Research on the time delay law of water-aluminium alloy interface based on ultrasonic phased array technology

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Abstract. Based on the ultrasonic phased array technology, the time delay law of ultrasonic deflection and focusing at the water-aluminium alloy interface is studied in this paper. By changing the delay time applied on each array element, the immersion ultrasonic phased array technology can realize the preset deflection angle and focusing depth, so as to detect different angles and depth positions of the work piece. The principles of ultrasonic phased array deflection and focusing are studied based on Huygens principle, and the time delay law is obtained when the sound beam is deflected and focused. When ultrasonic waves deflect and focus at the water-aluminium alloy interface, the Matlab software is used to simulate the time delay law and sound field distribution, which verifies the correctness of the design and calculation of the time delay law.

1. Introduction

Aluminium alloy has become the second most widely used metal material in the world due to its light weight, good corrosion resistance and good low temperature resistance [1]. The development of modern industry, transportation, aerospace, medical equipment and many other industries is inseparable from aluminium alloy die casting, and the use of aluminium alloy die casting has covered various fields of social development [2]. In the process of die casting, due to the improper processing technology, the entry of impurities and other reasons, various defects are caused in the die casting work piece. The occurrence of defects will not only cause greater property losses, but also cause major personal safety problems [3]. The common defects of aluminium alloy die casting mainly include holes, inclusions and cracks, and these defects are the main reason of die casting scrap [4].

In recent years, with the rapid development of microelectronics, computer and other high-tech technologies, phased array technology has begun to shift from medical field to industrial detection field [5]. The ultrasonic phased array contains a certain number of array elements. The transmission and reception time of each array element is realized by a computer, which forms the deflection and focusing of the sound beam to detect the defects at different angles and depth positions of the work piece [6]. The ultrasonic phased array technology is used as the detection method for the defects of aluminium alloy die casting, and water is used as the coupling agent. The probe and the aluminium alloy die casting are all immersed in the water for detection. Water as the coupling agent during the detection eliminates the phenomenon of poor coupling effect. At the same time, it can reduce the wear of probe, and improve the accuracy and efficiency of detection [7]. Stratoudaki T et al [8] improved
the acquisition method of full matrix capture data and the imaging algorithm of full focus post-processing by combining laser technology with phased array, and established a model to verify that the combination of laser and phased array can increase the accuracy of defect detection. Bolotina I et al [9] developed a method for detecting pipelines using phased array technology. The resolution of the detection system developed using this method was two times higher than before and the accuracy was higher. The pattern of the array was studied, and the experiment results were obtained. Brizuela J et al [10] combined the three ultrasonic technologies of phased array receiving dynamic depth focus, synthetic aperture focus and phase coherent imaging, and developed a method that can better image the results. The simulation and experimental analysis of the imaging method were carried out. Ma Hongwei et al [11] of Xi’an University of Science and Technology studied and calculated the time delay law of one-dimensional linear phased array. Through the preset deflection angle and focusing depth of ultrasonic beam, the delay time of each array element was calculated, and the ultrasonic space pulse response generated by each array element was summed, so as to obtain the sound pressure value at any place in the sound field space. Water immersion ultrasonic phased array can realize the deflection and focusing of sound beam flexibly, and has a good detection effect on the defects of aluminium alloy die casting. To achieve accurate deflection angle and focusing depth, the delay time required by each element must be accurate. Therefore, the time delay law of water immersion ultrasonic phased array in the detection of aluminium alloy die casting is studied.

2. Deflection principle and focusing principle of ultrasonic phased array

When ultrasonic phased array technology is used to detect the defects, different delay time is applied to each array element by industrial computer to form preset sound beam effect. Due to the time difference between the transmission and reception of each array element, the ultrasonic beams emitted by each array element will produce different phase relations in the sound field so that the sound beams superimpose or cancel each other. Because of the superposition or cancellation of sound beams in the sound field, the ultrasonic sound beam is deflected and focused.

Deflected sound beam: When the transducer emits ultrasonic wave, the delay time of the excitation between each array element is equal interval, and each sub beam is superposed and cancelled in the sound field, thus forming the phenomenon of ultrasonic beam deflection [12]. As shown in figure 1.

![Figure1. Deflection of ultrasonic beam.](image1)

Focused sound beam: When the transducer emits ultrasonic wave, the time applied to each element increases from both sides of the element to the central element in turn, that is, the delay time of the central element is the longest of all elements [13]. Because of the superposition and cancellation of the sound beams generated by each array element, the wave front of each element will eventually converge at a point. As shown in figure 2.

![Figure 2. Focusing of ultrasonic beam.](image2)

3. Research on the time delay law at water-aluminium alloy interface

During the detection of aluminium alloy die casting by water immersion ultrasonic phased array, the defects of aluminium alloy die casting are detected by submerging the probe and work piece in the water tank. There is a certain water distance between the probe and the work piece in the water tank. When the ultrasonic wave propagates from the water to the interface between the water and the die
casting, due to the difference of sound speed, it will produce reflection and refraction. Based on the calculation of time delay law of deflection and focusing for single medium aluminium alloy die casting, the time delay law for water-aluminium alloy die casting interface is studied.

3.1. Research on the time delay law of ultrasonic wave deflection at the water-aluminum alloy interface

When the phased array probe is placed in the water to detect the work piece, or when the phased array probe is placed on the wedge to detect the work piece, figure 3 can be used to simulate the sound beam deflection to study the time delay law.

