Multi-Angle Phased Array Ultrasonic Line-Scan Method for Steel Reinforced Polyethylene Electro-fusion Welded Joint

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Abstract. In view of the difficulties and ultrasonic blind zone problems in the ultrasonic inspection of electro-fusion welded joint of steel reinforced polyethylene composite pipes, an inspection method based on phased array inspection technology, which compounds multi-angle line scan image, is proposed in this paper. It inspects by forming a plurality of B-scan images through setting up multiple line scanning channels and quick switching in the inspection process, then forming a new B-scan image after optimizing and reconstructing by computer and retaining relevant A-scan signal data for defect evaluation, thus realizing rapid and efficient real-time imaging inspection on the ultrasonic blind zone of the electro-fusion welded joint of steel reinforced polyethylene composite pipes.

Key words: Steel reinforced polyethylene composite pipes; phased array imaging; ultrasonic blind zone inspection.

1. Introduction

The steel reinforced polyethylene composite pipes is a double-sided anti-corrosive pressure pipe with low carbon steel wire as the reinforcement phase and high-density polyethylene as the base and formed by extruding and filling of steel wire mesh and plastics and then extruding and molding on the production line [1-2]. Polyethylene is connected through metal mesh holes, and the whole pipe body is similar to reinforced concrete, as shown in Figure 1. The main methods to connect the steel reinforced plastic composite pipe are: electric melting connection and flange connection. The electric melting connection is to insert the composite pipe behind the electric-melting pipe fittings and then electrify the heating wire embedded in the inner surface of the pipe to heat it. The heating resistance wire will melt the inner surface of the pipe to produce melt. The melt expands and fills the gap between the pipe and the pipe fittings until melt is also produced on the outer surface of the pipe and the two melts melt together [3]. After cooling and molding, the pipe and pipe fittings are tightly connected, as shown in Figure 2.

There are many researches on ultrasonic and phased array ultrasonic inspection technology of the welded joint of PE composite pipe which is without steel reinforcement both in China and in the world. But most of them only focus on the characteristics of PE pipes, the related inspection methods on electro-
fusion welded joint and feasibility of phased array ultrasonic inspection on thermal-fusion welded joints [4-6].

Steel reinforced polyethylene composite pipe is an emerging type of pipe applied in engineering and is widely used as water supply pipes in industrial or civil engineering and other key projects in cities. However, the non-destructive testing technology on it is still in its infancy and the composite pipe is of complicated structure so that conventional non-destructive testing technology cannot be applied. There is no mature NDT technology and process for inspection of this type of pipe so far.

This paper proposes a multi-angle line scan compounded imaging method based on phased array inspection technology to realize rapid and efficient real-time imaging inspection of blind zone of the electro-fusion welded joint of steel reinforced polyethylene composite pipes.

2. Inspection difficulties

The steel reinforced PE composite pipe has more complex structure than the ordinary PE pipe, with circumferential and axial steel reinforcement in the pipes. It is fused by the inner pipe and outer pipe. Since the molding process is complicated, it is easier to have more quality defects, which bring difficulties and challenges to non-destructive testing.

The welding quality of the pipe is mainly judged by inspecting the arrangement of resistance wire in the conventional inspection process of the electro-fusion welded joints of PE pipes. While the resistance wires in the welded joints of steel reinforced polyethylene plastic composite pipe is located below the perforated steel plates in the casing and above the steel reinforcement of inner pipe. If adopting phased array vertical line scanning, such structure will have strong interference with and reflection sound beam and the resistance wire right below the vertical projection of perforated steel plates in the casing can not be detected due to its position. The blind zone of inspection is exist , as shown in the box in Figure 3(a). If any inclined line scan at mono-angle is adopted for inspection, blind zone will exist at a different area.

