

A Review of Ultrasonic Testing Applications in Spot Welding: Defect Evaluation in Experimental and Simulation Results

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Abstract Today, spot welding plays a special role in many engineering industries. Important industries such as automobiles use this method to connect different parts of sheets in the car body. The most important part of spot welding is to ensure that the weld is healthy, and it is very important and the best way to inspect using non-destructive tests. Ultrasonic testing (UT) has a high ability to detect defects in spot welding. The present article intends to review the ultrasonic testing techniques used in spot welding. The importance of fault detection and interpretation of defect signals in the ultrasonic test and the time of obtaining the defect for this weld have been reviewed. In the present paper, most of the proposed stainless steel and aluminum sheets have been inspected by spot welding and accurate results are available. The best mechanism and method for measuring their defects according to time calculations is proposed. It is easier to detect access defect echo and way of detecting it in the experimental test. For all sheets, cracking, porosity and single pore defects have been investigated and reported. The simulation process for all defects is also classified and brought according to the defect echo time calculations to ensure the experimental method. The choice of ultrasonic testing methods in the detection of defects is a new and good method. The spot welding process depends on non-destructive testing and the capabilities and techniques of ultrasound.

Keywords Spot welding · Non-destructive testing · Ultrasonic testing · Experimental test · Defect · Simulation

1 Introduction

Spot welding is a method in the field of resistance welding. In this category of welding, due to the electrical and thermal resistance of the material, welding is performed [1–3]. In this way, at a certain point of the two pieces, for example, two sheets tangent to each other by increasing the electrical resistance, it increases the temperature to the degree of melting of the material and welding is performed [4, 5]. This method is mostly used for welding metal plates and sheets [6]. After the temperature rises to a melting point due to electrical resistance, a connection is made at that point by applying pressure, and thus spot welding is performed [7]. The main application of spot welding is in places where parts are not accessible, like the middle of two plates or sheets, for example, in connecting two parts of a car body [8, 9]. For this weld, sensors can even be identified to prevent their occurrence [10–13]. Ultrasonic testing is one of the most accurate non-destructive testing methods used for spot welding inspection [1, 13]. In ultrasonic test, high-frequency sound waves (in the range of MHz) are inserted into the sample or sheet under inspection to identify internal defects and check the properties of the material. Sound waves move inside the material due to the phenomenon of sound attenuation, and they are reflected in the joints and boundaries [14]. The ultrasonic testing welding test involves examining the reflected echoes to identify defects and determine their position, as well as quantitative assessments, tracking and analysis [15]. Nowadays, due to the high penetration power of ultrasonic waves entering the workpiece to identify defects and the high sensitivity of the relevant equipment, ultrasonic testing has a relatively low cost and a suitable speed of operation to control the quality of the parts [16]. In 2009, Chen et al. investigated the ultrasonic evaluation of spot welding for two layers of identical coated stainless steel

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sheets. Based on the analysis of the wavelet transform, they concluded that by using the wavelet transform, the effect of the random signal and the accident factor that occurred in the ultrasonic test is reduced, and the localization and the event factor for the porosity defect and crack are increased [17]. In 2015, Liu and his colleagues analyzed and investigated the ultrasonic test for spot welding in two layers of identical coated stainless steel sheets. Based on the wavelet packets, they concluded that the method based on the analysis of wavelet packets in the time–frequency domain can easily quantitatively evaluate the defect by extracting high-frequency signals in different spot welding positions [18]. In 2019, Hua and Wang investigated the detection quality of ultrasonic waves in spot welding using an embedded transducer and found that the correct detection rate of in situ ultrasonic waves can be close to 96% [19].

Reviewing of article discusses the use of ultrasonic testing techniques for spot welding inspection, both simulation and experimental testing. The purpose of the present manuscript is to address the ultrasonic testing method used to detect defects in spot welding. Considering that few researches have been done in the field of spot welding of aluminum alloys and stainless steels and investigating the defects caused by welding, in this article, the connection of the mentioned alloys and then the study of the defects of porosity and cracks for these connections by using a non-destructive method have been discussed. Ultrasonic

has been checked. Due to the fact that the non-destructive analysis of the defects of this welding has received little attention, this article has tried to fully investigate these defects and the shape of the echoes received from ultrasonic waves and analyze them using finite element analysis in the COMSOL software environment. The experimental results and the finite element provide a very acceptable match, and in point of view, the above article provides complete and comprehensive results compared to previous researches.

2 Spot Welding

2.1 Processes and Defects

In spot welding, various defects are created in the sheets, and identification of these defects can be useful for the industry. The problems of spot welding have their own reason that if the issues are not observed during welding, it will cause damage to the welded part and piece [20]. Some of these defects are potentially affected by these conditions such as cracks and holes, splashes and burns, unstable weld quality, apparent quality mismatch with the healthy part, porosity and single pore, weld adhesion, weak weld core, loose detection by manual movement quality equipment, workplace issues, costs, breakdowns (maintenance on the production line), maintenance, efficiency [1, 21–23]. To provide the basics of defect interpretation, the porosity defects, crack defects and single pore defects have been investigated. Figure 1 shows a schematic of the spot welding process. According to the shape of the welded samples in Fig. 2, sample 3 shows the best type of spot welding in terms of quality for stainless steel sheets,

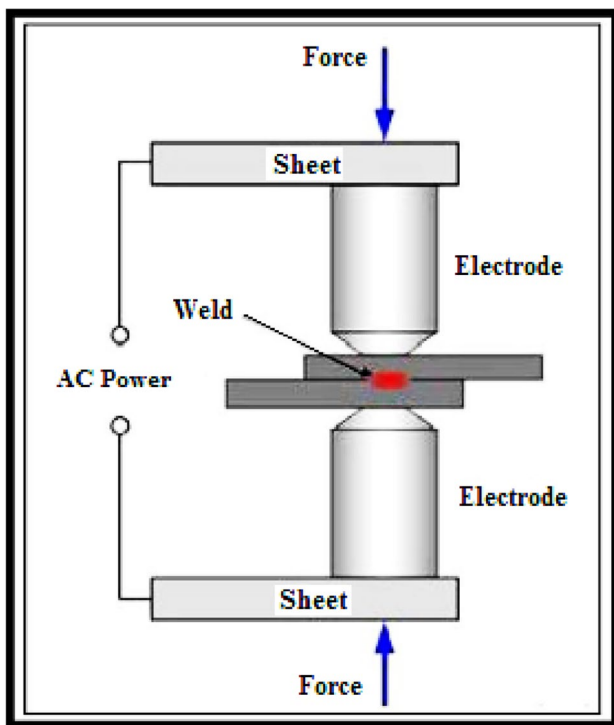


Fig. 1 Schematic view of the spot welding process [15]



Fig. 2 Welded samples of stainless steel sheet [1]



Fig. 3 Aluminum sheet welded sample [3]

and in Fig. 3, sample 2 shows the best type of spot welding in terms of quality for aluminum sheets.

