Investigation on the Inspection Technology of GH3535 Alloy Butt Weld With Linear Array Probe

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Abstract

The critical problem to accurately characterizing defects in GH3535 alloy weld is the deflection of the acoustic beam and scattering due to the coarse columnar grains. Signal-to-noise ratio is an important index to indicate whether the grain scattering is severe in the ultrasonic inspection. In this paper, the phased array ultrasonic testing of GH3535 alloy butt weld was studied using sector scan mode with linear array probe. The soundfield characteristics of the linear array probe with different focusing parameters were analyzed, and the signal-to-noise ratio in the detection was calculated. The results show that: the acoustic beam of the linear array probe can cover the weld, based on the removal of weld reinforcement. The signal-to-noise ratio of transverse hole with $\varnothing 3\text{mm}$ located at the weld-fusion line is more than 15dB, when the front end of the probe is located directly above the transverse hole of weld-fusion line.

1 Introduction

The Thorium Molten Salt Reactor (TMSR) belongs to the 4th generation of nuclear power system, which has a series of unique advantages, including high inherent safety, flexible fuel cycle, availability of thorium based fuel and nuclear non proliferation, etc.^[1-2]. GH3535 alloy processes high-temperature stability and corrosion resistance, therefore, it has been used as a main structural material of the TMSR^[3-4]. The manufacture of the reactor requires a lot of welding, and the integrity of the weld determines the reliability of the reactor. The integrity of weld cannot be separated from Nondestructive Testing. In the implementation of ultrasonic testing, GH3535 alloy weld is characterized by an anisotropic and inhomogeneous structure^[5], resulting in disturbance such as splitting and skewing of the ultrasonic beam along its propagation and deteriorating the signal quality^[6].

The traditional ultrasonic detection method for coarse grain weld is usually low frequency twin crystal longitudinal wave probe. In general, multiple probes with different refraction angles and focusing depths are used for scanning, ensuring that defects with different orientations and depths can be detected. However, this method requires larger mount scanning space. At the same time, it has the problem of long time consuming and low defect detection rate. It is challenging to meet the high quality requirement of GH3535 alloy weld in TMSR. With the development of information technology and probe fabrication technology, PAUT has been widely used to obtain quantitative information on the ultrasonic wave propagation. Meanwhile, PAUT has the advantages of multi-directional and multi-angle scanning, which improve the sensitivity and efficiency in comparison to current capabilities.

Ultrasonic simulation technology, with the advantages of visualization of sound field and cost saving, has been applied in the field of phased array ultrasonic testing. Chassignole et al. analysed the elastic anisotropy and the attenuation of alloy 182 welding through experiment, and the model of conventional ultrasonic detection was built by the FEM code ATHENA 2D^[7]. However, the sound field characteristics of probes and the effective detection area of sound field are not considered in that paper. Rui et al. designed a dual matrix array probe for 316L weld on the basis of CIVA^[8-9]. Although the double matrix array probe

has the characteristics of traditional transmit-receive, the beam is wider than that of the LA probe. Under the same SNR, the LA probe has a higher resolution of defects.

In this paper, the characteristics of sound field of the linear probe were analyzed using simulation. Probe setting parameters and focusing rules were determined by combining the butt weld specimens of reactor pressure vessel shell, and the detection technology of GH3535 alloy butt weld were verified by experiments.

2 Materials And Methods

2.1 Butt weld and test blocks

The circumferential weld of the reactor pressure vessel shell of the (TMSR) was made by the narrow gap automatic welding method, in a horizontal position and with filler materials of 1.12mm diameter. Following industrial practices, the butt welding mold was obtained from the welding certificate along with the reactor pressure vessel. Figure 1 shows the diagram of welding structure. A sample near the fusion line in the middle part of the weld was cutted for microstructure analysis. The crystallographic microstructure and orientation, along the base metal across the heat affected zone (HAZ) to the weld, were mapped with a step of 10 μ m by EBSD.

