Power Plant Small-diameter Tube Phased Array Inspection Verification and Inspection Technology

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Abstract. In this paper, the phased array inspection is carried out on the small diameter pipes with artificial groove defects and natural defects, and then the conventional ultrasonic inspection and the penetration inspection after cutting and dissection are carried out respectively. The ultrasonic phased array inspection results are compared with the conventional ultrasonic and compared with the results obtained from penetrant testing, the reliability of ultrasonic phased array testing technology in the application of small-diameter pipe testing is analyzed. Then, taking the detection of the small pipe socket of the high-temperature superheater header of Huadian Weifang Power Plant as an example, it is verified that the ultrasonic phased array detection is feasible in the detection of small diameter pipe welded joints. Finally, the ultrasonic phased array testing process and testing technology of power station boiler small-diameter pipes are summarized, and the development direction of phased array testing application in power plant equipment inspection is prospected.

1. Introduction
The electric power industry has developed rapidly in recent years. With the increase in the pressure and temperature of the working medium of units, the requirements for the level of boilers metal materials of power station and the welding quality control and non-destructive testing techniques have also become higher and higher. The small diameter pipe of the power station has a small outer diameter and a thin pipe wall. It is extremely difficult for conventional ultrasonic inspection to complete a comprehensive coverage scan of the weld, resulting in missed inspections. While radiographic inspection has the main disadvantages of large radiation and long inspection cycle. Therefore, the ultrasonic phased array detection technology is gradually introduced into the detection of small diameter pipes in power stations. This paper verifies the reliability of the phased array detection results of small diameter pipes in power stations through comparative experiments, and writes down the small diameter pipes general inspection techniques and procedures.
2. **Comparative test method**
Doppler's ultrasonic phased array detector with 7.5S16-0.5×10-D10 natural focus probe and SD10-N60S-FLAT curved wedge was used. The GS test block was selected as the standard test block. The scanning sensitivity is set to 36 dB, and the engine oil was used as couplant. Two sets of comparative tests were carried out to verify the defects detection results for the base metal of the small diameter pipe and the butt weld, respectively.

3. **The test results**

3.1. **The verification of near surface defects of pipe**
Take a section of φ47.5×7 mm small diameter pipe, cut a V-groove artificial defect with a depth of about 1 mm, and use a calibrated ultrasonic phased array flaw detector for inspection, as shown in Fig. 1. Due to the small outer diameter of the small-diameter pipe of the power station boiler, it is difficult to maintain stable contact between the ultrasonic probe and the pipe when scanning and verifying reflection. This kind of inspection difficulty is solved by using a manually operated ring-encoded scanner, as shown in Fig. 2. The scanner can make the probe and the small diameter pipe to be inspected firmly contact.[4]
The conclusion of the inspection shows that the ultrasonic phased array inspection can detect the defect of 1 mm deep near the surface of the small diameter pipe. And the performance meets the requirements of JB/T10061-1999 after calibrate the instrument with the A-type digital pulse ultrasonic flaw detector. To make DAC curves with the DL-1 test blocks and 2.5P6×6K3 shear wave oblique probes according to DL/T820.2-2019 Technical Regulations for Ultrasonic Inspection of Pipeline Welded Joints. Then, the probes are used to scan the artificial defect positions in a zigzag pattern. The experimental results show that the near surface belongs to the detection blind zone, and the first wave cannot be effectively tested.

3.2. The verification of internal defects in welded joints

In order to verify the results of ultrasonic phased array testing of welded joints of small diameter pipes, a plurality of small diameter pipes with natural defects in boiler parts of a power plant were cut and dissected. And the detection data were compared with ultrasonic phased array inspection and penetration inspection to verify the reliability of the results of ultrasonic phased array testing of small diameter pipes.

The small-diameter pipe for verification is shown in Fig. 4. The size of the small-diameter pipe is φ60×7.5 mm, and its material is 12Cr1MoV. We take 3 small-diameter pipes with natural defects which were denote as 1, 2, 3, respectively.

