Research on quality inspection model of spot welding of equal-thickness three-layer sheets based on ultrasonic A-scan

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Abstract. To judge the spot welding quality automatically and effectively, this thesis uses the conventional ultrasonic A-scanning to study the mathematical model of nugget diameter for equal-thickness three-layer sheets. The finite element simulation model of the spot welding ultrasonic nondestructive (NDT) testing for equal-thickness three-layer low carbon sheets is established. The calculated values of the nugget diameter between different laminates are studied. Finally, the experiment of the spot welding ultrasonic nondestructive testing is carried out. This thesis verifies the correctness of the finite element simulation and the mathematical calculation model. The research results are of great significance to ultrasonic automatic inspection technology of spot welding.

1. Introduction
According to the requirements of automobile body design structure technology, multilayer resistance spot welding is widely used in many important structural parts, such as front rail, column A, B, C and so on. According to statistics, there are at least 20 spot welding of multilayer boards in the frame alone [1]. In three-layer sheets resistance spot welding, compared with the conventional two-layer sheets, quality problems such as too small welding spot diameter, virtual welding, missing welding, surface crack and deep welding indentation are more likely to occur, which seriously affect the quality of automobile manufacturing [2-4]. At present, for the spot welding quality problem of three-layer sheets, post-welding treatment is generally adopted, which affects the production efficiency of automobile and the surface quality of spot welding. However, ultrasonic nondestructive testing technology has a great prospect in the online evaluation of welding spot quality of automobile.

Traditional ultrasonic testing methods for spot welding include A-scan and C-scan. A-scan can identify various kinds of defects according to the characteristics of reflected oscillogram and spot welding quality assessment. C-scan mainly uses images to measure the nugget diameter. But the equipment is relatively complex, the scanning time is long, the result of the imaging processing method and the fusion quality assessment of nuclear technology remain to be perfect [5]. It is not applicable to on-line automatic detection [6].

In this paper, ultrasonic nondestructive testing of spot welding is carried out to obtain A-scan. According to the characteristics of oscillogram, theoretical analysis is carried out to obtain the calculation of nugget diameter. Then establishing the finite element model of spot welding ultrasonic nondestructive testing to study the characteristics of different size of the weld with equal-thickness three-layer sheets. Finally, the experiment of the spot welding ultrasonic nondestructive testing is carried out to verify the correctness of the mathematical model and finite element model.
2. Mathematic Model of Weld Nugget Diameter of Equal-thickness Three-layer Sheets Based on A-Scan Oscillogram

Figure 1a shows the schematic diagram of ultrasonic nondestructive testing for spot welding of equal-thickness three-layer sheets. Based on the principle of reflection and transmission of ultrasonic waves, initial waves sent by the transducer will propagate in the delay block and reflect on four surfaces: a, b, c and d as shown in Figure 1b, which respectively represent the bottom of delay block, the first faying surface, the second faying surface and bottom of the second spot weld. $P_a$, $P_b$, $P_c$ and $P_d$ respectively refer to the reflected waves at a, b, c and d.

![Figure 1. a Ultrasonic testing of the spot weld, b Ultrasonic propagation paths in the spot weld](image)

When $d_1 > D$, $d_2 < d_1$, the value of $P_b$ is zero, the value of $P_c$ represents acoustic waves reflected at bottom of the second sheet which refers to the difference between the area of the first nugget and the second nugget. The value of $P_d$ represents acoustic waves reflected at bottom of the third sheet which represents the area of the second nugget. When $d_2 \geq d_1$, the values of $P_b$ and $P_c$ are zero, the value of $P_d$ indicates the area of the second nugget.

