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Influence of polyethylene pipe butt fusion welding in ultrasonic non-destructive testing

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Abstract. Butt fusion welding is a commonly used manufacturing method for polyethylene pipes. To investigate the influence of butt fusion welding on oblique ultrasonic wave in ultrasonic non-destructive testing, a numerical simulation model was established for polyethylene pipe with welding joints. Wave propagation in the polyethylene pipe was analysed, which showed that there exist longitudinal and shear waves propagating and their mode conversion. Detection signals of pipes with different defects and different acoustic attenuations were calculated. The special structure of welding joint was then modelled. Results show that the signal response declines with acoustic attenuation coefficient. Butt welding joints, especially the inner joints, would affect waves propagation. Finally, the welding process of polyethylene pipes was also simulated. The influence of cooling time was discussed, which indicated that insufficient cooling time would cause thermal residual stress and then alter the ultrasonic signal.

1. Introduction

With the advantages of corrosion resistance, good sealing and long service time, polyethylene(PE) pipe has been widely used in gas, water transportation and nuclear power[1-3]. The key technology affecting pipeline application is pipeline welding[4]. When the nominal diameter is above 90 millimeter, the main connection method of 2 pipes is butt fusion welding[5], whose convenient operation also helps site work. At present, polyethylene pipe is developing to the direction of large diameter and high pressure resistance, which provides more research topics for butt fusion welding.

In welding and manufacturing, transient thermal stress, residual stress or deformation would occur within the welded joints due to uneven heating, cooling or material variation[6-7]. Their existence would affect the strength, stiffness and service life of the welded structures, then leading to losses in production and life safety. According to the investigations by relevant organizations in the United States[8] , 13% of failures in PE pipes are attributed to joint failures

As the earliest and a commonly used non-destructive testing technology, ultrasonic detecting technology has good adaptability on polyethylene pipes and been widely studied[9-16]. The database has been preliminarily established[17].

At the same time, researches have been carried out on the failure mode and damage mechanism[18-21] of welded joints, while they focus more on the generation of cracks. More detailed relationship between signal of NDT and joints could be explored further, such as the structure of joints and the welding process, which concerns with thermal simulation.

Through experimental and finite element simulation methods, Gu[22] conducted the first analysis of temperature and stress distribution during welding process. Based on this, Lv[23] further deepens his study and gave a more detailed introduction of simulation. He[24], used orthogonal experimental methods to indicate that welding temperature, welding pressure and heating time are three significant factors influencing the mechanical properties of joint. Cooling time is often considered a minor factor, and there is limited research on it. However, experiments indicate that ultrasonic detection signals are notably different without sufficient cooling time.

In this paper, a mechanical model is established for analyzing the wave propagation in the PE pipe and the influence of the joint on ultrasonic detection signal. A thermal and viscoelastic based finite element model is created to simulate the welding process and explore the influence of cooling time.

2. Waves in PE Pipe

An oblique ultrasonic wave is incident on the pipe and might generate longitudinal wave(P wave) and shear wave(S wave), as shown in figure 1. A 2D finite element model was established for simulating ultrasonic non-destructive testing process. Considering the need of rapid detection and the tolerance of experimental conditions, the pitch-catch method was chosen. A transducer is located on the hypotenuse of a wedge, and the material of the wedge is polymethyl methacrylate (PMMA), which is commonly used for steel pipe ultrasonic testing. The received signal would be extracted from different point of the model, as shown in figure 1. Besides a PE pipe model, a steel pipe model is also built for comparison. The physical field ‘Elastic waves, time explicit’ is used, in which absorbing layers are added on both ends of the pipe to avoid wave reflection.

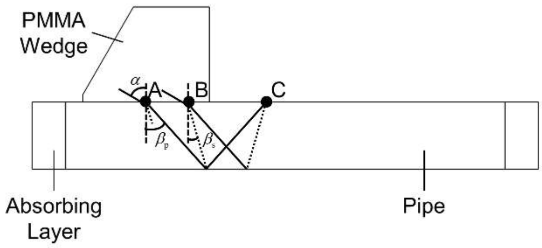

Figure 1. Ultrasonic non-destructive testing model

From Snell’s law $\frac{\sin(\beta_p)}{\sin(\alpha)}=\frac{c_{p2}}{c_{p1}}, \frac{\sin(\beta_s)}{\sin(\alpha)}=\frac{c_{s2}}{c_{p1}}$, where α is the incident angle, β_p and β_s are the refractive angle of longitudinal and shear wave, respectively. And the subscript 1 refers to PMMA wedge and 2 refers to the pipe.