The reference block was also taken from the welding certificate as mentioned above. The block was designed, referring to the Boiler and Pressure Vessel Committee on Nondestructive Examination 2017 version (ASME PBVC.V-2017) of the American Society of Mechanical Engineers Standards^[10]. Six transverse holes with Φ 3mm were machined in different depths (11.5mm, 23mm, 34.5mm) and positions (weld center and weld-fusion line) of the weld to verify the SNR and feasibility of the detection process. The picture of the reference block is shown in Fig. 2. Two rows of holes are distributed on both sides, one row in the weld center and the other row in the weld fusion line. The transverse holes in the weld-fusion line can verify the SNR of the beam through the base metal and verify that of the beam through weld.

2.2 Instrument and Probe

The ultrasonic phased array test was carried out with the GEKKO 64-128PR device supplied by M2M Company. Data signals were collected and analyzed with a LA probe and a longitudinal wedge (Fig. 3).

LA probe with a longitudinal wedge is usually used to detect coarse grains weld. The LA probe adopts linear delay focusing, while the focusing area of the matrix array probe is a diamond area. The focusing beam of LA probe is narrower than that of the matrix array probe. Therefore, there is a higher resolution of LA probe in the range of detection capability of the probe^[11].

There are many parameters affecting the sound field characteristics of the LA probe, such as the number of channels, the size of array element, the focal length, excitation frequency, incidence angle and so on. Detailed parameters of the probe are shown in Table 1.

Table 1
Parameters of the LA probe and the wedge

Array type	Number of channels	Center frequency	Total active length	Width of element	Incidence angle
Linear array	64	2.25MHz	38.3mm	10mm	19.87°

2.3 Simulation and Detection scheme

The deflection and focusing characteristics of the LA probe determine whether the echo of the weld defect can be captured effectively. In the sound field simulated software CIVA, the longitudinal wave sound velocity and attenuation coefficient of GH3535 weld obtained by experiment are respectively defined as 5530m/s and 0.25dB/mm. According to the data collected by CIVA, the images of the sound field distribution were drawn by the Matlab program. The focus position, maximum sound pressure and the size of focused column were analyzed under the non-focusing or different focusing depths(FD), providing technical support for the subsequent establishment of the focusing law. The specific detection scheme is shown in Fig. 4, which clearly reflects the sound field of the probe through base metal, weld center and across the weld to fusion line.

3. Results And Discussion

3.1 Weld microstructure

The microstructure near the fusion line, including base metal, HAZ and weld, was shown in Fig.5. The base metal had clearly isometric crystal with the grain size of 40-100 μ m. The HAZ includes coarse-grain zone with the grain size of 100-300 μ m and fine-grain zone with that of 40 μ m. Moreover, the weld metal had significantly anisotropic coarse crystal with the grain size up to 500 μ m.

According to the dominant Rayleigh scattering mechanism^[12-13], the wave would be sensitive to a minimum scatter size of $\lambda/10$, resulting in scattering of the grains and attenuating the ultrasonic energy. According to the Snell's law^[14], when the acoustic beam propagates between the grains with different orientations, it is easy to be reflected on the interface, forming grain noise, at the same time, the refraction angle will change, resulting in positioning deviation.

3.2 Sound field of the probe

When the whole elements are excited under the non-focusing state, the sound field of the LA probe is distributed along the natural angle of 58° of the wedge. The length of the near-field area of the LA probe is about 47.4mm, which is calculated by experience formula^[15]

$$N_0 = \frac{A^2}{4\lambda} (1)$$

where A is the excitation aperture, and λ is the wavelength.

Given the propagation of sound waves through the wedge, the length of near

field area of sound wave in the weld is about 25mm, which is calculated by experience

formula^[14]

$$N_2 = N_0 - l \frac{v_1}{v_2} (2)$$

where l is the propagation distance in the wedge; v_1 is the speed of sound in the

wedge; v_2 is the speed of sound in the weld.

Fig.6 (a) and (b) show the sound field and pressure amplitude curve with natural refraction, respectively. The color scale represents the sound pressure amplitude in Fig.6 (a). There is a maximum sound pressure at a depth of about 27mm in the curve, corresponding to the focal area in the S-scanning.

