Research on on-line ultrasonic testing of small diameter thin wall stainless steel straight welded pipe

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Abstract: In the production process of thin-walled stainless steel longitudinal welded pipe, there are many defects, such as cracks, porosity, partial welding, incomplete penetration, incomplete fusion. In this study, a local coupling water tank and six ultrasonic linear focusing probes with a center frequency of 5MHz were used to realize the defect identification of the straight welded pipe in the twisted state through the combined detection of the ultrasonic shear wave, longitudinal wave and creeping wave, which can meet the on-line inspection requirements of small-diameter thin-walled stainless steel straight welded pipe.

1. Introduction
Small diameter thin-walled stainless steel straight welded pipe is widely used in nuclear power, automobile and aviation fields [1]. Most of the welding processes separate heat input from deposition rate to provide a higher degree of control over welding parameters, to obtain high-quality welded pipe. Although the welded pipe has high forming flexibility, the production process relies too much on the continuous adjustment of welding parameters and forming mould by welding personnel. This leads to weld defects such as cracks, blowholes, partial welding, undercut, incomplete penetration, incomplete fusion and other weld defects, especially for the small-diameter thin-walled pipe, the welding seam distortion is caused by the stress caused by pipe forming and welding. The on-line detection of defects such as porosity, partial welding, incomplete penetration and incomplete fusion has become more complicated. The industry has been lack of mature and reliable comprehensive non-destructive testing methods.

At present, the non-destructive testing method of thin-walled stainless steel longitudinal welded pipe is mainly off-line testing, and the detection methods include eddy current testing, radiographic testing, ultrasonic testing and hydraulic testing. Among them, eddy current testing is primarily sensitive to the surface or near-surface defects of stainless steel welded pipe due to skin effect. Still, it is difficult to distinguish the defects inside the weld[2,3]. Radiographic testing is sensitive to volumetric defects. However, it is easy to miss the inspection when the ray direction is consistent with the crack depth direction, and the radiographic inspection is harmful to the human body and has low detection efficiency, which is often used as an auxiliary detection method [3-5]. The hydraulic test mainly determines the quality of the welded pipe by observing the leakage of the pipe wall after pressuring the water medium in the pipe. The main disadvantage of this method is that it can only be inspected. It is challenging to meet the requirements of mass inspection in the production process because of the slow detection speed.
As a common non-destructive testing method [6], the ultrasonic testing method has obvious advantages, mainly reflected in the strong ultrasonic penetration ability, high detection accuracy, suitable for on-site mass on-line detection, etc.

At present, most of the research on ultrasonic testing technology of welded pipe weld defects focuses on off-line manual detection, and shear wave detection is the primary method. There are two main reasons for less off-line high-speed ultrasonic testing of stainless steel straight welded pipe: first, after the stainless steel welded pipe is formed, there may be uncertain torsion in the weld, so it is difficult to determine the exact position of the weld, which is not convenient for accurate detection of the weld; second, because the welded fabric itself and weld internal reinforcement will produce reflection signals, which seriously affects the effective identification of weld defects. In this paper, the local weld defects of thin-walled stainless steel were detected using longitudinal wave and longitudinal wave probe.

2. Local coupling and ultrasonic testing

After the stainless steel welded pipe is formed on-line, there may be a small range of uncertain torsion at the weld position. As shown in Fig. 1, it is difficult to determine its accurate position, which increases the difficulty of on-line ultrasonic testing. According to the process and quality requirements of small-diameter thin-walled stainless steel welded pipe, the allowable angle range of welding seam torsion is 15° counterclockwise and 15° clockwise respectively. Therefore, it is necessary to combine various ultrasonic waves to cover the whole range of effective detection of weld defects. In this study, a local coupling water tank was designed according to the production needs, including the ultrasonic probe adjustment mechanism. Three ultrasonic line focusing probes were arranged on both sides of the steel pipe axis. The probe's incident angle was adjusted according to the steel pipe's diameter to realize the ultrasonic longitudinal wave, shear wave, and creeping wave flaw detection [6-9]. The installation position of flaw detection is shown in Figure 2.

![Fig. 1 weld torsion diagram](image)

2.1 Shear wave detection

As shown in Fig. 3, the acoustic beam emitted by the linear focusing probe is obliquely incident on the workpiece's surface. The transverse wave acoustic beam generated by the waveform conversion on the water/welded pipe surface is used to detect the welded pipe's defects. The distance h between the probe and the surface of the welded pipe should be adjusted according to the stainless steel medium's sound speed to ensure that the bottom wave of the welded pipe weld is before the secondary water interface's reflection wave.
The circumferential pure shear wave testing condition for the welded pipe is that the thickness diameter ratio is satisfied:

\[ \frac{T}{D} \leq 0.226. \]

Where: D and T are diameter and wall thickness of the steel pipe respectively;

At this time, the incident angle of the probe beam should meet the following requirements:

\[ \sin \beta _1 \leq \frac{R}{R} \]

Further:

\[ \alpha \leq \frac{D - 2T}{2\sqrt{DT - T^2}} \]

\[ \frac{T}{D} \leq \frac{1}{2} \left( 1 - \frac{\alpha}{\sqrt{1 + \alpha^2}} \right) \]

Where R and R are the inner diameter and outer diameter of the steel pipe, respectively.