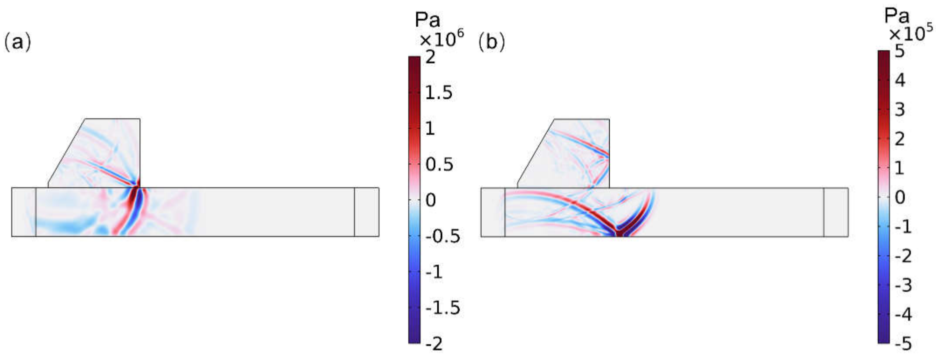

Figure 2. Waves in (a) steel; and (b) PE pipe

Figure 2 shows ultrasonic wave propagation in PE and steel pipes, respectively. As the velocity of P and S waves in steel pipe are about 5880 m/s and 3230 m/s, and the velocity of P wave in wedge is about 2720 m/s. The P wave velocity of PMMA is smaller, it could propagate only S wave in the steel pipe by controlling the incident angle, such as $\alpha = 60°$ in this model. However, the velocities of P wave, 2110 m/s, and S wave, 860 m/s in PE pipe are smaller than the velocity of P wave in wedge. Thus there would always exist P wave and S wave propagating in the pipe, which is different from waves in steel pipe.

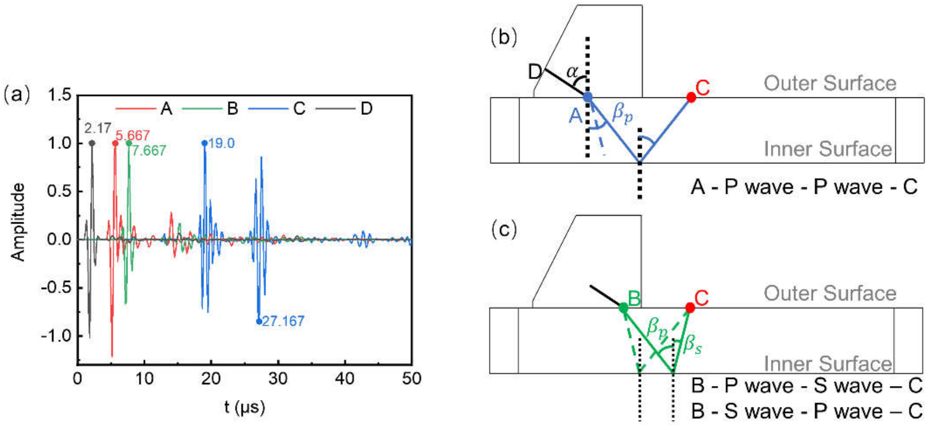

Figure 3. Waveforms of different receive point.

Signals of different points are plotted in figure 3. Ultrasonic wave would propagate not only from point A (midpoint of the bottom edge of the wedge) to C through P wave - P wave, but from another point B to C through P wave - S wave and S wave -P wave. From figure 3(a), velocities could be calculated through arrival time and distance, whose results are compared with theoretical values in table 1. The simulated results are in accordance with theoretical results.

Table 1. Velocities in PMMA wedge and PE pipe.

	Theoretical(m/s)	Simulated(m/s)	Path
P wave in PMMA wedge	2716.5	2637.7	A-D
P wave in PE pipe	2114.2	2152.4	A-C
S wave in PE pipe	863.12	859.13	B-C

3. The influence of defects, attenuation and joints

In this section, the influence of defect and attenuation of pipe on received signal are first described. Then the process of butt fusion welding is introduced, and the effect of joint is explored.

3.1. Defects

In actual welding, due to material properties, construction environment or other factors, defects in PE pipe joints are always irregular. Their sizes are large in one direction and small in other directions, thus it is suitable for using ellipses to approximate different defects.