3 Ultrasonic Testing

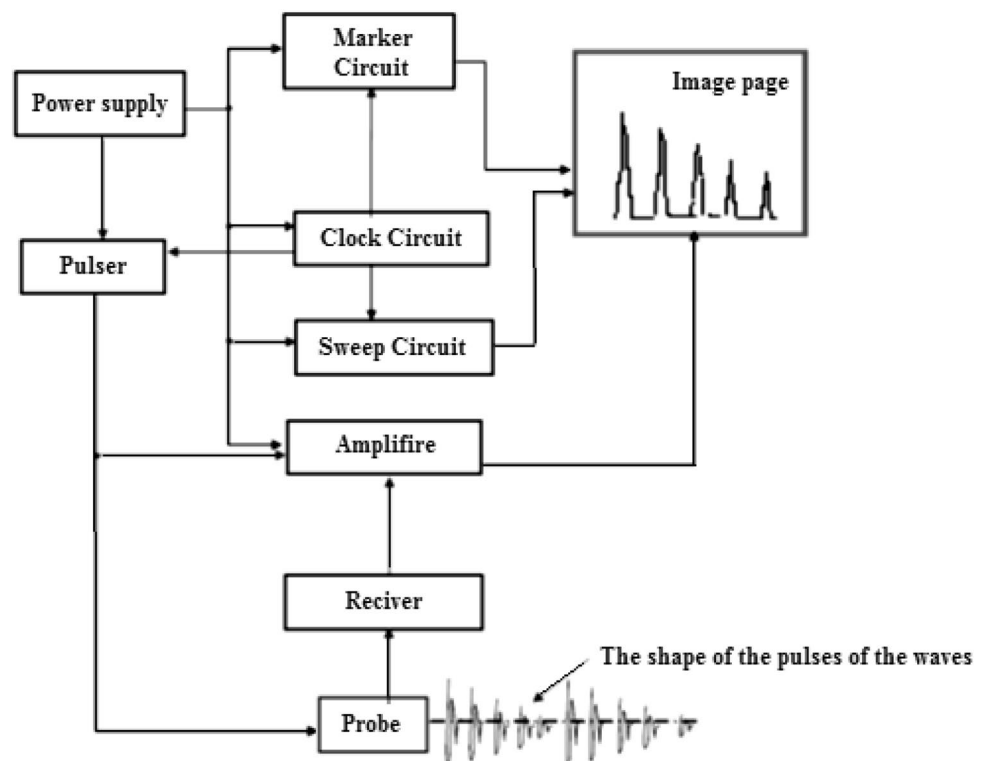
One of the inspection methods and techniques for spot welding is non-destructive testing and ultrasonic testing. This method is used to evaluate and diagnose internal defects such as cracks and porosities [24, 25]. In ultrasonic experiments, ultrasonic waves are emitted into a test piece and their interaction with defects is used to identify and evaluate defects [26, 27]. Ultrasonic testing can be performed in two modes of contact or immersion. In the contact state, the ultrasonic probe is in direct contact with the test piece, while in the immersion test, a column of water is located between the probe and the test piece [28, 29]. In most contact tests, a thin layer is applied to the test surface to facilitate the transmission of ultrasonic waves to the material. In the contact method, the probe is in direct contact with the surface of the part. In order to eliminate the air gap between the probe and the work piece surface and better transfer of sound energy, it uses a liquid called coupling. In the ultrasonic test method, different couplings are used in order for the probe to have better contact with the surface of the part. Common coupling include oil, grease, glycerin, water, liquid soap

and a mixture of wallpaper glue and water [27–30]. In this review article, ultrasonic immersion method is considered. Figure 4 shows the schematic and the A-scan system.

3.1 Ultrasonic Testing in Spot Welding

The ultrasonic device generates timing electrical pulses and transmits them into the transducer via a coaxial cable. The probe converts electrical pulses into high-frequency sound waves (usually 1–10 MHz) and transmits them into the part under test. It is an environment in which the density or speed of sound propagation is different from the original environment. If the direction of the reflector is perpendicular to the direction of the sound, the reflected sound returns to the probe [1, 30]. But the remarkable advantage of the ultrasonic method is the ability to evaluate all three dimensions of a defect without limitation of distance and thickness [30–33]. The speed of ultrasonic waves, as mentioned before, depends on the physical parameters of the material environment. When an elastic material vibrates, each particle of the material oscillates around its equilibrium point at a certain elastic velocity and transmits its kinetic force to the adjacent particle [34, 35]. Ultrasound test is one of the relatively advanced tests in the category of non-destructive tests. This method is fast and is able to detect internal defects without the need to destroy the welded part. Because this method is closely controlled, it has the ability to provide accurate and

Fig. 4 Schematic and how A-scan works [1, 39]



required information of the welded part, without the need for a series of laborious operations [36]. Even for operations that we do not have access to, this process can be controlled through ocular sensors [37]. This method identifies, locates and measures both surface defects and internal defects of the part. Ultrasonic testing is performed by a wave emitted from a transmitter of a specified wavelength and frequency. Ultrasonic waves are passed through the test piece and are reflected by any change in the piece. The reflected waves appear on the screen of the device as protrusions relative to the baseline [38]. A-scan system for the ultrasonic test in Fig. 5 (a) and (b) shows for spot welding [15]

3.2 Interpretation of Oscilloscope Image Page Pulses

By interpreting the state of each pulse on the image screen, some of the geometric properties of the defects can be understood. In order to prepare the ground for the interpretation of defects, it is necessary to examine the types of defect reaction pulses in the image screen at the beginning of this section and define each pulse in the form of a set of changes and reactions with a specific model [40, 41].

