Research on Ultrasonic TOFD Testing Method of Electron Beam Weld

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Abstract. With the development of aerospace technology, electron beam welding technology has become an important part of the welding field. More and more aircraft and spacecraft parts adopt electron beam welding technology. However, in the process of electron beam welding, due to the influence of the incident angle of the electron beam, the deviation of the weld bead and the electromagnetic field, it is easy to produce defects such as unfused and blowholes. Therefore, it is necessary to conduct a non-destructive testing study on the electron beam weld. Aiming at the characteristics and defects of electron beam welds, the TOFD inspection method of electron beam welds was developed, the basic principles of TOFD inspection were introduced in detail, the TOFD acoustic beam coverage was calculated, and the TOFD inspection of electron beam welds was carried out based on self-developed systems. Experiments show that the ultrasonic TOFD detection method can quickly and accurately detect electron beam welds, which is an effective method for electron beam weld detection.

1. Introduction
Electron beam welding is a fusion welding method that does not add solder. It uses a high-speed, high-energy-density electron beam current to penetrate the material deeply in a vacuum environment. Electron beam welding is widely used in the nuclear industry, aerospace industry, precision machining and heavy machinery due to its high energy density, small heat-affected zone, good organizational performance, and high production efficiency [1]. This welding method is currently the fastest growing and widely used welding technology. However, in the welding process, due to factors such as the incident angle of the electron beam, the deviation of the weld bead, the influence of the electromagnetic field, etc., it is easy to produce defects such as unfused, micro-cracks, pores. These defects will reduce the performance of the welding seam and may cause serious consequences. Therefore, a non-destructive testing study should be carried out on the electron beam-welding seam [2].

At present, the detection of electron beam welds mainly includes X-ray detection and ultrasonic detection methods. X-ray inspection, especially real-time imaging and industrial CT, are intuitive and easy to record for defect display [3]. Compared with other inspection methods, they show great advantages. However, X-ray inspection is not sensitive to longitudinal cracks in the weld, which may cause missed inspections, and the penetration ability of the ray to thick plates is limited. Ultrasonic detection methods include water immersion ultrasonic C-scan, air-coupled ultrasonic detection, phased array ultrasonic detection [4]. Although these detection methods can also detect electron beam welds, the detection speed is slower and the efficiency is relatively low, which cannot meet the requirements of rapid inspection of large electron beam welds, and these inspection methods are not reliable, about
50%-70% [5]. Ultrasonic TOFD inspection technology is a method for detecting defects based on the diffraction energy obtained from the “end angle” and “end point” of the internal defect of the sample to be inspected. Its advantages are high defect detection rate, fast implementation on site, and inspection high efficiency and high reliability, about 75% ~ 90%. In theory, it can detect defects in any direction, the depth of the defect and the accuracy of height measurement, it can regularly monitor the crack propagation, and it can permanently remember the ultrasound imaging view. Therefore, the detection of flat butt welds based on TOFD technology has high detection accuracy and efficiency. Especially for the detection of defects such as cracks with greater harm and unfused layers, the advantages of TOFD technology are more prominent [6].

2. TOFD Inspection Technology
TOFD inspection technology is a method of defect detection and quantification using the difference in the propagation time of diffracted waves at the ends of defects. This technique was proposed by Silk and Lidington of Harwell Laboratory (UKAEA) in the United Kingdom in 1977 based on the phenomenon of ultrasonic diffraction [7].

2.1. Basic Principle of TOFD Detection
As a relatively new ultrasonic inspection technology, TOFD inspection technology is different from the previous pulse reflection method and sound wave penetration method. It uses the diffraction generated by the fastest longitudinal wave in the solid at the defect end for detection [8]. TOFD inspection technology uses two probes for one send and one receive for testing, usually broadband narrow pulse probes, which are symmetrically arranged with respect to the weld or crack centerline [9]. The unfocused longitudinal wave beam generated by the transmitting probe is incident on the workpiece under inspection at a certain angle (the range of incidence angle is usually 45° to 70°), in which part of the beam propagates along the surface and is received by the receiving probe, and part of the beam is reflected by the bottom surface and is received by the probe [10]. The receiving probe determines the position and height of the defect by receiving the diffraction signal at the tip of the defect and its time difference [11], see figure 1.