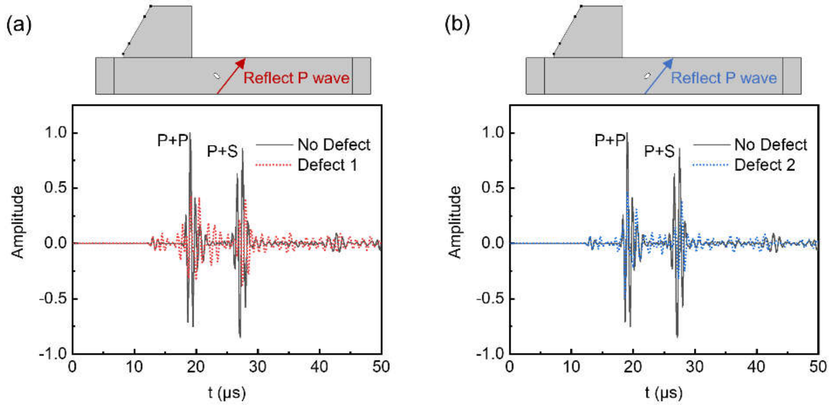

Figure 4. Signals of Point C, when orientation of defect is: (a) vertical to the reflective P wave; (b) parallel to the reflective P wave

Two elliptical holes in same size but different orientations were created. They are vertical and parallel to the reflected P wave, respectively. Figure 4 shows the received signal at Point C, both two defects affect the waveform of received signals, especially when it is vertical to the ultrasonic wave.

3.2. Attenuation

In general, due to the existence of P wave and S wave, multi waves would propagate to C point. While due to the acoustic attenuation coefficient varies with pipe, amplitudes of each signal would be different, as shown in figure 5.

The larger the attenuation coefficient is, the smaller the amplitude of waves are. Sometimes the second wave even disappears.

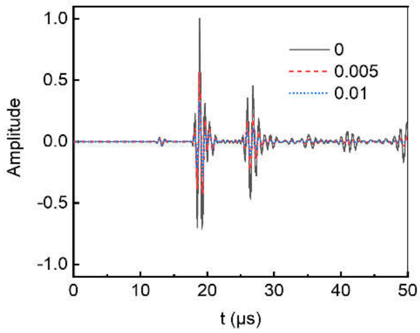

Figure 5. Influence of attenuation of pipe

3.3. Butt fusion welding and influence of joints

The process of butt fusion welding contains four steps: preheat, heat, hand-off and cool period, as shown in figure 6. During preheat period, a plate is settled between 2 pipes whose ends are under pressure, and the temperature of the plate increases to specified value and would be held as constant during heat period. After that, the plate and pressure would be removed during hand-off period. Finally, two pipes would connect under the action of axial pressure before it cools to the softening temperature. During cool period, two melting layers around heated position are tightly squeezed together, when part of the polymer chains moves and tangles to connect of the pipe. Under the temperature and pressure, the polyethylene material would be extruded outward under pressure to form joints at the inner and outer surfaces.

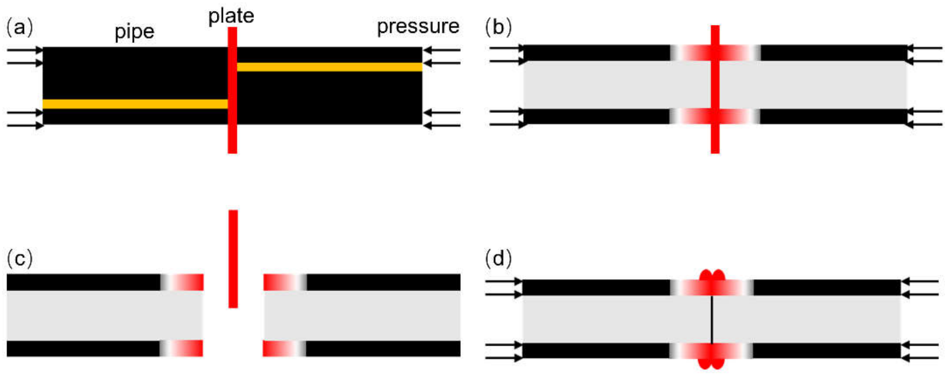

Figure 6. Diagram of butt fusion welding: (a) preheat; (b) heat; (c) hand-off; (d) cool

To explore the influence of joints on received signal, pipes with only inner joint, only outer joint and both of them are modelled, respectively, and the joints are created as semicircles. Dual transducers are placed at 2 sides of joints, and the normal stress is chosen as received signal. It is hard to use point C for detection when existing joints, because it is inside the outer joint. Point E is the midpoint of receiving transducer (not modelled in simulation, but exist in experiments). The signal would contain both P-wave and S-wave in every waveform.