3.3 Pulse Models

In order to facilitate subsequent references, any signal that appears as a result of the reaction of the waves in collision with an obstacle or defect in the image of the ultrasonic device, it is called a pulse model. Each pulse is distinguished from other pulses by characteristics such as amplitude, width, number of oscillations and teeth and because each pulse model has a special feature, it is introduced with a model number. To introduce the types of pulse models, the three main features were examined including the wavelength cross section, the pulse view on the ultrasonic device image plane and the wave amplitude oscillation model on the oscilloscope plane. Several tests and different techniques were used to define each model [40, 41].

3.4 Types of Pulse Models in Spot Welding

3.4.1 Pulse Models One

This pulse model is created by the collision of waves with round and spherical defects. Model 1 pulse amplitude occurs with a rapid ascending and descending cycle without time delay (Fig. 6a). The pulse shape of model one is seen in the

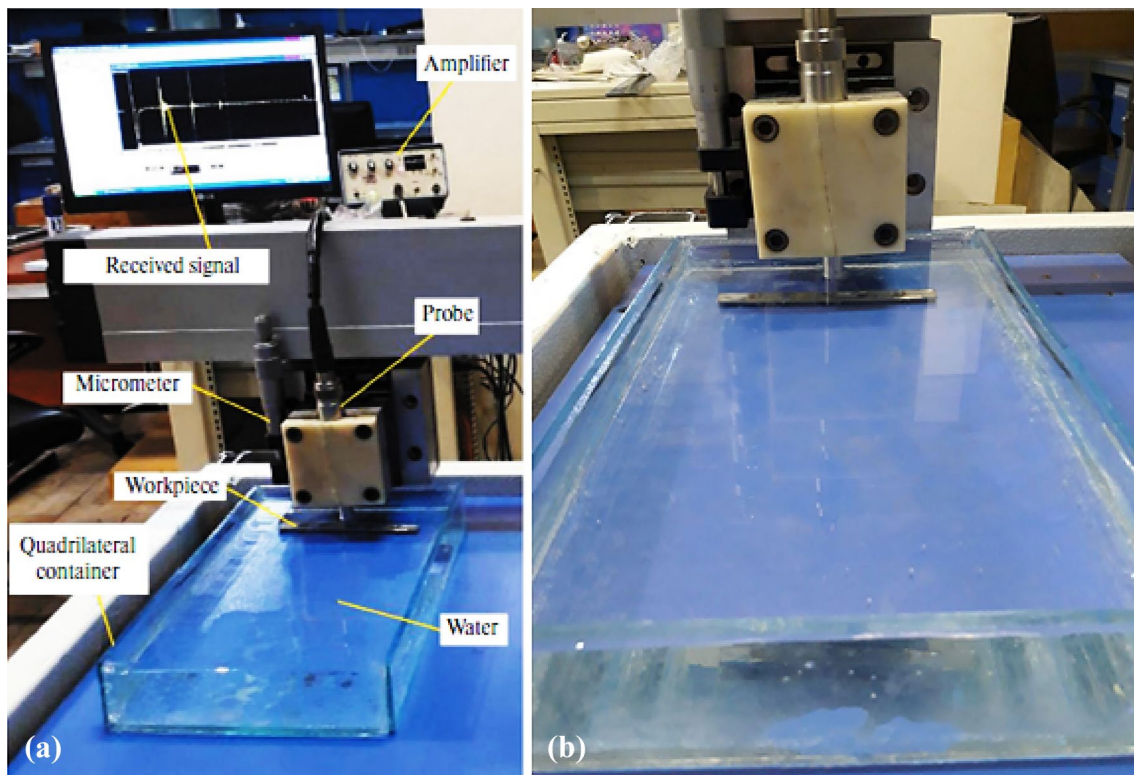


Fig. 5 A-scan system. **a** A-scan system (when receiving a signal) and **b** placement of the probe in water [1]

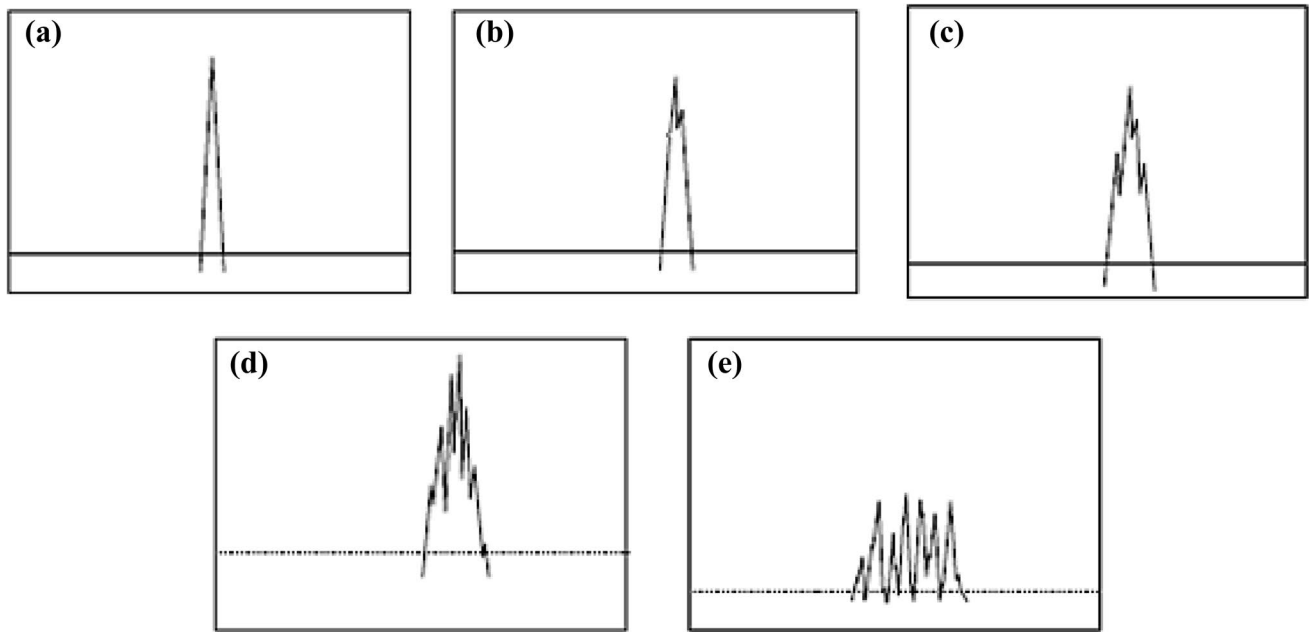


Fig. 6 Amplitude and pulse changes of the image screen [40, 41]. **a** pulse models one, **b** pulse models two, **c** pulse models three, **d** pulse models four, **e** pulse models five

image screen of the ultrasonic device as a narrow pulse, without teeth and relatively long [40, 41].