It can be seen from formula (3) that due to the limitation of thickness diameter ratio, the smaller the incident angle is, the larger the detectable thickness of the welded pipe will be. When P-wave's incident angle is between 14.5 ° and 27.1 °, the P-wave is fully reflected, and the end angle reflectivity is 100%.

Because the wall thickness of the welded pipe is generally thin, and the shape of the weld surface and the root is complex, the ultrasonic shear wave is easy to produce deformation wave, and surface wave signal in weld detection interferes with the identification of weld defects. When using the shear wave method to detect the weld, the second wave is usually used. The second wave has a good signal-to-noise ratio for the thin-walled welded pipe, and the external surface of the weld is not flattened, which leads to the serious scattering of the acoustic wave. The direct direction of the primary wave is easy to cause the interference of deformation wave and cylindrical wave \[^{[11,12]}\].

Most of the area type defects (cracks, incomplete fusion, etc.) in the weld of thin-walled stainless steel welded pipe are perpendicular to the base metal's surface or have a certain angle. Suppose the transverse wave detection with small refraction angle is used. In that case, the effective acoustic beam reflection area of the defect is small, and the sound pressure reflectivity is low, so it is easy to miss the inspection. To take into account the radial area defect detection in the weld, the thin-walled butt weld is often detected by large refraction angle shear wave \[^{[13-17]}\].

2.2 Longitudinal wave method

The P-wave method means that when the longitudinal wave beam's incident angle is less than the first critical angle, a longitudinal wave is formed in the welded pipe to realize detection. At this time, there
are both P-wave and S-wave in the welded pipe. Because of its fast propagation speed, P-wave is almost twice as fast as S-wave. When propagating in the same medium, ultrasonic P-wave has strong penetrability. It is not sensitive to grain boundary reflection or scattering, so the workpiece's thickness is the largest among all wave modes.

The coarse grain structure of austenitic stainless steel weld is coarse. The coarse grain has a strong attenuation effect on the ultrasonic wave. The scattering superposition of sound wave leads to false signal, which is difficult to detect by shear wave method. The degree of ultrasonic attenuation depends on the ratio of wavelength to grain size and the frequency. To improve the signal-to-noise ratio of the ultrasonic signal and the accuracy of defect location, the low-frequency longitudinal wave is the most appropriate choice [20].

![Waveform conversion diagram of transverse and longitudinal wave detection](image)

Although both surface wave and shear wave can detect cracks to a certain extent, they can not monitor the cracks with different tendencies. From the geometric verification in Fig. 4, it is found that when there are area type defects parallel or nearly parallel to the detection plane in the weld, the probe is not easy to receive the reflection wave of the shear wave. In contrast, the longitudinal wave's reflection wave with a small angle of 2 ~ 3° is easy to receive [21].

2.3 Creeping wave test
The creeping wave is also generated by the waveform transformation of an ultrasonic wave propagating to the two heterogeneous interfaces. When the longitudinal wave's incident angle from the focusing probe is near the first critical angle, creeping waves, i.e. subsurface longitudinal waves will be generated in the stainless steel welded pipe.

The sound field of the focusing probe is shown in Fig. 5. The sound field excited by the focusing probe has the characteristics of multi-wave type, and the creeping wave and shear wave are generated at the same time. Under the condition that the probe is fixed, the shear wave radiated by the creeping wave propagating along the surface attenuates itself. The creeping wave propagates at a velocity close to that of P-wave. The velocity ranges from 0.8 to 0.9 (\( C_L \) is the velocity of a longitudinal wave in steel), and the direction of the maximum radiation value is at a small angle to the surface [22]. It is almost perpendicular to the thickness direction of the workpiece to be inspected. Therefore, it has a good detection sensitivity for vertical cracks and has the characteristics of less interference by discontinuities such as scratches, irregularities and depressions on the surface of the workpiece.
The detection effect of the creeping wave is the best in several wavelength ranges below the surface of welded pipe (the wavelength of the creeping wave in stainless steel is about 1.9 mm), which can meet the detection requirements of different depth defects of small-diameter thin-walled welded pipe weld [23,24].

3. Experimental demonstration

3.1 Sample control preparation

To verify the effectiveness of the three methods for the automatic on-line detection of the welding seam of stainless steel thin-walled welded pipe, the sample pipe with artificial defects was made. The sample pipe material was 304 austenitic stainless steel welded pipe with an outer diameter of 20 mm and a wall thickness of 1 mm. The automatic argon arc welding process was adopted. According to GB / T 5777-2019 "full circle automatic ultrasonic testing for longitudinal and transverse imperfections of seamless and welded (except submerged arc welding) steel pipes", longitudinal grooves of 10 mm × 0.5 mm × 0.08 mm (length × width × depth, the same below) are carved on the outside of welded pipe weld, ignition pattern of 10 mm × 0.5 mm × 0.08 mm is used on the inside of welded pipe weld, and vertical through-hole of φ 0.4 mm is drilled on welded pipe weld. The grooves and through-holes on the sample tube are located in the heat-affected zone, and their distribution is shown in Fig. 6.