When $d_1 \leq D$, $d_2 < d_1$, it is obvious that the value of $P_b$ increases which represents acoustic waves reflected at bottom of the first sheet which refers to the difference between the area of the delay block and the first nugget. When $d_2 \geq d_1$, the value of $P_b$ is not zero, and the value of $P_c$ is also zero, the value of $P_d$ indicates the area of the second nugget. The values of $P_b$, $P_c$ and $P_d$ satisfy:

$$\begin{align*}
  P_b / P_a &= (D^2 - d_1^2) / (d_1^2 - d_2^2) \\
  P_c / P_d &= (d_1^2 - d_2^2) / d_2^2
\end{align*}$$

(1)

To express this relationship, two parameters $k$ and $\lambda$ are defined as equation (2) and equation (3) show [7]:

$$k = \begin{cases} 
  d_1^2 / D^2 & d_1 < D \\
  1 & d_1 \geq D
\end{cases}$$

(2)

$$\lambda = \begin{cases} 
  d_2^2 / d_1^2 & d_2 < d_1 \\
  1 & d_2 \geq d_1
\end{cases}$$

(3)

The Gaussian pulse is generated by the transducer:

$$g(t) = Ae^{-\left(\sigma f(t-t_p)\right)^2}$$

(4)
The pulse round-trip time in delay block $\tau_1$ and in single sheet $\tau_2$ respectively satisfy $\tau_1 = 2l / c_1$ and $\tau_2 = 2h / c_2$. In the case that time delay of $P_{a_1}$, $P_{b_1}$, $P_{c_1}$ and $P_{d_1}$ are respectively $i\tau_1$, $\tau_1 + i\tau_2$, $\tau_1 + 2i\tau_2$ and $\tau_1 + 3i\tau_2$. What’s more, due to the equal thickness, $P_{b_2}$, $P_{c_2}$ and $P_{d_2}$ have the same time delay as Figure 3 shows. The absolute acoustic pressure $P(t)$ can be deduced as follows:

$$P(t) = P_0(t) + \sum\left| P_{a_1} + P_{b_1} + P_{c_1} + P_{d_1} \right| = g(t) + \sum_{j=1}^{\infty} \left\{ r_1^j g(t - j\tau_1) + \sum_{i=1}^{\infty} t_i^j t_1^{+3} \right\}$$

$$\left[ (1-k) g(t - j\tau_1 - i\tau_2) + (k - \lambda) g(t - j\tau_1 - 2i\tau_2) + \lambda g(t - j\tau_1 - 3i\tau_2) \right]$$

$$P(t) = \left\{ \begin{array}{ll}
\kappa_1 = P_1 / P_2 \\
\kappa_2 = P_2 / P_3
\end{array} \right.$$

$$\begin{align*}
d_1 &= \frac{D\sqrt{1+k_1}}{\sqrt{1+k_2+k_1k_2}} \\
d_2 &= \frac{D}{\sqrt{1+k_2+k_1k_2}}
\end{align*}$$

Figure 2a shows the calculated curve of equation (5) when $k = 0.62$, $\lambda = 0.25$, it illustrates the relationship between the pressure amplitude and time. $P_1$ is $P_{a_1}$, $P_2$ is $P_{c_1}$ and $P_3$ is $P_{d_1}$. Defining $\kappa_1$ as the ratio of $P_1$ to $P_2$, $\kappa_2$ as the ratio of $P_2$ to $P_3$ (equation 6), nugget diameter $d_1$ and $d_2$ can be deduced based on equations (1-3) and (6):

When $k = 0.62$, $\lambda = 1$, the relationship between the pressure amplitude and time is shown as Figure 2b shown.

When $d_1 \leq d_2$, according to the analysis, the value of $P_{a_1}$ represents the area of the first nugget, however the value of $P_{c_1}$ is zero. The value of $P_{b_1}$ refers to the difference between the area of the delay block and the first nugget. Defining $\kappa_3$ as the ratio of $P_1$ to $P_3$, nugget diameter $d_1$ can be deduced based on equation (8):

$$\begin{align*}
P_{a_1} / P_{d_1} &= (D^2 - d_1^2) / d_1^2 \\
\kappa_3 &= P_1 / P_3 \\
d_1 &= D / \sqrt{1+k_3}
\end{align*}$$
In this case, $d_2$ cannot be calculated, but the three-layer sheets can be inverted to calculate the nugget diameter.