3.4.2 Pulse Models Two

This pulse model is obtained from the collision of waves with a smooth linear defect (Fig. 6b). Model 2 pulse amplitude occurs with a uniform ascending and descending cycle but with a long and slow time delay. Sometimes this pulse model also has a fine tooth. The appearance of the model 2 pulse is seen in the ultrasonic image screen, similar to the model 1 pulse, but with a wider width [40, 41].

3.4.3 Pulse Models Three

This type of pulse model is formed from the collision of waves with uneven and irregular defects such as impurities on metallic and non-metallic surfaces. Model 3 pulse amplitude is associated with several rapid and intermittent ascending and descending cycles. The pulse shape of this model appears in the ultrasonic image plate as a dent with small concaves (Fig. 6c) [40, 41].

3.4.4 Pulse Models Four

This type of model is obtained from the collision of waves with a large toothed defect and very uneven. Peak amplitude changes are seen irregularly with repetitive oscillations, and in each pulse, several peaks with alternating oscillations will

be ascending and descending. In the ultrasonic image plane, the pulse of model 4 appears irregularly by numerous and concave peaks (Fig. 6d) [40, 41].

3.4.5 Pulse Models Five

Such a pulse is formed from the collision of waves with several small and complex defects (clusters) such as complex gas bubbles in the boiling pool (Fig. 6e). Model 5 pulse amplitude changes are seen as multiple and small oscillations with short and unequal amplitudes. On the ultrasonic imaging plane, it will appear as repetitive and short pulses with different amplitudes [40, 41].

3.5 The Effect of Transducer and Piece Distance Calculations in the Experimental Test

To calculate where the signals appear in the oscilloscope, the time intervals must be multiplied by two, given that the going and return distances of the sound waves are displayed. The speed of sound in water and in the sample piece is in meter/second (m/s) [29]. The test method is immersion, which is discussed in this article. Equation (1) is used to determine the distance of the concentrating transducer to the surface of the part in the immersion test [42]:

$$S_d = FL_w - S_m \times \frac{C_m}{C_w} \tag{1}$$

where the parameters are defined as follows: S_d the distance of the transmitter to the surface of the part, FL_w the focal length of the transmitter, S_m the distance that the sound travels in the part, C_m the speed of sound in the part, C_w the speed of sound in water [42]. According to the above point, unlike the focal length of the transmitter, which is determined by the manufacturer, we set the sound distance in the piece, S_m , which has been considered here as one (mm). The time interval between the first back surface signal Back Wall (BW) and the desired single pore and porosity defect (for identical stainless steel sheets) is calculated as follows [43]. When the sound enters the part, it should be concentrated 0.9 mm forward because the thickness of the first sheet is 1 mm and the second sheet is 2 mm; these two sheets are fused during welding and cause shrinkage, which is calculated according to Eq. (2) [42]:

$$V = \frac{\Delta_x}{T_{real}} \rightarrow T_{real} = \frac{\Delta_x}{V} \quad (2)$$

where V is the speed of sound and Δ_x is the distance from the surface of the transmitter to the surface of the part and T_{real} is the time of appearance of the main signal. First, the location of the first BW signal is calculated, and then the location of the fault signal is calculated. The time interval between the first BW signal and the single pore defect is also calculated according to Eq. (2) [42]. When sound enters the part, the distance from the edge of the part to the defect (the amount of weld) should be focused further forward (on the defect of the single pore). This time interval is calculated according to Eq. (2).

3.6 Experimental Results

In this section, the results obtained from the experimental activities including the spot welding have been approved, and then the results obtained by the ultrasonic test are examined. Before the ultrasonic examination, we need to have the necessary information about the interpretation of the signs of defects, which are fully interpreted in the following sections of the echoes of the defects and their shape. When the transducer is connected to the oscilloscope, two types of echoes appear on the screen [1, 44]. The first echo is the reflection from the surface of the piece, and the second echo is related to the reflection of the wave in the opposite surface [45]. This pattern shows that the device is in suitable condition in terms of internal defects. When an internal defect or crack is found by the processor, it produces a third echo that is recorded and displayed on the screen between the first and second echoes. The method used is the A-scan system [46]. An echo appears on the left side of the oscilloscope screen that corresponds to the original echo, and other echoes appear on the oscilloscope screen that correspond to the received echo mark. The height

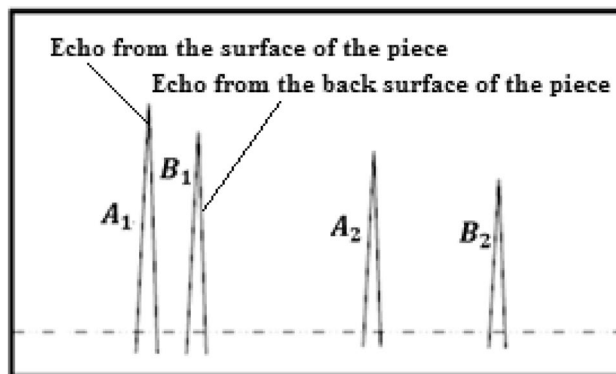


Fig. 7 Interpretation of symptoms in the immersion method [9, 41]

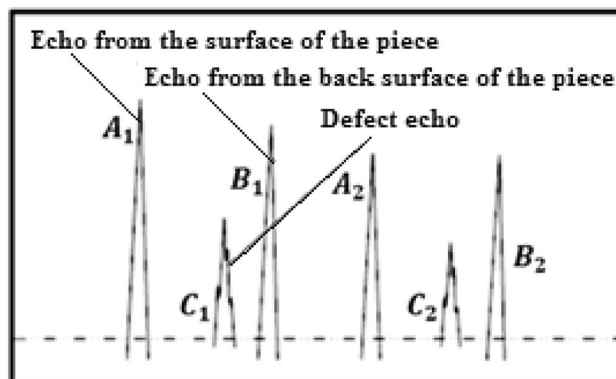


Fig. 8 Interpretation of symptoms in the immersion method when dealing with a defect [9, 41]

of the echoes is usually proportional to the size of the reflection surface [47]. Many applications of ultrasound have been used in most of the automotive industry for all of its components, such as the method and function described [45, 48, 49].