At the same time, the size parameters of various structures in welded joints also bring great difficulty to phased array detection. For example, the depth of the top perforated steel plate is located in the middle of the casing, and the distance between the resistance wire and the steel plate is about 8mm-9mm, the gap between the steel plate is about 3mm-4mm, while the diameter of the resistance wire itself is not more than 1mm, and the distance between the resistance wire and the steel skeleton is about 3mm-4mm from the detection depth. The diameter of steel skeleton steel wire is about 2 mm, and the spacing formed by crisscross is about 7 mm. Therefore, the probe beam can only be detected partially through the gap of the perforated steel plate, and the difficulty of detecting the reflection echo which may be blocked is also need to be solved.

**Figure 1.** Schematic diagram of the structure of inner pipe of the steel reinforced PE pipe

**Figure 2.** Diagram of the section of electro-fusion welded joint of steel reinforced composite polyethylene pipe
(a) Coverage of sound beam by vertical line scanning or inclined line scanning at a certain angle

(b) Coverage of sound beam by multi-angle line scanning

**Figure 3. Coverage of sound beam**

### 3. Phased Array Multi-angle Line Sweep Detection Method

In view of the difficulties and blind zone problems in the ultrasonic inspection of electro-fusion welded joint of steel reinforced polyethylene composite pipes as set forth in the preceding paragraphs, a multi-angle line scan compounded imaging method based on phased array inspection technology is proposed in this paper. This method inspects by forming a plurality of B-scan images through setting up multiple line scanning channels and quick switching in the inspection process, then forming a new compounded B-scan image after computer processing and retaining relevant A-scan signals.

Firstly, the principle of phased array detection is introduced. The ultrasonic phased array sensor is composed of a group of relatively independent piezoelectric wafers. Each independent wafer element can emit ultrasonic beams. If the array elements are excited according to different rules, the beam emitted by each element can be superimposed and deflected. Similarly, ultrasound imaging can be achieved by delayed signal reception according to certain rules.

Assuming that the linear array transducer has N+1 elements and takes the 0th element as the coordinate origin, the time delay \( t_{n1} \) of the nth element relative to the 0th element is:

\[
t_{n1} = \frac{nd \sin \theta}{v}
\]

In the formula: \( d \) is the element spacing, \( v \) is the velocity of sound, and \( \theta \) is the deflection angle.

If the beam finishes focusing at a depth of \( F \), the required focusing delay time \( t_{n2} \) is:

\[
t_{n2} = \frac{F}{v} \left[ 1 - \left( 1 + \left( \frac{nd}{F} \right)^2 \right)^{1/2} \right]
\]

In formula: \( F \) is the focus depth, and \( t_0 \) is a time constant to avoid negative delay time.

Combining the above two calculation principles, the delay time \( t_n \) of deflection focusing of a beam at any point A is:
With the above formula, any point in the detected object can be focused. Secondly, the line scanning technology of ultrasonic phased array inspection instrument is used to circularly send ultrasonic signal in the axial direction of composite pipe. Such scanning method can control the ultrasonic signals to deflect at different angles and focus at different depth in the depth direction of composite pipe wall without moving the probe, so as to achieve the goal of line scanning at a certain angle. Then, the B-scan image is formed after data processing based on the echo signal produced in the propagation of ultrasonic signal in the composite pipe to be inspected and the A-scan signal at different angles should also be retained.

Finally, the focusing rule for the joint to be tested in this paper should include three independent line scan parameter setting channels. The technical parameters of inspection at different angles and focus depths can be set respectively. According to the inspection requirements of the welded joints of composite pipe, one of the line scanning channel is set to be 0° vertical line scanning and the other two are set to be line scanning at a certain angle. The angular deflection should be set opposite, as shown in Figure 3 (b).

In the scanning process, the signal acquisition module quickly switches back and forth among the three line scanning modes without moving the probe, and retains the B-scan image and corresponding A-scan waveform signals formed under the three line scanning channels.

