1]. To detect these defects, pulse echo method is generally used in steel production line. Recently, ultrasonic phased array technique has been researched and adopted for billet inspection.[2] This technique enables high-resolution inspection by focusing or steering ultrasonic beam. However, many of such inspection methods using pulse-echo method have difficulties for high attenuation billet because the echo becomes feeble as the distance between transducer and defect increases.[3]

Ultrasonic computerized tomography (CT) using time of flight (TOF) of longitudinal wave has been proposed by the authors.[4] This method is effective for detecting defects inside high attenuation billet because we can gain enough level of the received signal by employing transmission method.[3] Moreover, defects are visualized as well as detected by using CT method. Instead of acculate defects detection, it requires long time for a measurement because of huge number of paths must be taken for CT.

Therefore, we proposed a defect detection and size estimation method for billet inspection using transmission method with linear scanning as shown in **Fig. 1**.[5,6] This method reduces measurement time compared with CT method by a linear scanning. Estimation of defect size is expected to contribute to improve manufacturing quality of billet. Defect size estimation is conducted by comparing the profile of $\Delta\tau$ measured deviation of TOF ($\Delta\tau$) profile and temprate $\Delta\tau$ profiles when a defect is at the center of a cross section. However, estimated defect size differs from actual defect size when defect is not on the center of a measured cross section because position of a defect varies $\Delta\tau$ profiles.

In this paper, relations between defect size,position, and $\Delta\tau$ profile are evaluated by numerical simulation. The results may contribute to the estimation of defect size from the profile.

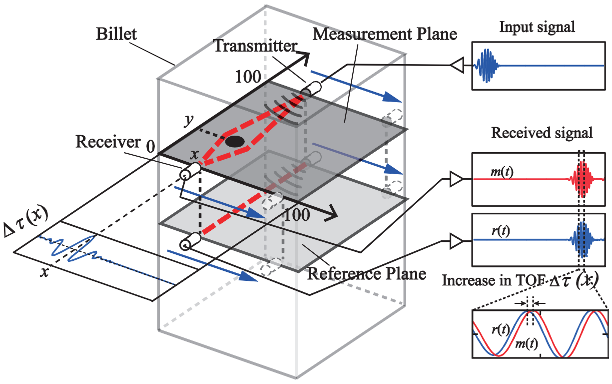

Fig. 1 Schematic view of transmission method with linear scanning and $\Delta\tau$ calculation.

## 2. Principle of Defect Size Estimation

### 2.1 *Time of Flight deviation ($\Delta\tau$) measurement*

Figure 1 shows the outline of $\Delta\tau$ measurement. Ultrasonic signal is projected to a billet by transmitter and received by receiver at opposite side. TOF increases if defect is on a propagation path of ultrasonic signal. This increase of TOF appears as time-shift of received signal compared with at the same path in reference plane, which is defect free, and $\Delta\tau$ is obtained by calculating cross-correlation function between these two signals. In the proposed method, linear scanning is performed on measurement plane and reference plane. So that $\Delta\tau$ profile is obtained as a function of measurement position.

### 2.2 *Defect position estimation*

Defect position is estimated from $\Delta\tau$. In advance, template $\Delta\tau(x)$ in which defect is at the center of the cross-section is prepared. Estimated position of defect is obtained by cross correlation function between measured and template profile, and determined as position of $x$ in which cross correlation function takes maximum value. This estimates only defect position of scanning direction.

### 2.3 *Defect size estimation*

Defect size is estimated from $\Delta\tau$ at the positon of defect which is expected to increase along with the defect size. From relationship between $\Delta\tau$