![Figure 1. Basic principle of TOFD detection.](image)

Set the distance between the sound beam incident points of the two probes 2S, the longitudinal wave velocity is CL. After t1 time, the diffracted wave at the upper end of the defect is received, and after t2 time, the diffracted wave at the lower end of the defect is received. The distance d between the top of the defect and the inspection surface is [12],

$$d = \frac{1}{2} \sqrt{C_L^2 t_1^2 - 4S^2} \quad (1)$$

The height of the defect itself is
When the ultrasonic beam propagates from a high-impedance medium to a low-impedance medium, the beam phase changes after the interface is reflected. If the beam is a negative cycle before it encounters the interface, it changes to a positive cycle after the interface is reflected. As shown in figure 1, when the beam passes through the upper endpoint and the bottom surface, the reflection and phase change at the heterogeneous interface, so the waveform phase is similar. When the beam passes through the lower breakpoint, it is equivalent to that the beam surrounds the bottom of the bottom defect, and the phase does not change.

2.2. TOFD Imaging Method
TOFD imaging is not a display of the actual image shape of the defect, which is not intuitive, but by converting the A-scan data received by the probe during scanning into a grayscale image of black and white [13], as shown in figure 2.

2.3. TOFD Sound Beam Coverage
The TOFD two probes send and receive one at a time. The sound wave propagation process is very different from the sound wave emitted by the phased array. The calculation process is mainly based on the half diffusion angle of the sound field. The ultrasonic wave is emitted from the probe, passes through the interface of the wedge, the wedge and the workpiece to be inspected, and then enters the workpiece. The schematic diagram of the refraction path is shown in figure 3. The calculation process of the range is as follows.
(1) Calculate the half-diffusion angle of the longitudinal beam in the wedge $\theta$.
\[
\theta = \arcsin \frac{F \lambda}{D} = \arcsin \frac{F V_w}{D_f} \quad (3)
\]
where $F$ is the diffusion factor and its value determines the calculation result of the sound beam range, $\lambda$ represents the wavelength in the medium, and $D$ represents the wafer size.

(2) The incident angle $\alpha$ of the central acoustic wave at the interface is equal to the slope of the wedge.
\[
\alpha = \omega \quad (4)
\]

(3) Calculate the incident angles $\alpha_{\text{min}}$ and $\alpha_{\text{max}}$ of the boundary sound beam in the wedge.
\[
\begin{align*}
\alpha_{\text{min}} &= \alpha - \theta \\
\alpha_{\text{max}} &= \alpha + \theta
\end{align*} \quad (5)
\]

(4) According to Snell's law, calculate the sound wave refractions $\beta_{\text{min}}$ and $\beta_{\text{max}}$ in the workpiece.
\[
\begin{align*}
\beta_{\text{min}} &= \arcsin \left( \frac{V_w}{V_p} \sin \alpha_{\text{min}} \right) \\
\beta_{\text{max}} &= \arcsin \left( \frac{V_w}{V_p} \sin \alpha_{\text{max}} \right)
\end{align*} \quad (6)
\]

(5) Calculate the depth coverage of the upper and lower boundary of the acoustic wave in the workpiece.
\[
\begin{align*}
h_{\text{upper}} &= \frac{l_1}{2 \tan \beta_{\text{max}}} \\
h_{\text{lower}} &= \frac{l_2}{2 \tan \beta_{\text{min}}}
\end{align*} \quad (7)
\]
where $h_{\text{upper}}$ is the distance from the upper end of the effective coverage of the acoustic wave to the upper surface of the workpiece, $h_{\text{lower}}$ is the distance from the lower end of the effective coverage of the acoustic wave to the upper surface of the workpiece, and $l$ is the horizontal distance between the two TOFD probes, as shown in figure 4.

Figure 4. TOFD coverage diagram.

3. Sample Test
The hardware system of the TOFD inspection system of the electron beam welding seam is shown in figure 5, which mainly includes an industrial computer, monitor, an ultrasonic board, and an inspection
control system. The workflow of each component is as follows: the application program on the industrial control computer initializes and sets the parameters of the portable Pocket ultrasound board. Fix the TOFD probe on the scanner by pushing the scanner to scan the workpiece. The portable Pocket board stimulates the probe to emit the sound beam and collect data at the same time. The application on the industrial control computer obtains the board through the API interface provided. The data collected by the card and its subsequent processing mainly refers to the calculation and storage of imaging data.