After receiving the A-scan and B-scan images formed under the three line scanning channels, the computer calculates the corresponding spatial range covering the inspection area under the conditions of the current setting parameters for the three channels. In the area covered for many times, the maximum wave amplitude signal is selected as the sound pressure amplitude response for multiple wave amplitude signals at the same spatial location. Finally, a new compounded reconstructed image is formed after further processing and displayed as the inspection result.

4. Inspection results
Since the welding quality is mainly evaluated by inspecting the arrangement of resistance wires in the inspection of electro-fusion welded joints of PE composite pipe, testing the casing of a steel reinforced PE composite pipe (as shown in Figure 4) in this paper can also effectively explain the inspection effect of this method on the electro-fusion welded joints of steel reinforced PE composite pipe.

**Figure 4.** Schematic diagram of physical inspection

**Figure 5.** Inspection results before optimization

In Figure 4, the inspection position where the probe is placed contains a perforated steel plate signal and has multiple reflections (as shown in the rectangular box in Figure 4 and 5), which can detect the resistance wire signal obstructed by the unperforated steel plate (as shown in the circle in Figure 4 and 5). While the resistance wire signal directly under the perforated steel plate could not be effectively detected due to obstruction.
Figure 6. Inspection results after optimization

Figure 6 is the inspection result obtained by inspecting the same part with multi-angle line scanning inspection method. As shown in the figure, the white box in the figure shows the inspection results of perforated steel plates in the casing. Compared with the black box in Figure 5, the signal is less clear, many clutters are fused together, and the signal characteristics of the perforated steel plate cannot be well reflected. This is because the picture is an image fused by the inspection results under three different focusing laws, two of which are line scanning modes at a certain angle. In this mode, because the ultrasonic waves are incident at a certain angle when they encounter perforated steel plates, they will have a certain amplification effect on the inspection results and the amplification effect will be more obvious after the inspection results are superimposed. Although the inspection result of perforated steel plate is not as ideal as that shown in Figure 5, the inspection effect of perforated steel plate is not served as one of the basis for the effectiveness of multi-angle line scanning inspection method since the welding quality is mainly evaluated by testing the arrangement of resistance wires in the inspection of electrofusion welded joints of polyethylene composite pipe.

Secondly, as shown in the white circle in Figure 6, the first row of dot signals are structure signals of resistance wire and the second row of signals are signals of casing bottom. The inspection results show that the resistance wire structure shielded under the perforated steel plate can be effectively inspected after optimization with multi-angle line scanning inspection method. The inspection result is obvious, and the resistance wire signal is clear and easy to distinguish.

To better verify the capacity of such method to inspect the blind zone, we artificially made a φ2mm short cross-hole in the cross section of casing pipe. Such hole is located right below the perforated steel plate and is 2mm vertically away from the resistance wire, as shown in Figure 7.

Figure 7. Schematic diagram of inspection

Figure 8. Inspection results

The inspection results shown in Figure 8 demonstrate that multi-angle line scanning technology can effectively inspect the φ2 short cross-hole which is 2mm vertically away from the resistance wire in the original blind zone. This indicates that such method can effectively inspect the improper operation such as over welding and light welding in the welding process and reflect the arrangement of resistance wires. Meanwhile, once a φ2mm volume defect or area defect shows in the fusion surface, such as pores and slags, it can be effectively inspected, regardless of whether such defect is located in the original blind zone.
5. Proficiency testing
In order to better verify the capability of this method, three kinds of pipelines with different welding qualities, such as normal welding, over-welding and light welding, were selected for phased array detection and anatomical comparative analysis. The effectiveness of this method is demonstrated from the actual detection results.

5.1. Normal Welding
Firstly, we carried out inspection on the No.1 sample pipe which was normally welded. We axially cut the No.1 sample pipe and the results are as shown in Figure 9. It can be seen from Figure 9 that the resistance wires in normally welded pipe are arranged regularly and there is no obvious misalignment or inconsistent spacing.