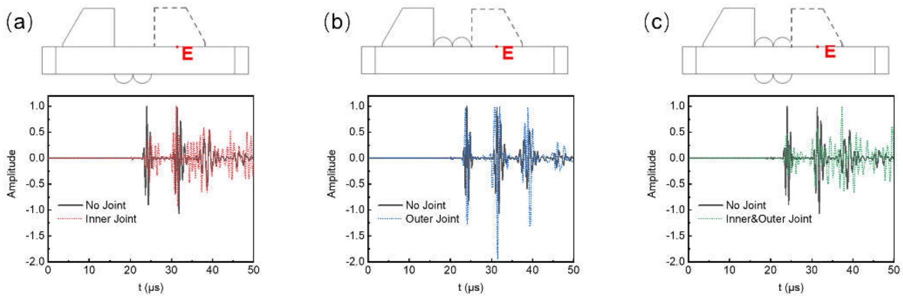

Figure 7. Influence of welding joints

(a) inner joint; (b)outer joint; (c) both inner and outer joints

From figure 7, it could be found that both the inner and outer joints alter the waveform, but the inner one influences more, whose reason is that ultrasonic wave would reach firstly at the inner joint, and the propagation path is changed.

3.4. Experiments

Experiments were first performed on pipes with different attenuation coefficients, as shown in figure 8. Results indicated that the number of received signal at non-welded area depends on the attenuation characteristics of pipe.

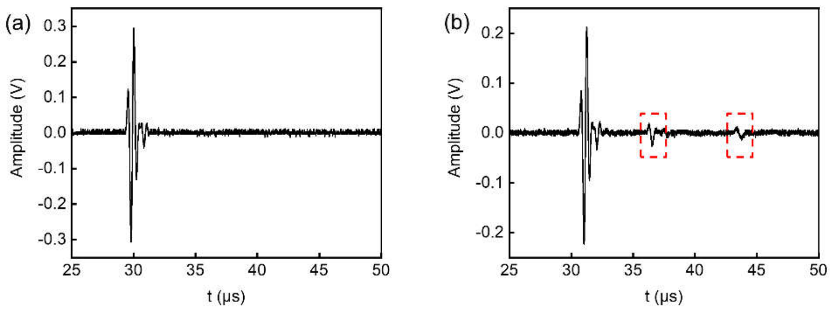

Figure 8. Experimental results of pipes with different attenuation coefficients

Then, experiments were carried out in non-welded area, welded area without defects and welded area with a defect inside the joint. Figure 9 shows that both joints and defects would change the waveform, so it is important to distinguish them in actual non-destructive testing.

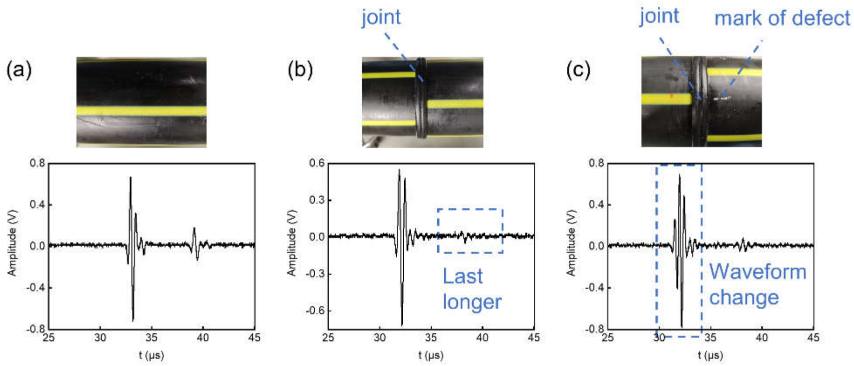

Figure 9. Experimental results in (a) non-welded area; (b) welded area without defects; (c) welded area with a defect.

4. Influence of welding time and ultrasonic testing

4.1. Welding Process

In this section, the butt fusion welding process simulated. Through finite element method, a 2D axisymmetric thermal structure indirect coupling model (Figure 10) is established. The temperature field distribution and thermal stress distribution of the butt fusion welding process are calculated successively, then the difference between sufficient and insufficient cooling time is explored. The diameter of the pipe is 160mm and the diameter to thickness ratio is SDR17. The temperature and stress fields are calculated using fluid heat transfer and solid mechanics, respectively.