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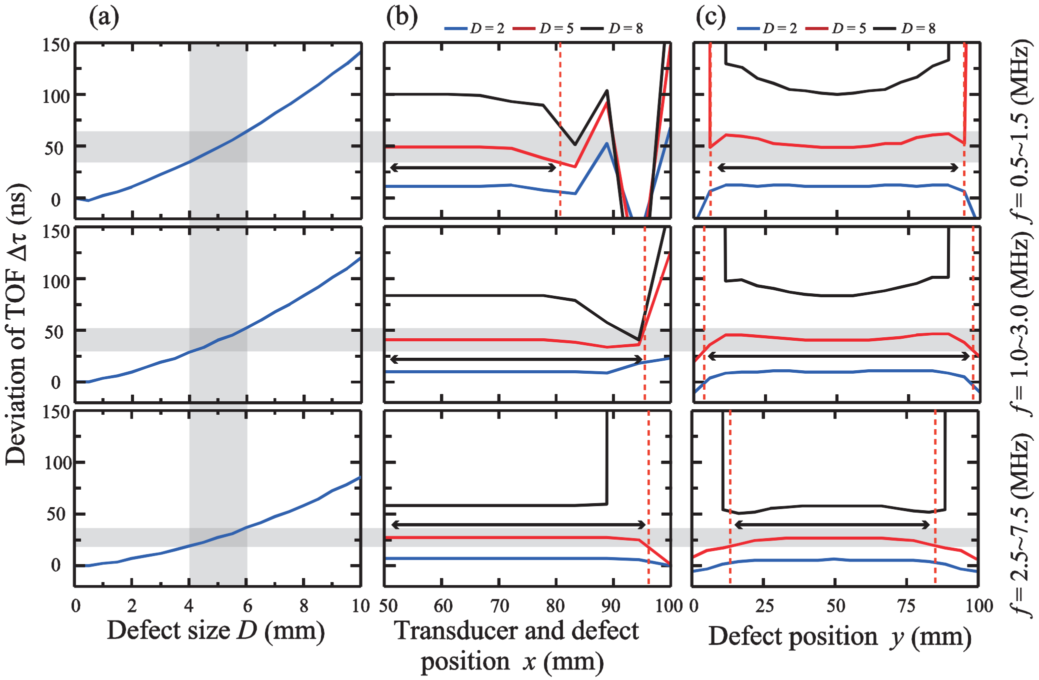

Fig. 2 Deviation of TOF, Defect is at: (a) (50,50), (b) (*x*,50), (c) (50,y).

and defect size, defect size can be determined.

## 3. Numerical Simulation

Finite-Difference Time-Domain (FDTD) method was employed to simulate the longitudinal wave propagation. Tested billet was assumed to be steel which has cross section of 100×100 ($\mathrm{mm}^2$) with mesh size of 0.1 mm, and sound velocity was assumed to be 5,950 m/s. The surfaces of a billet was assumed to be hard wall. A defect, whose diameter is *D,* exists at (*x*, *y*), shown in Fig.1. Input signals were three up-chirp signals, whose frequencies were swept in the ranges, *f* =0.5-1.5, 1.0-3.0, and 2.5-7.5 (MHz) in the durations, 10, 5, 2.5 µs, respectively. Transducers were located at (*x*, 0) and (*x*, 100). The aperture of transducers is 6 mm.

To evaluate relationship between defect size and $\Delta\tau$, a defect was located at center of a cross section (50, 50), and size of the defect *D* was varied from 0 to 10 (mm). **Figure 2** shows $\Delta\tau$ of each conditions. Figure 2 (a) shows the relationship between $\Delta\tau$ and increases as the size of defect *D* becomes larger. From these curves, it is clear that *D* could be estimated by $\Delta\tau$ at least when the defect is located at the center of the cross section.

To evaluate relationship between defect position and $\Delta\tau$, a defect was located at (*x*,50) or (50,*y*). The defect size was 2, 5, and 8 (mm). Figure 2 (b) shows $\Delta\tau$ when defect position of *x* was varied. $\Delta\tau$ increases as defect and surface of billet become closer. This effect becomes larger when lower frequency signal is used. In Fig. 2, shaded area means the range of the position where defect size can be estimated in error range of 1 mm. The ranges wider as signal frequency is higher. The estimation error in defect size can be corrected from estimated defect position *x* and the relationship shown in Fig. 2 (b). However, the error correction and size estimation becomes difficult when defect is near surface because the deviation of $\Delta\tau$ rapidly changes with the position.

Figure 2 (c) shows $\Delta\tau$ when defect position of *y* was varied. These graphs show $\Delta\tau$ deviates when a defect is close to a transducer. Defect size can be estimated only if defect is in a shaded area of the graphs.

## 4. Conclusions

In this paper, we consider relations between defect size, position, and $\Delta\tau$ profile for estimation of defect size. Defect size can be estimated if defect position is known and it is in a limited area by proposed method. If defect position is unknown, defect size cannot be estimated because the defect is possibly near the transducers. For precise defect size estimation, the location of the defect must be known. To know the location, we may use other feature values of $\Delta\tau$ profile or perform a linear scan on other surface of a billet.

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