3.6.1 Interpretation of Symptoms

In the immersion method, ultrasonic waves hit the surface of the part after passing through a volume of water, and when the waves hit the front and back of the part, two reactions occur [9]. The first reaction occurs due to the change of environment from water to the piece and the second reaction occurs due to the change of environment from the piece to the water behind the piece [9]. Figure 7 shows the first echo. A_1 is the result of the reflection of the waves in contact with the front surface of the object, and A_2 is the echo reflected from behind the object [9, 41].

3.6.2 Interpretation of Symptoms in Immersion

If there is a defect in the piece, in addition to the two echoes in the front and back of the piece, in the distances between the two thick front and rear echoes, a return echo also appears [9, 41]. In Fig. 8, the echoes C_1 and C_2 are the results of the wave response in the event of a fault. The larger the defect, the higher the reflective echo height and the shorter the reflected echo from behind the piece, but none of this affects the echo height and position in front of the piece [15, 45]. Experimental results are for the interpretation of signals from defects and the detection of defects with respect to time intervals which are shown in Fig. 9 (a–d) for stainless steel sheets and stainless galvanized sheets for porosity and crack defects [1, 50]. It is shown in Fig. 10 (a–d) for 5XXX series aluminum and 6XXX series aluminum for porosity and crack defects [1, 50]. The first BW echo time is between

25 and 30 microseconds. Defects are also reported according to the presented formulas, and its approximate calculations are between 30 and 35 microseconds.

4 Simulation of Ultrasonic Wave in Spot Welding

In the past, experimental methods were used to justify and interpret physical problems. With the development of mathematical sciences, it became possible to theoretically analyze various problems [51]. With the advent of computers, the method of numerical solution has been added to the methods of theoretical analysis [52]. Of the three methods, the analytical method is the most valuable one because the answer to these analyzes has the least error, but will not be able to analyze physical problems that have complex geometry or boundary conditions [53]. Experimental or laboratory

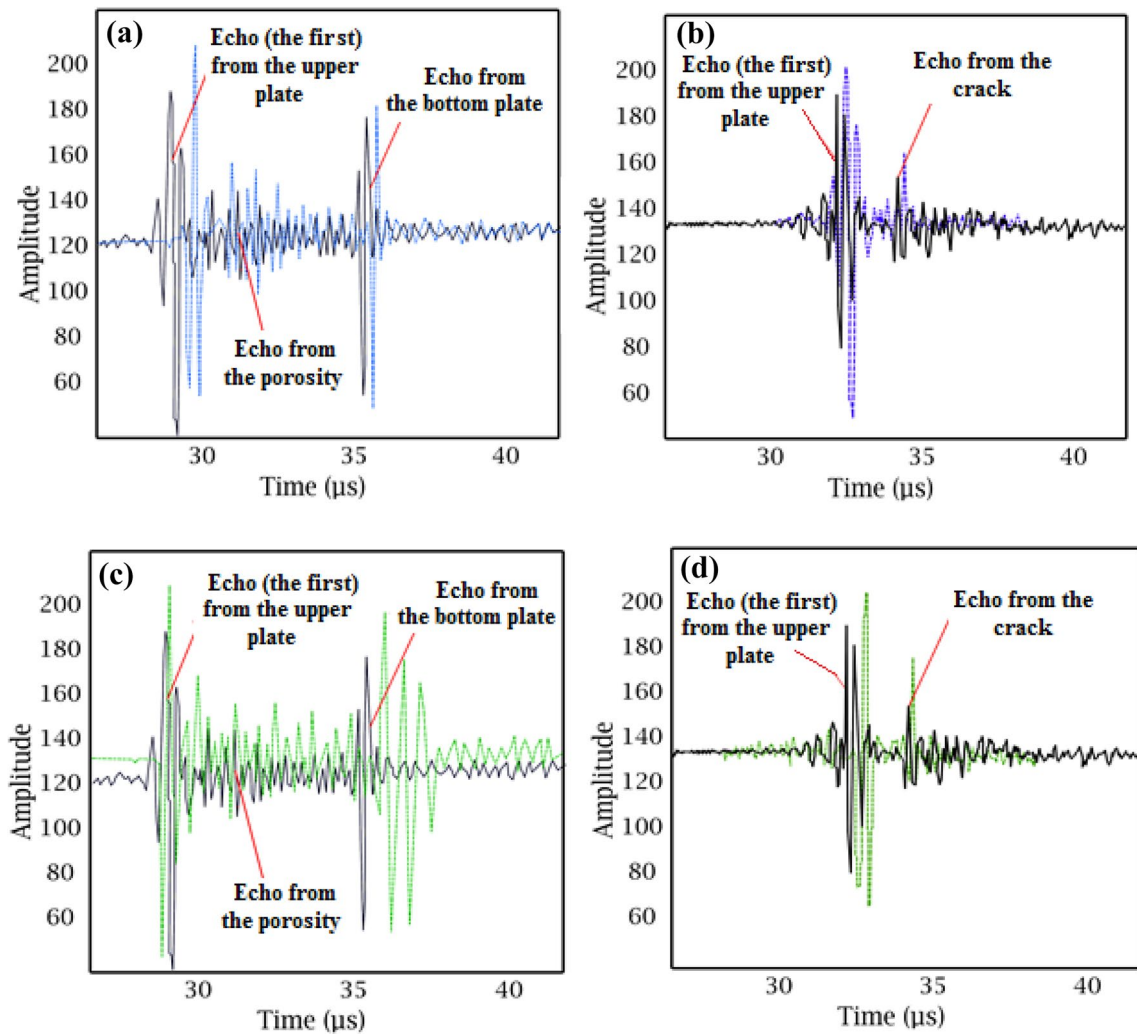


Fig. 9 Experimental test echo of porosity and crack defect signal for stainless steel sheets and for stainless galvanized sheets. **b** and **d** echo of porosity and crack defect signal for stainless steel sheets and **a** and

c echo of porosity and crack defect signal for stainless galvanized sheets [1, 50]