![Fig. 4.Small diameter tube used for comparison verification](image)

First, the welded joints of the selected small diameter pipes were detected using the ultrasonic phased array equipment. The equipment is the aforementioned Doppler equipment, with a 7.5S16-0.5×10-D10 natural focus probe and SD10-N60S-FLAT curved wedge. The GS test block is selected as the standard test block, as shown in Fig. 5. The scanning sensitivity is set to 36 dB, and the engine oil is used as couplant. The defect detection results are shown in Table 1.

| Defect parameters | 1   | 2   | 3   |
|-------------------|-----|-----|-----|
| Defect depth      | 3.8 mm | 5.7 mm | 7.0 mm |
| Defect length     | 3.7 mm | 2.9 mm | 2.3 mm |
| Defect height     | 2.5 mm | 2.7 mm | 2.9 mm |
Fig. 5. GS test block

The results of ultrasonic phased array testing for welded joints of small diameter pipes numbered 1, 2, and 3 are shown in Figs. 6, 7, and 8.

Fig. 6. Phase array detection results of small diameter pipe 1
Fig. 7. Phase array detection results of small diameter pipe 2

Fig. 8. Phase array detection results of small diameter pipe 3

After the results of the ultrasonic phased array inspection are saved, the horizontal position of the defect is marked on the surface of the welded joint. And the small diameter pipe is dissected longitudinally and the welded joint is dissected at this position, as shown in Fig. 9 and Fig. 10, respectively.
Fig. 9. Anatomy of the longitudinal line of the small diameter pipe

Fig. 10 Lateral anatomy of small diameter pipe welded joint

The penetrant inspection is performed on the cut small diameter pipe. The process standard is NB/T47013.5-2015 " Non-destructive Testing of Pressure Equipment Part 5 Penetration Inspection ". The defect parameters found in the penetrant inspection are shown in Table 2.

Table 2. The defect parameters after penetration testing

| Defect parameters | 1   | 2   | 3   |
|-------------------|-----|-----|-----|
| Defect depth      | 3.9 mm | 5.3 mm | 6.8 mm |
| Defect length     | 3.9 mm | 3.0 mm | 2.5 mm |
| Defect height     | 2.8 mm | 2.9 mm | 3.1 mm |

The results of the two detection methods are compared and analyzed, and the data comparison is shown in Table 3.
### Table 3. Comparison of the results of the two test methods

| Defect parameters | Detection method  | Whether to check out | 1    | 2    | 3    |
|-------------------|-------------------|----------------------|------|------|------|
|                   | Phased array      | Yes                  | 3.8 mm | 5.7 mm | 7.0 mm |
|                   | Penetration       | Yes                  | 3.9 mm | 5.3 mm | 6.8 mm |
| Defect length     | Phased array      | Yes                  | 3.7 mm | 2.9 mm | 2.3 mm |
|                   | Penetration       | Yes                  | 3.9 mm | 3.0 mm | 2.5 mm |
| Defect height     | Phased array      | Yes                  | 2.5 mm | 2.7 mm | 2.9 mm |
|                   | Penetration       | Yes                  | 2.8 mm | 2.9 mm | 3.1 mm |

From the comparison of defect data of ultrasonic phased array inspection and penetration inspection, it can be concluded that both the inspection methods can detect defects in small diameter pipe welded joints. However, there are differences between the parameters of defects. The data of penetration testing is larger than that of ultrasonic phased array testing. This is mainly because the principle of penetrant detection is capillary phenomenon. The red penetrant is adsorbed and filled among the developer particles. In the process of displaying the shape of the defect, the defect is naturally enlarged.

Compared with ultrasonic phased array inspection, penetrant inspection has two shortcomings. First, as the conclusion from the above comparison data, penetrant inspection has the insufficiency of magnifying the size of the defect. Moreover, it will inevitably cause errors that used the eye and measuring tools to measure defects. Second, penetration testing can only detect surface opening defects of small diameter pipe welded joints after cutting, and cannot detect internal defects or near-surface defects.