When a focused depth was set to 30mm, the acoustic beam energy was concentrated in the range of the FD (Fig.7(a)). Fig.7(b) shows the variation of focal pressure with different FD. The maximum sound pressure of focus point decreases gradually with the increase of FD. When the FD increases to 40mm, the maximum sound pressure tends to be stable.

Due to the fluctuation of sound wave, there is an interference effect of sound wave near the focus. The focus of the focused acoustic beam is a cylindrical focusing region rather than a point. During the inspection, the location and the size of the focus influence the detective resolution and positional precision. The maximum sound pressure determines the location of focus, and the size of the focus, including the depth and width, are determined by half of sound pressure. Fig.8 shows the change law of the position through setting different FD. Within 20mm depth, the actual focused depth(actual FD) differs little from the FD to be set. As the FD increases, the actual FD deviation increases and is smaller than the FD. When the actual FD reaches 25mm, it tends to be stable with the increase of the FD. The turning point of 25mm corresponds to the depth of the near field of the sound field mentioned above. Once the FD exceeds the near field, it will lead to deviation in the quantification and location of defects. Fig.9 shows the change law of size of actual focus by setting different FD. As the FD increases, the length and width of the effective focusing region increase, which also indicates that the diffusion of the acoustic beam becomes larger and the directivity of the acoustic beam decreases. Furthermore, the near field and directivity of a probe are related to the structure of the probe itself, such as the number, spacing, size of channels and other designed parameters. These factors are not described in detail here.

To ensure the detection of defects and high efficiency, this paper adopted S-scanning projection focusing mode. According to the above simulation results of sound field distribution, the weld area was covered as much as possible by the sound field of the probe. The focus law parameters in butt weld are listed in Table 2. The horizontal projection distance was set to 20mm, and the scanning angles ranged from 30° to 85°. The horizontal displacement from weld center was set to -10mm. Fig.10 shows the distribution of sound field under the focus law. If one focus law can meet the requirements of weld inspection coverage, it can reduce the number of zone scanning and improve the inspection efficiency. As shown in Fig.10, the acoustic beam can cover the entire thickness of the weld. When the front end of the probe is close to the weld center, the upper surface can be inspected.

Table 2 Focus law parameters in butt weld

focusing distance	Scanning angle range	Main beam angle	Depth coverage with main beam -6dB	Detecting depth
20mm	30°-85°	58°	10-34mm	0-46mm

3.2 Detection results

According to the above detection setting, the reference block was inspected with a perpendicular beam. The S-display was recorded when the amplitude of $\phi 3\text{mm}$ side transverse hole was up to 80%. At the same time, the SNR of these $\phi 3\text{mm}$ side transverse holes in different depths was recorded.

Fig.11(a-c) are the S-display of $\phi 3\text{mm}$ side transverse holes with a depth of 11.5mm at different locations of weld, which visually shows the change of the background noise. The horizontal displacement from weld center was set to -10mm. When the amplitude of the three holes with a depth of 11.5mm reaches 80%, the reflected sound pressure values are different on the three locations, although they have the same depth. The background noise is mainly invisible (Fig.11 (a)), when the beam crosses over the base metal, apart from the interference signal on the coupled surface. The noise of the beam across to the weld center (Fig.11 (b)) is comparable to that through the base metal. However, the noise of the beam across the weld to fusion line is serious (Fig.11 (c)). In this case, some minor defects may be missed due to the lower SNR. Fig.12 shows the S-display of $\phi 3\text{mm}$ side transverse holes with a depth of 34mm at different locations of weld, which visually exhibits the change of background noise.

Fig.13 gives the sound pressure values and SNR of $\phi 3\text{mm}$ side transverse holes at different depths in all three cases. The results show that the sound pressure values of $\phi 3\text{mm}$ transverse holes in the fusion line on the opposite side of the weld increased by 7dB compared with that on the side of the base metal. At the same time, the SNR decreased by 8.7dB, the SNR of the beam across the weld to fusion line is only 10.6dB; this is consistent with the increase of the background noise in Fig.11(c). According to the ASME PBVC. V-2017 Standard, the signals with more than 20% of the amplitude need to be recorded and qualitative analyzed^[10], suggesting that the SNR cannot be lower than 12dB during the detection.