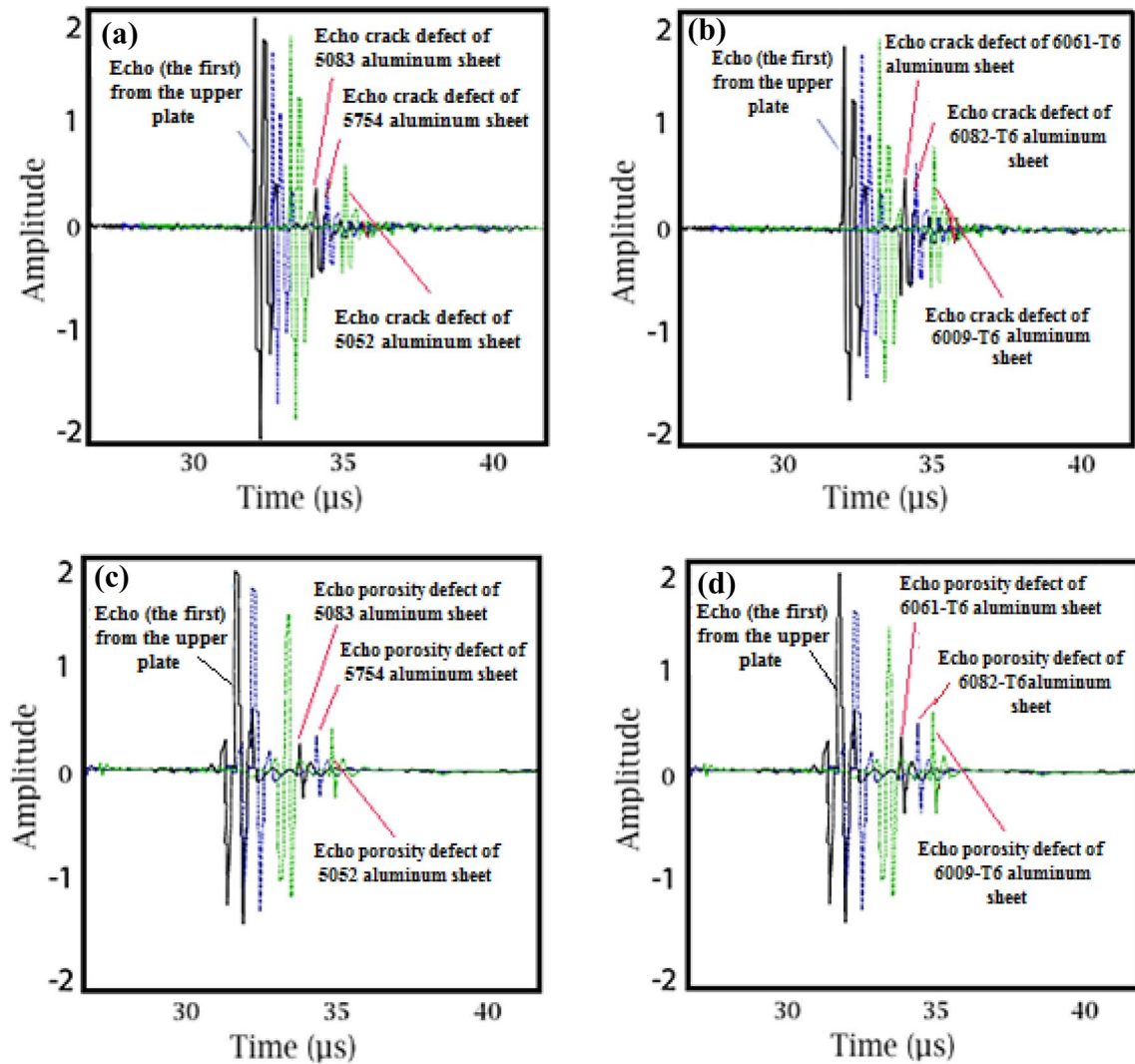


Fig. 10 Experimental test echo of crack and porosity defect signal for 5XXX aluminum and for 6XXX aluminum. **c** and **d** echo of porosity and crack defect signal for 5XXX aluminum and **a** and **b** echo of porosity and crack defect signal for 6XXX aluminum [1, 50]

method is also a suitable method due to the realistic nature of the problem [54]. The results obtained from the numerical method are less accurate than the other two methods. But there are advantages over the other two methods. One of these advantages is low cost of this method compared to the experimental method [55]. For example, in welding with complex and nonlinear nature geometry and boundary conditions, the numerical method has more accurate answers [56]. COMSOL Multi-physics software is a simulation software that solves the differential equations of nonlinear systems by partial derivatives of finite element method in one-, two- and three-dimensional spaces [57]. The finite element method has made great strides in the study of ultrasound and to the extent that in many cases, its results have been suitable solutions for adaptation to numerical results and advances in industry [58]. A number of dynamic problems

were unsolvable before the finite element method. One of the main characteristics of diffusion problems is that its response to the system changes with time. The procedure for analyzing a dynamic problem is similar to that for analyzing a static problem. In this type of problem, the variables in relation to the equilibrium of the components depend on time, and the purpose of the analysis is to calculate the variables for all times [59, 60]. In simulation, different models and theories can be used, each of which has their advantages and disadvantages, as well as the geometry of the structure and boundary conditions. In particular, in simulating the propagation of waves in the sheet, it is necessary to use a two-dimensional solid model. The sheets are modeled in two-dimensional mode, and its boundary conditions are shown in Fig. 11. In the finite element method, the amplitudes of the differential equations are divided into single regions [59,