Ultrasonic phased array testing uses computer software to evaluate, measure, and analyze the testing data, reducing the deviation, and the testing results are relatively objective and accurate. Therefore, the results of ultrasonic phased array testing can more truly reflect the defects. Moreover, ultrasonic phased array inspection can now display both A scan and sector scan at the same time, which is more conducive to the judgment and analysis of the nature of defects.[5,6]

#### 3.3. Summary

Through the comparison of the phased array inspection of small diameter pipe and butt welds, it is proved that the phased array inspection method is faster than the conventional inspection method. The inspection results are intuitive, reproducible, and can be displayed in real time. The weld can be analyzed and scanned while scanning. Moreover, the defect location is judged accurate with this method, and the detection sensitivity is high [7-9]. Finally, a phased array inspection process for specific components is formed, which plays an important role in the supervision of the metal technology of the power plant. In this case, the inspectors will have more confidence in the safety of the equipment and ensure the safe operation of the unit after repair.

#### 4. Practical application

More than 1,200 small-diameter pipes are installed on the high-temperature superheater header of Huadian Weifang Power Plant for temperature or pressure sensing sampling, medium transfer and drainage. These small-diameter pipes have an outer diameter of 108 mm or less, and are mainly made of alloy materials such as P91 and 12Cr1MoV. Because these small diameter pipes are affected by vibration and temperature changes, they are prone to high-cycle fatigue cracks, which can lead to failure. Although the failure of welding of small-diameter pipe sockets has a little impact on the safety of power plant operation, the power supply interruption caused by the loss of production capacity and the shutdown for maintenance purposes will cause serious economic losses.

At present, Huadian Weifang Power Plant conducts conventional manual and automatic ultrasonic tests on small-diameter pipe socket welds. However, due to the limitations of the reachable area, the reliability of the inspection is reduced. In order to solve the problem, we tried to use ultrasonic phased
array testing technology to inspect the welded joints of the four main pipe sockets of the power station and the welded joints of the high-temperature superheater header pipe row. During the actual inspection on site, more than 10 defects were found. Weifang Power Plant conducted cutting verification and found that the inspection result was completely correct, as shown in Fig.11. This inspection eliminated the hidden danger of defects in the header of the high-temperature superheater, and provided a reliable guarantee for the safe and stable operation of the power station. It fully verified the feasibility of the phased array technology to detect the small diameter pipe of the power station.

Fig. 11. Phased array inspection found defective socket

5. Ultrasonic Phased Array Inspection Process and Technology of Small Diameter Tube

The application of ultrasonic phased array testing technology to the field of non-destructive testing of power station components is still in its initial development stage in China, and there is no different testing process for professional equipment components. Combined with the actual operation in Huadian Weifang Power Plant this time, the phased array inspection process of power station boiler small-diameter tubes was obtained, and it has been extended to China Huadian Group. This process is a theoretical extension based on the principle of phased array detection, and has important reference significance in the inspection and detection of small-diameter tubes of actual power station boilers.

5.1. Inspection process

1. Select appropriate instruments, probes, qualified phased array ultrasonic detectors, self-focusing curved surface wafer linear array probes, and probe wedge that can be equipped with the curvature of the inspected pipe [10,11].

2. Select the appropriate test block. The instrument performance test and calibration select CSK-IA test block and sound beam control evaluation test block, respectively. DL-1 type contrast test block is used for measuring probe parameters.

3. To calibrate the instrument and probe system. The scan line and sensitivity on the comparison test block should be checked before testing, and the encoder should be calibrated.

4. Clean the testing surface. Before testing, clean the splashes, rust, oxides and other pollutants in the moving area of the probe.

5. Determination of the focal law. The focal law is determined according to the selected scan type. It is necessary to determine the parameters of the wafer, module parameters, number of wafers, position, angle, distance, sound velocity, workpiece thickness, probe position, focusing sound path or depth.