There are two main reasons why three different positions at the same depth are different. One reason is the scattering due to the coarse microstructure. According to the Rayleigh scattering mechanism mentioned above, the scattering will occur when the weld grain size exceeds 240mm. However, the grain size of GH3535 alloy weld obtained by metallographic observation is up to 500 μ m. There will be obvious scattering, resulting in the reduction of the penetration ability of the acoustic beam, reducing the amplitude of the reflection echo, and increasing the grain noise. The grain size near the fusion line is coarser than that of base metal. Therefore, the echo and the SNR decrease when the beam crosses over the weld. The other reason is the effectiveness of beam deflection. The beam energy tends to be concentrated near the main beam. With the deflection angle away from the main beam, the energy gradually decreases(Fig.10). According to the distribution of the sound field in Fig.10, the distance between the probe and the fusion line can be shortened so that the acoustic beam energy covers the upper surface of weld.

Fig.14(a) and (b) show the S-display of ϕ 3mm side transverse holes on the fusion line at the horizontal displacement from weld center-10mm and +10mm, separately. The weld was penetrated and covered by the acoustic beam. The SNR of the latter one is significantly higher than the former one. However, the latter one requires the weld reinforcement to be polished smoothly. One half width of the weld is covered by the acoustic beam and the other half needs to be inspected from the other side using the same process.

6 Conclusion

- (1) The simulation of the sound field of the LA probe shows that the phased array can realize the deflection focusing of the beam. With the increase of FD, the actual FD increases and tends to be stable. Meanwhile, the effective focusing area expands and tends to be stable.
- (2) Based on the removal of weld reinforcement, it can effectively detect the ϕ 3mm side transverse holes of GH3535 alloy weld in the thickness of 46mm by narrow gap weld. At the same time, the SNR is greater than 15dB, meeting the requirement of standard.
- (3) Considering the scattering effect of weld during the actual detection, it is suggested to take the transverse hole on the fusion line with beam across to the weld as the detection sensitivity, and carry out bilateral scanning to ensure the detection of dangerous defects.

Declarations

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare no competing interests.

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Authors' Contributions

XY was in charge of the whole trial; XY wrote the manuscript; ZY carried out the simulation test; ZL, KY and JW assisted with sampling and inspection analysis. All authors read and approved the final manuscript.

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Figures

Figure 1

The diagram of welding structure

Figure 2

The Picture of reference blocks

Figure 3

Profile of LA probe and wedge

Figure 4

Schematic diagram of experimental test (a) Base metal (b) Weld center (c) Fusion line on the opposite side of probe

Figure 5

The microstructure map of weld

(a) Sound field (b) Sound amplitude curve

Figure 6

Sound field and pressure amplitude curve with natural refraction

(a) Sound field of the FD at 30mm (b) Variation of maximum pressure

Figure 7

The effect of the FD on the sound field and focuses pressure of 58° beam

Figure 8

The contrast between FD and actual FD at 58° beam

Figure 9

The change of focus size with the FD at 58° beam

Figure 10

Sound field simulation of focus law 30°-85°

(a) Base metal(b) Weld center (c) Fusion line at the opposite side of probe

Figure 11

S-display of $\phi 3\text{mm}$ slide drilled holes with 80% amplitude at different positions in 11.5mm depth

Figure 12

S-display of $\phi 3\text{mm}$ slide drilled holes with 80% amplitude at different positions in 34mm depth

Figure 13

The amplitude curve and SNR of $\phi 3\text{mm}$ side transverse holes at different positions

(a) -10mm

(b) +10mm

Figure 14

S-display of $\phi 3\text{mm}$ side transverse holes with 80% amplitude at different horizontal displacement from weld center (a) -10mm (b) +10mm