3. Simulation and Analysis

3.1. Geometry

Spot welding process of ultrasonic nondestructive testing of simulation involves the sound field. Acoustic simulation models of ultrasonic nondestructive testing for spot welding of equal-thickness three-layer sheets are established in COMSOL. Then the pressure amplitude-time relationship of the acoustic waves can be obtained. According to the relationship between acoustic pressure and nugget diameter, the nugget diameter can be calculated.

The finite element method is used to analyze the propagation mechanism of acoustic waves in the weld. The 2D model is established to study the oscillogram of ultrasonic nondestructive testing for spot welding of equal-thickness three-layer sheets and the calculation time can be saved.

3.2. Results and discussion

When $h=1.0\text{mm}$, $d_1=6\text{mm}$, $d_2=5\text{mm}$, the pressure amplitude-time relationship of the acoustic waves can be obtained in Figure 3.

![Figure 3. Received ultrasonic signals in simulations when $d_1=6\text{mm}$, $d_2=5\text{mm}$](image)

It’s obvious that the value of $P_1$ is maximal because of most of the acoustic waves reflected and received at the bottom of delay block, others pass into the sheets. Due to $d_1\leq D$, the value of $P_1$ refers to fewer transmitted waves reflected at the first faying surface. Because of $d_2<d_1$, fewer transmitted waves reflected at the second faying surface, a smaller echo $P_2$ is formed. Most of the residual transmitted waves go through the second weld, a larger echo $P_3$ is formed. In theory, the value of $P_3$ is larger than that of $P_1$ and $P_2$, the value of $P_1$ is also larger than that of $P_2$. However, the value of $P_1$ is approximately the same as the value of $P_2$ in Figure 3. Because of the same thickness of the three layers, part of the reflected waves at the bottom of the first faying surface is formed as $P_1$, the other part of reflected waves generates a second echo, which overlap with the reflected waves of the second faying surface, making the value of $P_2$ larger. Similarly, reflected waves generate a third echo at the bottom of the first faying surface, which overlap with the reflected waves of the second faying surface, making the value of $P_3$ larger.

Since the value of $P_1$, $P_2$ and $P_3$ are certain in Figure 5, the weld nugget diameter $d_1$ and $d_2$ can be calculated by equation (6) and equation (7). According to the calculation, $d_1=6.87\text{mm}$, $d_2=6.06\text{mm}$. Due to the values of $P_2$ and $P_3$ are larger, the value of $k_1$ is significantly smaller, $d_1$ and $d_2$ are both significantly larger.
When \( h=1.0 \text{mm}, \ d_1=6 \text{mm}, \ d_2=7 \text{mm} \), because of \( d_1 \leq D \), the value of \( P_1 \) refers to fewer transmitted waves reflected at the first faying surface. Because of \( d_2 > d_1 \), no transmitted waves reflected at the second faying surface, the value of \( P_2 \) is zero. Most of the residual transmitted waves go through the second weld, a larger echo \( P_3 \) is formed. However, the value of \( P_2 \) is not zero in Figure 4. Because of the same thickness of the three layers, part of the reflected waves at the bottom of the first faying surface is formed as \( P_1 \), the other part of reflected waves generates a second echo, which overlap with the reflected waves of the second faying surface, making the value of \( P_2 \) not zero.

Since the value of \( P_1, P_2 \) and \( P_3 \) are certain in Figure 4, the weld nugget diameter \( d_1 \) can be calculated by equation (8). According to the calculation, \( d_1=6.77 \text{mm} \). Due to the values of \( P_2 \) and \( P_3 \) are larger, the value of \( k \) is significantly smaller, \( d_1 \) is significantly larger. Because of \( d_2 > d_1 \), the value of \( d_2 \) can be calculated by changing the probe to the surface of the third layer plate (opposite of the spot weld) and testing again.