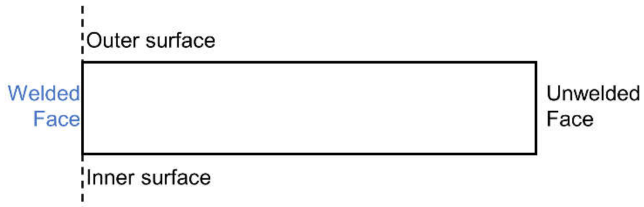

Figure 10. Diagram of welding process model

In fluid heat transfer, the material needs to be set as phase-change material varied between solid state and molten state. The heat source is set as a certain temperature at the heating plate. The coefficients of heat convection on the outer and inner surface could be calculated as $\alpha_{\text{out}} = 7.631\ W/(m^2 \cdot °C)$ and $\alpha_{\text{in}} = 0.713\ W/(m^2 \cdot °C)$, respectively.

Butt fusion welding process is simulated as three steps, because the pre-heat period is considered finished at zero moment. Before 94 s is the heating period, where a plate of $210\,°C$ is settle between two pipes. From 94 s to 97 s is the hand-off period, and after that is the cool period. Here the total calculation time is 1000 s. The difference of sufficient and insufficient cooling would be discussed at the stress calculation, they are the same in temperature in a indirect coupling model. The boundary conditions of temperature calculation are given in table 2.

Table 2. Heat Transfer in fluid (Temperature).

Period	Welded Face	Unwelded Face	Outer & Inner Surface
Heat	Temperature load	Adiabatic	Heat Convection
Hand-off	Heat flux equals to 0	Adiabatic	Heat Convection
Cool	Adiabatic	Adiabatic	Heat Convection

And the temperature distribution at different time is shown in figure 11. During the heating period, the heat transmits from the connection plane to both pipes, and the maximum temperature is the same as the heating plate. In the hand-off and the cool period, the maximum temperature declines gradually and heat still transmit towards two ends of the pipe. The region above softening temperature would form joints.

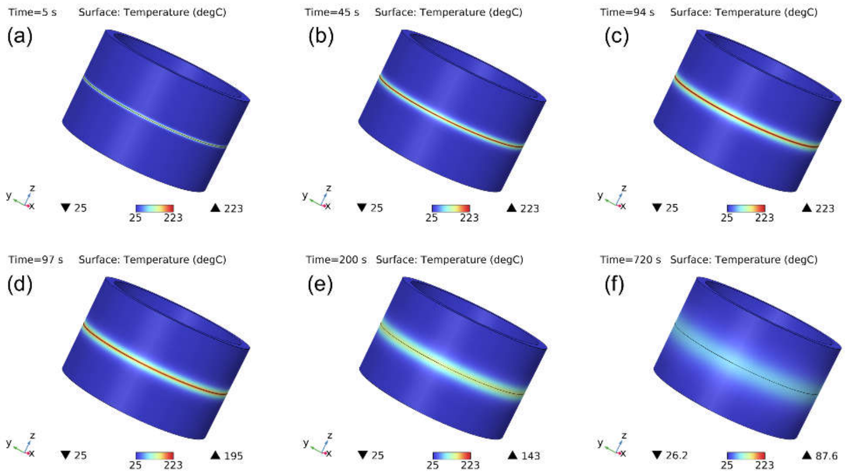

Figure 11. 3D temperature distribution at different time.

The stress is then simulated based on the calculated temperature distribution. The cooling time is set as till 720s and 480s, which are sufficient and insufficient cooling, respectively. When insufficient cooling, the maximum temperature is still above the softening temperature, but the pressure is not exerted, which would lead to poor welding quality. The boundary conditions in stress calculation are given in table 3. The total time is still 1000 s, and all boundaries are considered as stress free after the cool period.

Table 3. Solid Mechanics (Stress).

Period	Welded Face	Unwelded Face	Outer & Inner Surface
Heat	Pressure, 0.15 MPa	Axial Restriction	Free Boundary
Hand-off	No Load	Axial Restriction	Free Boundary
Cool	Pressure, 0.15 MPa	Axial Restriction	Free Boundary

The calculation of thermal stress in plastic welding is a thermoviscoelastic problem. When defining material properties, the parameters should vary with temperature. WLF equation and the generalize Maxwell equation[23] also need to be considered.