Fig. 11 Sheets modeled in two-dimensional mode and its boundary conditions

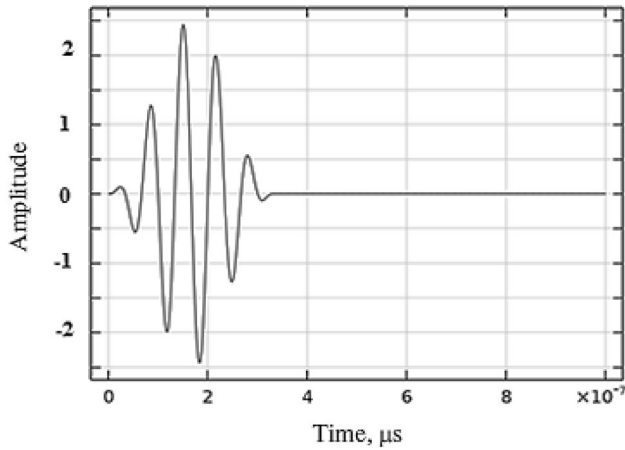
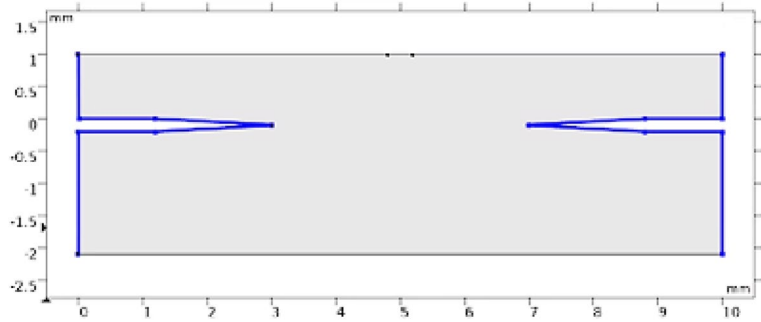


Fig. 12 Wave signal excitation at 15 MHz [1, 50, 61]

considering the interpolation functions, and the governing equations are extracted. By combining the equations for each component, the governing equations for the whole model are obtained. Finally the governing differential equations of the whole model are replaced by a set of algebraic equations. The finite element method is performed in several ways that simulate the propagation of ultrasonic waves which otherwise requires transducer modeling [1]. To stimulate the transducer, the use of a single frequency function has been used, which causes the wave to concentrate and thus increase the energy. In the desired function, the central frequency is $f_c = 15\text{MHz}$, which is defined as [1]:

$$F(t) = 0.5 \sin(2\pi f_c t) \left[1 - \cos\left(\frac{2\pi t f_c}{n}\right) \right] \quad (3)$$

60]. Each piece of the domain is called a component, and the vertices of the components are called nodes. Differential equations for each one of the components is solved by

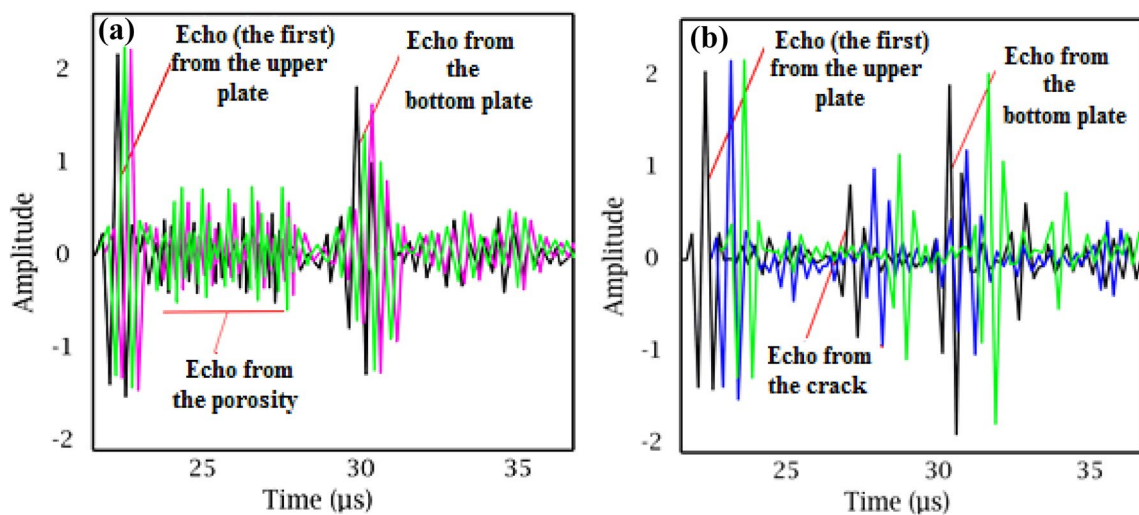


Fig. 13 Simulation echo of porosity and crack defect signal for stainless steel sheets and for stainless galvanized sheets. **a** echo of porosity defect signal for stainless steel sheets and stainless galvanized sheets

and **b** echo of crack defect signal for stainless steel sheets and stainless galvanized sheets [1]