6. It is necessary to cover the detection area, refer to the parameters of the focus law. Using the simulation software to adjust the distance of the welding edge, and determine the position of the
7. Drawing the DAC curve. Of course, the detection parameters need to be set and optimized before the curve is made. For example: workpiece thickness, sound path, sound velocity, display delay and suppression settings, the optimization of excitation mode, pulse width, excitation level and pulse repetition frequency, as well as the settings and optimization of filters, low-pass filtering, high-pass filtering, and detection modes. In addition, one need to set the starting point, door width, door height, as well as the excitation quantity and starting position.

8. The scan method detection, such as: scan sensitivity, scan mode, scan step, and display the scan image, and scan speed.[15]

9. To quantify and rate defects. It is necessary to quantify and evaluate defects based on corresponding data.

5.2. The adjustment of detection parameter

In the process of ultrasonic phased array detection of small diameter pipes of power station boilers, it can be roughly divided into two situations. One is to increase the detection speed, and the other is to increase the detection rate. When one want to increase the detection speed, we need to increase the acquisition frequency, the speed of the scanner, the size of the sound beam, and the acquisition step, at the same time, to minimize the number of A-scans, and the acquisition range, in addition to use dynamic focus. When it is necessary to increase the defect detection rate, it need to increase the working frequency, reduce the scanning speed, increase the fan scanning accuracy, use an appropriate aperture size, add additional scanning groups to use different gains, and use filters. Of course, the detection rate is also related to the characteristics of the workpiece itself, such as, thickness, structure and surface roughness.[16]

6. Conclusions and Outlook

6.1. Conclusions

Based on the current detection technology status of power plants, the ultrasonic phased array detection technology was introduced, and the test sample detection and actual detection applications were carried out on the pressure-bearing small diameter pipes of power station boilers. The main conclusions are as follows:

1. Perform phased array inspection on small diameter pipes with artificial groove defects and natural defects, and then perform conventional ultrasonic inspection and penetrant inspection after cutting and dissection respectively. The ultrasonic phased array inspection results are compared with the conventional ultrasonic and penetrant inspection results, and the reliability of the ultrasonic phased array inspection technology in the application of small diameter pipe inspection is analyzed.

2. Taking the detection of the small tube socket of the high temperature superheater header of Huadian Weifang Power Plant as an example, it is verified that the ultrasonic phased array detection is feasible in the detection of small diameter pipe welded joints.

3. This paper summarize the ultrasonic phased array testing process and testing technology for small diameter pipes of power station boilers.

6.2. Outlook

In recent years, with the development and application of ultrasonic phased array detection technology, this technology has become one of the most commonly used detection methods in actual detection. It not only has high precision, fast detection speed, but also optimizes detection results and improves defect recognition and has very strong practicality in actual production. For electric power construction enterprises, this method can meet the requirements of welding defect detection, and can also realize the simultaneous detection work and installation as well as the welding operations. It can also replace the radiographic inspection method to reduce safety management risks and reduce the
impact on the construction period to lowest. Therefore, the in-depth research and development of phased array ultrasonic testing technology is very necessary.

In the process of verifying and comparing the ultrasonic phased array detection technology of power station boiler small-diameter tubes, we found several deficiencies in the ultrasonic phased array detection technology. This is also the future research direction of ultrasonic phased array:

1. The failure of a chip in the array will inhibit phase interference and beam formation.
2. The phased array equipment, supporting probes and software are 10-20 times more expensive than conventional instruments.
3. It need to have compound talents in computer, imaging and ultrasound at the same time. Human factors will affect the determination of the test results. In the process of ultrasonic phased array testing, the adjustment of equipment is much more difficult than conventional ultrasonic equipment, such as delay calibration, TCG calibration, sensitivity compensation, etc.
4. In the current phased array inspection of fan formation, most of the defects are shown as elliptical. In the future, we can continue to study to remove the noise in the sound field, optimize the defect display, so as to reflect the defect imaging more truly.
5. When the structure of the workpiece is complex, the limit of the fan sweep angle must be adjusted at any time. This experiment is only aimed at the verification of ultrasonic phased array detection technology for small-diameter pipes in power station boilers. In the future, there will be parts such as the roots of power station steam turbine blades and rotor shaft diameters waiting for verification and comparison.

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