![Figure 3. Acoustic beam deflection at liquid-solid interface.](image)

Where $\rho_1$ is the density of liquid, $\rho_2$ is the density of solid, $c_1$ is the speed of sound beam in liquid, $c_2$ is the speed of sound beam in solid, and $\alpha$ is the angle between the phased array element and the liquid-solid interface. Assuming that there is no deflection of the phased array probe, the deflection angle in the liquid is $\theta_{10}$, the refraction angle in the solid is $\beta$, when the deflection angle in the liquid is $\theta_{10}$, and the refraction angle in the solid is $\beta_{20}$, then $\theta_{10} - \alpha$ is the deflection angle of the ultrasonic phased array probe in the liquid medium. According to Snell's theorem:

$$\frac{\sin \beta_{20}}{c_2} = \frac{\sin \theta_{10}}{c_1}$$

(1)

From equation (1), we can know the value of $\theta_{10}$. $\theta_{10}$ is the deflection angle of phased array probe in liquid medium, if the first array element is taken as the starting array element and $S_i$ is the sound path difference between the array element $i$ and the starting array element, the delay time of array element $i$ is expressed as follows:

$$T_i = \frac{S_i}{c_1} = \frac{d(i-1)\sin(\theta_{10} - \alpha)}{c_1}$$

(2)

![Figure 4. Acoustic beam deflection 30°.](image)
Figure 4 shows the time delay law that each array element needs to apply and sound field distribution when the transducer array element number is 32, the distance between the centers of two array elements is 0.6mm, the water distance is set to 10 mm, and the deflection angle is 30°. It can be seen from the sound field distribution that the deflection angle of 30° is formed in the aluminum alloy die casting after the sound beam passes through the water-aluminum alloy interface, so the calculation of the deflection angle of the water-aluminum alloy interface is correct.

3.2. Research on the time delay law of ultrasonic focusing at the water-aluminum alloy interface

In order to study the time delay law of sound beam deflection and focusing at the water-aluminum alloy interface, the propagation path from the center of the array element and the element N-1 to the focal point F is simulated. Based on the theory of single medium deflection and focusing, the time delay law of deflection and focusing of each element at the water-aluminum alloy interface is deduced.

![Diagram of acoustic beam deflection and focusing at liquid-solid interface](image)

Figure 5. Deflection and focusing of acoustic beam at liquid-solid interface.

It can be seen from figure 5 that since the propagation of sound beam conforms to Snell's law, the value of θ10 can be determined by equation (1). The position of point A at the liquid-solid interface and the value of D30 can be determined. The value of D20 and the D30 can be obtained by

\[
D_{20} = D_{10} \tan \theta_{10} \tag{3}
\]

\[
D_{30} = D_{20} + D_f \tan \beta_{10} \tag{4}
\]

The distance from the center of element N-1 to the center of element i is \(e_{N-1}\), the vertical distance to the liquid-solid interface is \(D_{11}\), and the horizontal distance to the focus is \(D_{31}\). The value of \(D_{11}\) and the \(D_{31}\) can be obtained by

\[
D_{11} = D_{10} + e_{N-1} \sin \alpha \tag{5}
\]

\[
D_{31} = D_{30} - e_{N-1} \cos \alpha \tag{6}
\]

The distance from the center of element N-1 to the center of element i can be written as

\[
e_{N-1} = \left[ (N-1) - N - \frac{1}{2} \right] d \tag{7}
\]

According to Snell's theorem

\[
\frac{\sin \beta_{20}}{c_2} = \frac{\sin \theta_{20}}{c_1} = 0 \tag{8}
\]

The equation (8) can be written as
The fourth-order equation about $D_{21}$ is obtained by square the two sides of equation (9). When $\alpha$, $N$, $d$, $D_{10}$, $D_f$, $c_1$, $c_2$ are given to solve it, a satisfactory solution can be obtained, that is, $D_{21}$ can be determined. Then the expression of the delay time of array element $N$-1 is

$$T_{N-1} = \frac{\sqrt{D_{21}^2 + D_{11}^2}}{c_1} + \frac{\sqrt{D_f^2 + (D_{11} - D_{21})^2}}{c_2}$$

(10)

The delay time of each element can be obtained by taking the distance $e$ that from the center of the array to the center of different elements into the formula. Since the aluminum alloy die casting and the probe are immersed in the water tank during the defect detection, and the phased array probe surface is parallel to the work piece surface, the value of $\alpha$ should be set to 0, the value of $c_1$ should be set to 1480m/s, and the value of $c_2$ should be set to 6260m/s during simulation. The value of $D$ is set to 32. $D_f$ is the focal depth, and $D_{10}$ is the water distance during detection. The water distance of the scan is set to 10mm, and the focal depth is set to 30mm to simulate the time delay law and the sound field distribution.

![Figure 6. acoustic beam focus 30mm.](image1)

![Figure 7. acoustic beam deflection 30° focus 30mm.](image2)

Figure 6 shows the delay time and sound field distribution of the array element when the transducer aperture is 32, the water distance is 10 mm, the focal depth is 30 mm, and the probe incident at a vertical angle. Figure 7 shows the delay time and sound field distribution of the array element when the transducer aperture is 32, the water distance is 10 mm, the deflection is 30° and the focal depth is 30 mm, and the probe is incident at a vertical angle. According to figure 6 and figure 7, when the sound beam propagates at the water-aluminium alloy interface, the preset deflection angle and focusing can...
be achieved by the design of time delay law. Therefore, the correctness of design and calculation of time delay law is verified.

4. Conclusion
The principles of deflection and focusing of ultrasonic phased array are analyzed based on Huygens principle, and the time delay law of ultrasonic wave propagating at water-aluminium alloy interface is studied. The time delay law of deflection and focusing of sound beam and the sound field distribution at the water-aluminium alloy interface are simulated by MATLAB software, and the correctness of the calculation of the time delay law is verified. In the next step of work, the time delay law of ultrasonic wave propagating needs to be further verified at water-aluminium alloy interface in the actual industrial detection process.

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