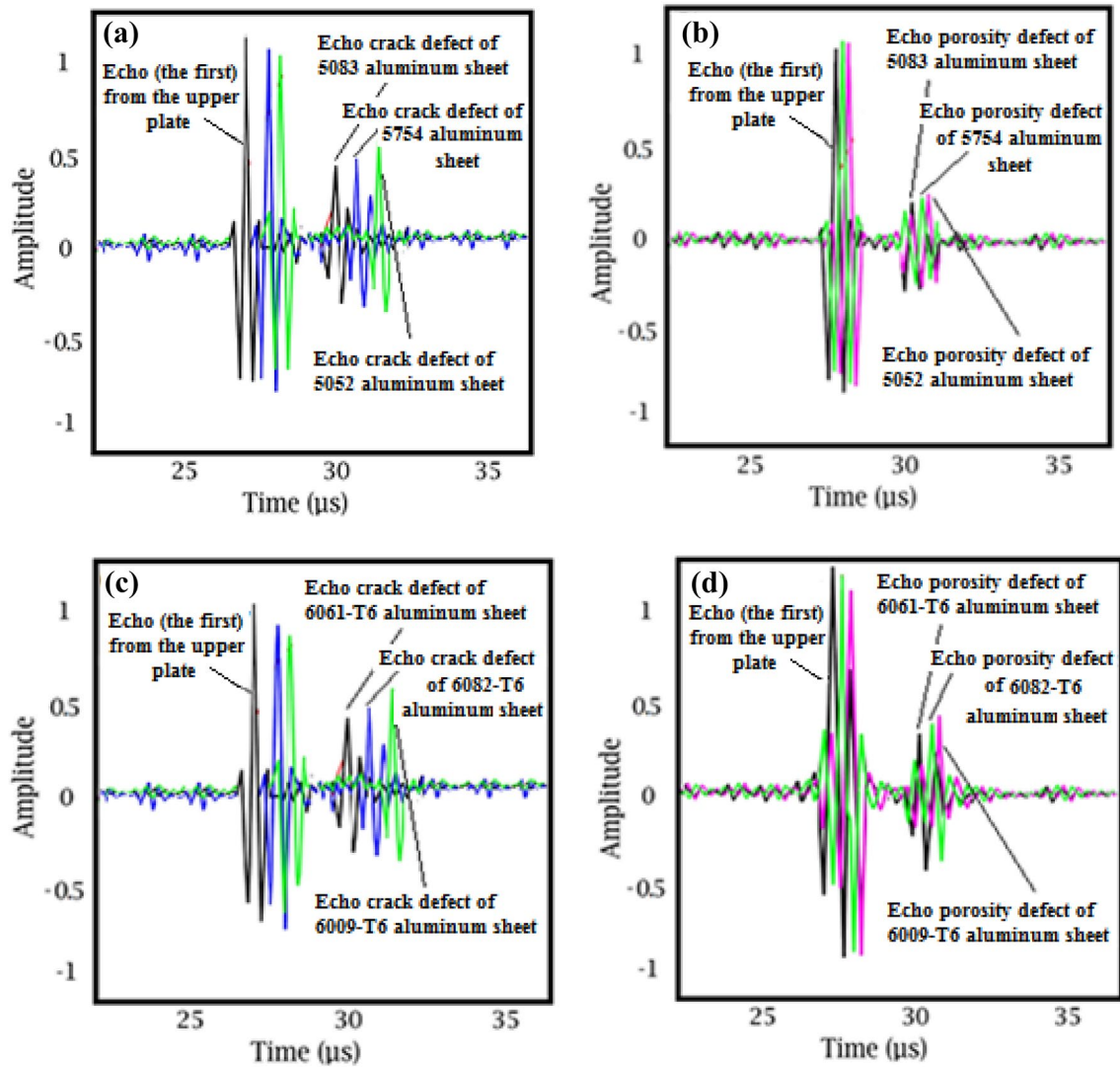


Fig. 14 Simulation echo of porosity and crack defect signal for 5XXX aluminum and for 6XXX aluminum. **a** and **b** echo of porosity and crack defect signal for 5XXX aluminum and **c** and **d** echo of porosity and crack defect signal for 6XXX aluminum [1, 50]

The excitation signal is examined by applying the Gaussian window by adopting 2.5 cycles for the sinusoidal signal (Fig. 12). The effect of crack and porosity defects on the signals of stainless steel sheet and galvanized stainless steel sheet in the simulation is shown in Fig. 13 (a) and (b) [1]. The effect of crack and porosity defects on the 5XXX and 6XXX series aluminum sheet signals is shown in Fig. 14 [1, 50, 61]. According to Fig. 15 in reference [62], the results of the presented finite element model have an acceptable overlap with the results obtained in this article, and the results of this article are far more reliable and complete.

5 Conclusion

In the present review article, the introduction of spot welding and its nature and then ultrasonic experiments and types of error wave models were investigated and stated. By simulation, the degree of defect definition of the results of point welding by simulated ultrasound waves and its defect with the experimental test were compared. From all similar studies, it can be concluded that the best solution for spot welding inspection is the use of non-destructive tests, especially ultrasonic testing. COMSOL Multi-physics software was used to simulate porosity and crack defects, and the obtained results were compared with experimental test results [1, 50]. Defect diagnosis was used to detect cracking and porosity by a new ultrasound device made of five probes (FDDP) [61]. Porosity and crack defects were simulated, and the echo

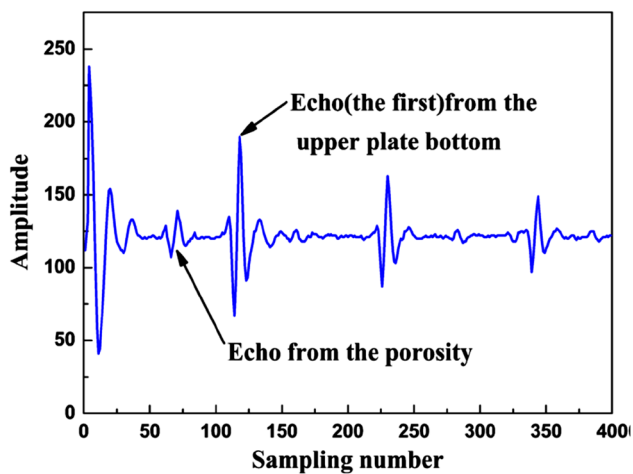


Fig. 15 Typical A-scanning waveform of defects [62]

received from the defect was in good agreement with the experimental echo [1, 50]. Analytical results for evaluation are as follows:

- The best way to evaluate for boiling point is non-destructive testing.
- Waveform in A-scan system due to the introduction of all fault signals for spot welding, all defects have different sizes at different points of spot welding.
- The new method (FDDP) was used to detect cracking errors, which according to the results, showed probes with a higher frequency range and defects more clearly.
- By comparing the signals obtained from the experimental and simulation results, we conclude that the larger the porosity defect diameter, the greater the amplitude of the impedance response.
- The greater the depth of the crack defect, the greater the intensity and amplitude of the defect wave response.
- The longer the crack, the greater the intensity and amplitude of the fault response.

Given the acceptable error rate of experimental results and simulation results, this article can be referred to as a reference for detecting errors in spot welding and its inspection methods in various industries [1, 50, 61].

Declarations

Conflict of interest The author declares that they have no conflict of interest.

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