3.2 Ultrasonic signal acquisition

When the ultrasonic signal is collected, the weld's position is always in the upper position, and the weld rotates in the range of 15 ° counterclockwise and clockwise. The detection device mainly includes: 6 panametics series linear focusing ultrasonic longitudinal wave probes with 5 MHz centre frequency, panametics 5800pr ultrasonic signal transmitting and receiving instrument, Ni pci5114 high-speed A / D acquisition card and PC. Six linear focusing probes are divided into two groups. The welded pipe
passes through the local coupling water tank, and the water layer thickness between the probe and the welded pipe is adjusted to 15 mm. The focus position of the focusing probe should be adapted to the curvature of the outer surface and the detection method. The smaller the focus width is, the larger the lateral acoustic beam is. The thinner the pipe wall is, the narrower the focal spot width of the probe is [25-30]. Different ultrasonic waveforms are used to detect different defects shown in Fig. 7, and the defect signals obtained are shown in Fig. 7.

(a) Detection of internal groove echo by shear wave method  
(b) External groove echo detected by shear wave  
(c) Through hole echo detection by shear wave method  
(d) Detection of internal groove echo by creeping wave method  
(e) Detection of external groove echo by creeping wave method  
(f) Through hole echo detection by creeping wave method
3.3 Discussion on test results

(1) According to the ten groups of ultrasonic pulse signals in Figure 7, for the external groove defects of welded pipe, the detection results of S-wave method and creeping wave method are easier to distinguish, and the detection sensitivity of the S-wave method is higher, which meets the needs of online detection of weld defects; for internal defects, the waveform amplitude of S-wave method is obviously lower than that of the other two methods, and the detection effect of the P-wave method is better; for through-hole defects, The three methods have obvious detection effect. Each detection method has little difference in the sensitivity of tube inner and outer wall defects and through-hole detection and has good detection effect. After repeated online test calculation, the sensitivity difference is less than 2dB, which meets the relevant standards' requirements.

(2) Most of the defects of stainless steel welded pipe weld can be identified by measuring the sound energy loss and reflected wave equivalent by shear wave method. It can be seen from the waveform shown in Figure 7 a-c, and different defects can be detected by adjusting different incident angles of the shear wave. In Fig. a, the primary shear wave can be used to detect the groove and crack defects on the inner wall of the welded pipe; in Fig. B and C, the secondary wave can be used to detect the defects on the inner and outer surface, and it is basically not affected by the interface wave. When the longitudinal wave method is used for online inspection of welded pipe welds, the incident angle should be comprehensively considered according to the critical angle of creeping wave and the diameter of welded pipe, so as to ensure that the edge of the sound beam does not generate a creeping wave in the welded pipe, and avoid the appearance of multiple reflections of a sound wave in welded pipe. The creeping wave method has high sensitivity in detecting welded pipe area defects, which can be used for supplementary scanning. The main difficulty of creeping wave in detecting welded pipe near-surface defects is that the surface reflection wave of welded pipe is very strong, and its echo signal may...
submerge the creeping wave signal. The transducer's diameter and position can be selected to suppress the pipe surface reflection wave so that the creeping wave signal can be easily distinguished. (3) Even if the oblique probe's incident angle is within the range of 6, it is still effective to adjust the welded pipe surface's incident angle. As shown in Fig. J, the results show that the welded pipe's internal natural double crack defects are detected after 15° deflection of welded pipe weld.

4. Conclusion

(1) In the welding seam detection of welded pipe, the ultrasonic shear wave method has high sensitivity and accuracy for the defects at an angle with the detection plane. The primary shear wave can be used to detect the root defects of stainless steel welded pipe weld, and the second wave can be used to detect the weld's internal and surface defects. The ultrasonic longitudinal wave method and ultrasonic creeping wave method also have high sensitivity for the defects such as cracks and holes in the welded pipe, which can be used as reference Auxiliary detection method.

(2) In the on-line ultrasonic testing of small-diameter thin-walled stainless steel welded pipe, because the ultrasonic water immersion line focused sound beam propagates along the pipe wall in a zigzag radial reflection mode, it is greatly affected by the curvature and thickness diameter ratio of the inside and outside of the pipe, so the detection sensitivity is affected by the position of the focusing probe. At least 6 line focusing probes should be used, with axial distribution on both sides, and different horizontal distance and incident angle should be set to meet the requirements of shear wave, longitudinal wave and creeping wave detection at different positions. Even if there is small angle torsion in the production process of welded pipe, the probe's incident angle is still within the scope of the effective detection method to realize the accurate identification of different types and different positions of defects in the weld.

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