![Figure 5. TOFD inspection system of electron beam welding seam.](image)

### 3.1. TOFD Detection of Electron Beam Simulated Sample

Electron beam simulation welding seam uses electric spark and wire cutting to process artificial linear cracks of different sizes to simulate the reheat crack defects under the base material. The base metal of the test block is ordinary carbon steel, and the surfacing layer is alloy steel. The size is 270mm × 30mm × 40 mm. 35mm, 30mm, 20mm, 10mm, and 5mm heights are processed at equal intervals on the surfacing layer of the test block, and the artificial crack with a width of 2mm is shown in figure 6.

![Figure 6. Electron beam simulated sample.](image)

The frequency of the probe selected in the test is 5MHz, and the diameter of the probe is 6mm. Using longitudinal wave detection, the wedge angle is 30°. The detection scheme is designed through the acoustic beam simulation software. The distance between the center of the transmitting probe and the receiving probe is 92mm. During the inspection, the scanner is held so that the wedge moves slowly from one end to the other side of the sample, as shown in figure 7.

### 3.2. TOFD Inspection of Electron Beam Weld

Figure 8 shows the TOFD inspection of the welding seam of two 20mm thick aluminum plates after electron beam welding. The center frequency of the transducer is 5MHZ and the step of the encoder is 0.5mm. The system was calibrated before testing, including depth calibration and sensitivity.
calibration. The center distance of the two transducers was set to 73mm and the sampling frequency was 250MHZ. Under the above testing parameters, the CTS-1008plus equipment developed by the Shantou Institute of Ultrasonic Instruments was used detection.

**Figure 7.** TOFD testing of electron beam simulated sample.  
**Figure 8.** Aluminum alloy electron beam weld.

### 4. TOFD Test Results

#### 4.1. Electron Beam Simulated Sample Testing Result

According to the above-designed inspection scheme and inspection process, the TOFD inspection of the electron beam welding seam simulation sample is carried out. The inspection result is shown in figure 9. Because TOFD inspection has a near-surface blind zone, the 1# crack is not effectively identified.

**Figure 9.** D-scan results of electron beam simulated sample.

The distance measurement results of each artificial simulated crack from the upper surface of the sample are shown in table 1.

| Crack | Measured Distance (mm) | Actual Distance (mm) | Error (%) |
|-------|------------------------|----------------------|-----------|
| 1#    | 10.375                 | 10.475               | 0.95      |
| 2#    | 12.375                 | 12.475               | 0.77      |
| 3#    | 14.375                 | 14.475               | 0.68      |
| 4#    | 16.375                 | 16.475               | 0.58      |
| 5#    | 18.375                 | 18.475               | 0.55      |

The average difference between the defect distance measured by TOFD inspection and the actual defect distance is 0.7375mm. Figure 10 shows the relationship between the crack distance of TOFD inspection and the actual distance. The maximum error is less than 4%. Therefore, the use of TOFD to detect welds has high accuracy, accurate positioning, high defect detection rate, and defect interpretation is more intuitive. However, TOFD testing is not sensitive to near surface defects, and there are surface blind areas. For example, in this test, the 1# crack was too close to the upper surface, so it cannot be detected.
Table 1. Data record of artificial crack height measurement of TOFD test specimen.

| Crack | Distance from upper surface (mm) | TOFD detection distance (mm) |
|-------|---------------------------------|------------------------------|
| 1#    | 5                               | 0                            |
| 2#    | 10                              | 10.37                        |
| 3#    | 20                              | 20.78                        |
| 4#    | 30                              | 30.92                        |
| 5#    | 35                              | 35.88                        |

Figure 10. TOFD detection measurement distance and error analysis chart.

4.2. Electron Beam Weld Testing Result
Figure 11 shows the TOFD test results of the electron beam welds on the aluminum plate. From the figure, it can be seen that there are defects inside the electron beam welds. The defects can be located by the cursor and the positioning is accurate. It can be concluded that the ultrasonic TOFD detection method is an effective method for electron beam weld inspection.

Figure 11. TOFD test result of aluminum alloy electron beam weld.
5. Conclusion
Ultrasonic TOFD detection technology has the advantages of high reliability, high quantitative accuracy, and fast detection speed. It can achieve fast and accurate detection of electron beam welds, and uses ultrasonic to detect flaws, without any harm to the environment and inspection personnel. It is the future. The reliable technology of electron beam weld inspection will play an increasingly important role in the detection of electron beam welds.

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