![Figure 9. Schematic diagram of axial cut of No.1 sample pipe](image1)

We used the above-mentioned instrument to inspect such joint and the results are shown in Figure 10. It can be seen from the figure that the resistance wires in normal electro-fusion welded joints are arranged regularly and there is obvious misalignment, as shown in the black circle in the figure. The inner wall of the electric-melting pipe fittings are fused with the pipe. Except signal of resistance wires, no remarkable brightening, shortening or disappear were exhibited. The signal of pipe inner wall is continuous and clear and there are no other significant signals showing in the melting areas.

5.2. Over Welding
Secondly, we carried out inspection on the No.2 sample pipe which was abnormally welded. We axially cut the No.2 sample pipe and the results are shown in Figure 11. It can be seen from Figure 11 that the resistance wires in abnormally welded pipe are arranged irregularly and exhibit obvious misalignment and inconsistent spacing.

![Figure 11. Schematic diagram of axial cut of No.2 sample pipe](image2)
The inspection results of No.2 sample pipe (over-welded pipe) are shown in Figure 12. It can be seen from the ultrasonic imaging results that over-welded pipe mainly exhibits the following characteristics: obvious misalignment and inconsistent spacing, as shown in the black circle in the figure.

5.3. Light Welding
Finally, we carried out inspection on the No.3 sample pipe (light-welded) which was abnormally welded. We axially cut No.3 sample pipe and the results are shown in Figure 13. Figure 13 shows that the cut face of light-welded pipe is very similar to that of normally welded pipe and no definite difference can be viewed with naked eyes. The resistance wires in light-welded pipe are arranged relatively regularly and no obvious misalignment and inconsistent spacing show. However, the actual inspection results will show definite indicative information, as shown in Figure 14.

What the black circle in Figure 14(a) shows is the advanced bottom wave signal. This is because that the fusion surface between casing pipe and inner pipe is insufficient fused due to multiple factors such as insufficient welding time or welding power during the welding process and a series of obvious bottom wave signals show below the signal of resistance wires.

Light welding is also called as cold welding. The ultrasonic image shows that the distance between characteristic line and resistance wire in cold-welded joints should be shorter than that in normally welded joints.

However, in the actual inspection, since the signal of characteristic line itself is weaker than the signal of resistance wire, higher frequency phased array probe should be used for inspection. We should observe whether there is signal of characteristic line in the scope of 2 to 3mm above the signal of
resistance wire. If the answer is yes, then it can be judged as cold-welded joints. Or else, there is no problem of cold welding.

What the black circle in Figure 14(b) shows is the signal of characteristic line. We did not find any obvious signal of characteristic line in No.1 sample pipe. This is because that the distance between characteristic line and resistance wire in normally welded joints is greater than that in cold-welded joints. In consideration of the structure complexity of steel reinforced polyethylene composite pipes, this paper believes that the signal of characteristic line in normally welded sample pipe should be located in the blind zone of upper surface. Therefore, we can determine whether the pipe has cold-welding problems by finding out whether there is signal of characteristic line in the scope of 2 to 3mm above the signal of resistance wire.

6. Conclusion

In order to solve the difficulties and blind zone problems in ultrasonic inspection of electro-fusion welded joints of steel reinforced polyethylene composite pipe, this paper mainly studies the following aspects:

1) This paper analyzes the structural characteristics of steel reinforced polyethylene composite pipe and the inspection difficulties of existing non-destructive testing method.

2) This paper proposes a multi-angle line scan compounded imaging method based on phased array inspection technology and expounds the principle of such inspection method, so as to realize rapid and efficient online real-time imaging of electro-fusion welded joints of steel reinforced polyethylene composite pipe.

3) This paper sets up artificially made defect in the joints of different welding quality and the inspection blind zone for comparative analysis. The results show that such inspection method can quickly and effectively judge the welding quality of composite pipe and greatly solve the blind zone problem of inspection.

The above experiments show that such method can realize rapid and efficient online real-time imaging inspection on the electro-fusion welded joints of steel reinforced polyethylene composite pipes and greatly improve the blind zone problems of inspection technically.

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