The simulation of PE pipe butt welding is a typical nonlinear transient problem. Due to the mechanical behavior of material, such as creep and stress relaxation, material characteristics alter with temperature and need to be defined. Young's modulus E and shear modulus G would be calculated from the values at room temperature with the following equations：

$$\log\frac{G(T_R)}{G(T)} \approx \log\frac{E(T_R)}{E(T)} = 1.15\frac{T_m / T_R - T_m / T}{T_m / T_R - 1}\,, \tag{1}$$

where R and m represents reference and melting temperature, respectively. And the other material characteristics could be modeled by interpolating through thermophysical parameters at typical temperature (Table 4) .

Table 4. Material parameters at classic temperature

Temperature	Density	Thermal Conductivity	Specific Heat

(°C)	(kg/m^3)	($W/m\cdot °C$)	($10^3 J/kg\cdot °C$)
28	980	0.49	1.92
125.6	900	0.32	5.56
134.7	850	0.31	15.51
210	780	0.26	2.73

The temperature and stress distribution of 720 s and 480 s are shown in figure 12. Compare 12(c)-(d), when the pipes are insufficiently cooled, it would generate residual stress at the welding region, which is caused by pipes under pressure at improper temperature(above softening temperature), as shown in figure 12(a)-(b). It is consistent with the conclusion of Zoetelief[19] that the thermal residual stress is the main influence factor.

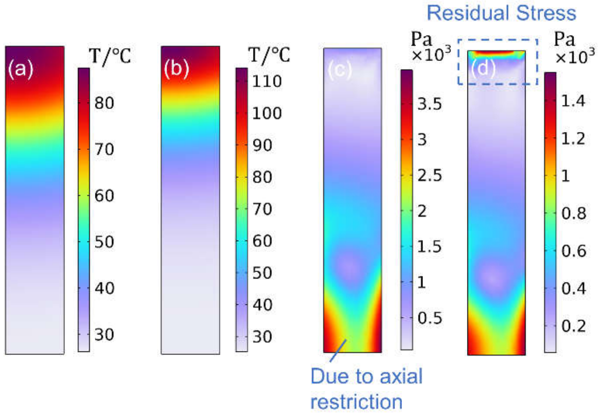

Figure 12. Temperature and stress distribution of section at different time
(a) temperature at 720 s; (b) temperature at 480 s; (c) stress at 720 s; (a) stress at 480 s;

4.2. Ultrasonic testing experiments

Samples under sufficient and insufficient cooling time were fabricated, whose parameters are consistent with simulation.

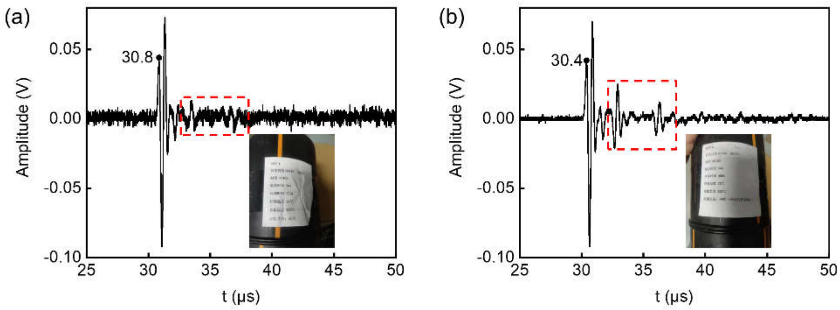

Figure 13. Experimental results of pipes cooling different times: (a) 720s; (b) 480s

Ultrasonic testing experiments in pitch-catch method are performed at both sides of joints. From figure 13, when the cooling time is not enough, the arrival time of ultrasonic signal would be in advance. This is because the residual stress would improve Young's Modulus and then increase both acoustic velocities of P wave and S wave. Besides, the second and third waves in red rectangle under insufficient cooling indicate that there exist possible defects in welded area.

5. Conclusion

In this study, finite element models for ultrasonic non-destructive testing and butt fusion welding were established. Wave propagation characteristics in PE pipes with joints and the process were explored, and the influence of cooling time were discussed. Main conclusions are as follows:

(1) When using a general PMMA wedge to detect a PE pipe, there always exist P wave, S wave and their waveform conversion.

(2) Joints, especially the inner joints, would change the received waveform of ultrasonic non-destructive testing. Besides, the attenuation needs to be considered.

(3) If the cooling time of welding is not enough, it would cause residual stress, which increases the acoustic velocities of P wave and S wave, and may also generate new defects.

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