When \( h=1.0 \text{mm}, \ d_1=5 \text{mm}, \ d_2=5 \text{mm} \), due to \( d_1 \leq D, \ d_1=d_2 \), no acoustic waves reflected at the second faying surface, the value of \( P_2 \) is theoretically zero. Most of the residual transmitted waves go through the second nugget, a larger echo \( P_3 \) is formed. However, the value of \( P_2 \) is not zero in Figure 5. Because of the same thickness of the three layers, part of the reflected waves at the bottom of the first faying surface is formed as \( P_1 \), the other part of reflected waves generates a second echo, which overlap with the reflected waves of the second faying surface, making the value of \( P_2 \) not zero.

The weld nugget diameter \( d_1 \) can be calculated by equation (8). According to the calculation, \( d_1=6.27 \text{mm} \). Because of \( d_1=d_2 \), the value of \( d_2 \) can be calculated by changing the probe to the surface of the third layer plate (opposite of the spot weld) and testing again.
4. Verification of Testing Results
Rectangular low-carbon steel plate is selected in this experiment, with the sheet sample 30×100 mm. The thickness of the selected material for spot welding of three layers of plate is 1mm. The experimental instrument includes an ultrasonic detector and an ultrasonic probe. The detector is produced by Guangzhou Doppler Company. The frequency of the ultrasonic probe is 15MHZ. The diameter and the length of delay block are 7.6mm and 12.7mm.

4.1. Comparative analysis of experimental and simulated oscillogram
For the three-layer plate spot welding sample, firstly, an ultrasonic nondestructive detector is used to detect the spot weld. The A-scan oscillogram is acquired as shown in Figure 6a. The acoustic pressure of received waves in simulations is obtained in Figure 6b when \(d_1=6\text{mm}, d_2=5\text{mm}\).

![Figure 6. When \(d_1=6\text{mm}, d_2=5\text{mm}\) a A-scan oscillogram b Simulated oscillogram](image)

Comparing the above two oscillograms, it can be found that the experimental and simulated oscillograms are roughly consistent. In Figure 6b, \(P_1\), \(P_2\) and \(P_3\) are concern to calculate the nugget diameter (equation 6), (equation 7) and (equation 8). The values of \(P_1\) and \(P_2\) are smaller, the value of \(P_3\) is larger. The finite element model of ultrasonic nondestructive testing for spot welding of equal-thickness three-layer plates is verified.

4.2. Comparative analysis of ultrasonic nondestructive testing and metallographic testing
The macrograph and the detecting oscillogram of the weld are shown in Figure 7.

![Figure 7. Macrograph and oscillogram of the weld](image)

Figure 7a shows when \(d_1>d_2\), the first and second echoes both exist, and the peak value of the first echo is larger than the second. Figure 7b shows when \(d_1=d_2\) approximately, the first echo exists, and
the peak value of the second echo is smaller, because the second echo is theoretically zero but the first small echo generating a second echo. Figure 7c shows when $d_1<d_2$, a first echo and a second echo with a smaller peak value exist, because the second echo is theoretically zero but the first echo generating a second echo. The overall trend of oscillograms is basically consistent with the finite element simulation results.

The nugget diameter is the decisive factor of spot welding quality. The simulation results in Figure 3-5 show the calculated values are approximately consistent with actual values, which may be caused by the diffraction, attenuation and other factors. The existing experimental results verify this testing and calculating method can ensure the applicable accuracy to judge the spot welding quality.

5. Conclusions

Based on the basic principle of reflection, transmission and attenuation of acoustic wave propagating in spot weld, analyzing the relationship between acoustic pressure and the size of spot welding, the mathematical model of ultrasonic nondestructive testing of spot welding of equal-thickness three-layer sheets is established.

A finite element analysis model of ultrasonic nondestructive testing of spot welding of equal-thickness three-layer sheets is established. The simulation results show that when $d_1>d_2$, the nugget diameter $d_1$ and $d_2$ can be calculated. When $d_2\geq d_1$, only $d_1$ can be calculated, $d_2$ can be calculated by changing the probe to the surface of the third layer plate.

The experimental results show that it is consistent with the simulated oscillograms, which verifies the validity of NDT finite element model and mathematical calculation model for the spot welding of equal-thickness three-layer sheets. The research results are of great significance to ultrasonic automatic inspection technology of spot welding.

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